AN ABSTRACT OF THE THESIS OF

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Jack F. Higginbotham

Exposure to moderately high levels of ionizing radiation (<20 Gy) has in some instances shown a hormetic effect in numerous vegetable-type crops. Past experiments performed in outdoor cultivars have shown a somewhat unpredictable increase in growth rate with a higher overall yield in a specified time when the seeds are exposed to ionizing radiation prior to germination.

This experiment has attempted to eliminate potentially confounding variables in the growth of a legume utilizing an Environmental Protection Agency controlled green house. The experiment was a completely randomized block design with six blocks and seven treatment groups. Each treatment group of pinto beans (Phaseolus vulgaris L.) were exposed to ^{60}Co radiation, given doses of 5-20 Gy, planted and grown for 40 days.

Due to the symbiotic relationship with rhizobium bacteria within a seed, the expected result was a lowered nitrogen fixation capacity as bacteria concentration was reduced due to sterilization by the high energy gamma, yielding a smaller plant mass. The predicted trend in reduction would be described by the linear no-threshold model.

A statistically significant increase in overall plant mass occurred in the 5 Gy treatment group, with a subsequent linear trend in mass reduction at treatment levels of 7.5, 10, 12.5 and 15 Gy. The overall quality and plant mass decreased markedly at a treatment level of 20 Gy. Additional possible contributions to plant differences in growth within a green house were light intensity, temperature, CO_2 level and soil water retention. The complete randomized block design attempts to remove these as potentially confounding variables.

Hormesis Effects in Pinto Beans From ^{60}Co Gamma Radiation

by

Darren M. Boone

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Darren M. Boone, Author

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1. INTRODUCTION

During the past two decades, land use has become more restricted, less available and over utilized in the farming community. Farmers must continually research new methods of crop production that have the potential to increase overall output per acre while conforming to stringent environmental regulations for fertilizer application. Numerous research projects have been conducted with the goal of shortening germination and crop cycle times.

Since at least 1975 there have been successful experiments which proved that exposing dormant seeds to ionizing gamma radiation would achieve the goal of shorter germination times and overall growth to maturity. The experiments yielded unpredictable results in that reliable results were obtained but with varying end points.

In an effort to produce statistically reliable results an experiment was designed utilizing an environmentally controlled green house where light intensity, period and temperature could be held relatively constant on a daily basis. A complete randomized design was used in a green house supplied by the Environmental Protection Agency to provide the most stable conditions available. Even with the best efforts, conditions of light intensity, temperature and CO_2 levels vary across a given bench in an enclosed environment such as a green house. To largely eliminate these potentially confounding variables and determine the extent of the differences, a completely randomized block design was performed which exposed each treatment group to the same possible environmental conditions on an individual unit basis.

2. LITERATURE REVIEW AND BACKGROUND

2.1 Radiation Hormesis: An Overview

Hormesis is best characterized as a process whereby low doses of an otherwise harmful agent, can cause a beneficial effect through some type of stimulus. This type of effect is most commonly found in nature where different levels of biological response can be found due to exposure to chemical and physical hazards.

In the study of the effects of radiation in environmental situations as in other disciplines of science, certain assumptions exist which interlock sets of assumptions regarding the operation and function of complex systems. This phenomenon is known as a paradigm. These interlocked assumptions generally dictate the direction of research and the acceptability of results. Data or theories which fall outside of an accepted paradigm are generally disregarded or even suppressed.

Environmental sciences definitely have their own paradigms. The set of theories most widely accepted concerning exposure to biological observations is that responses observed at high levels are representative of observations at much lower levels. Consequently, theories from interpolation of high level exposure influences acceptable results at levels slightly above background. Typically, a theory termed the linear no threshold theory (LNT) is widely accepted in the health physics community. The theory basically states that exposure to radiation or other environmental hazards is somewhat harmful at low levels with a linear increase in risk as level increase. Review of several articles reveal what appears to be to the contrary. (Sagan, 1987, Pergammon)

2.2 Factors Controlling Plant Response To Ionizing Radiation

The response in experimentation involving ionizing radiation can be explainable due to factors other than the radiation. These factors can potentially mask or confound the results and must be thoroughly researched in an attempt to identify and account for or eliminate possible sources of error.

2.2.1 Cultivar and Seed Lot Effects

Several researchers have observed hormesis only in certain cultivars (Shamsi et al., 1978). There were cultivars which when used produced a hormesis effect even when the experiments were several years apart (Simon, 1977). These differences in cultivars may be explained by seed vigor.

A separate explanation of differences between the cultivars may be due to the differences in seed lots. Vigor of the seed lot depends largely on the environmental conditions present during the growth of the parent plant as well as handling of the seeds. Some seed lot differences such as differences in moisture content are easily recognized and do in fact have a considerable effect in determining the level of hormesis, observable in Figure 1. (Bhattacharya, 1977). Of particular note however, is that experimentation has shown that manipulation of seed moisture content alone does not seem to cause a hormesis effect (Sheppard, 1987).

Other seed lot characteristics may be equally as important in the final analysis. A hormesis effect was observed (Sheppard, 1987) for seeds from the same lot when fresh but not when stored for a year.

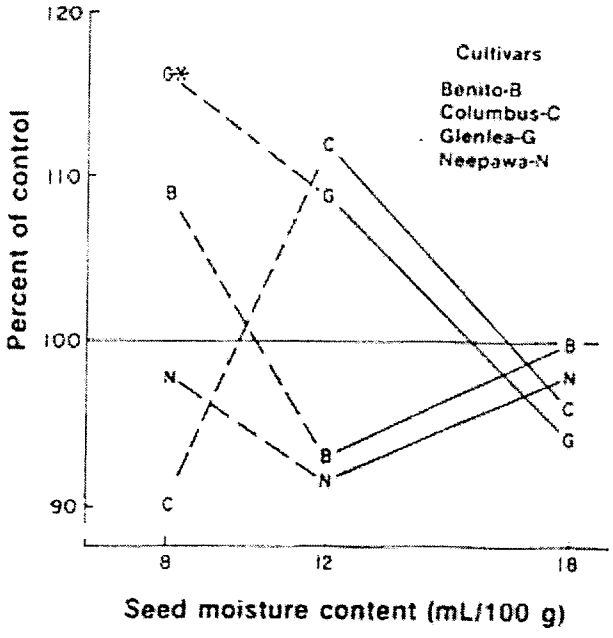

Figure 1. Effects of seed moisture content on overall plant growth.

2.2.2 Storage Time After Irradiation

A significant difference in hormesis response is likely if the seeds are allowed to sit for an extended period of time following irradiation and prior to planting, as noted in Figure 2. The response seems to be irrespective of the biological mechanism causing the hormesis. (Simon, 1977; Bariga, 1978).

2.2.3 Timing of Measurement

Seeds are extremely small when compared in size to the plants they produce. Logic dictates that the earlier in the growth cycle a particular plant is harvested and analyzed, the more pronounced the hormesis effect. Measurement of the plants at a later stage of development could very possibly mask any notable increase in growth rate or overall size in a given time. Measurements taken during the early stages of growth show an increased rate of emergence over non irradiated groups evident in Figure 3. This in no way implies however that an increased crop yield will be experienced after fully matured (Sheppard, 1987).

2.3 Mechanisms of Plant Growth

Pinto beans (Phaseolus vulgaris L.) develop from seeds that have two cotyledons , grow into plants with netted leaf venation, and produce flowers with parts in fours or fives or multiples of four or five. The vascular tissue in the dicot stem forms a circular pattern when viewed incross section (Mix, 1996).

Plant growth and cell differentiation occur from a small crown of cytologically active cells (the apical meristem) in a roundish or dome shaped cluster a the tip of the

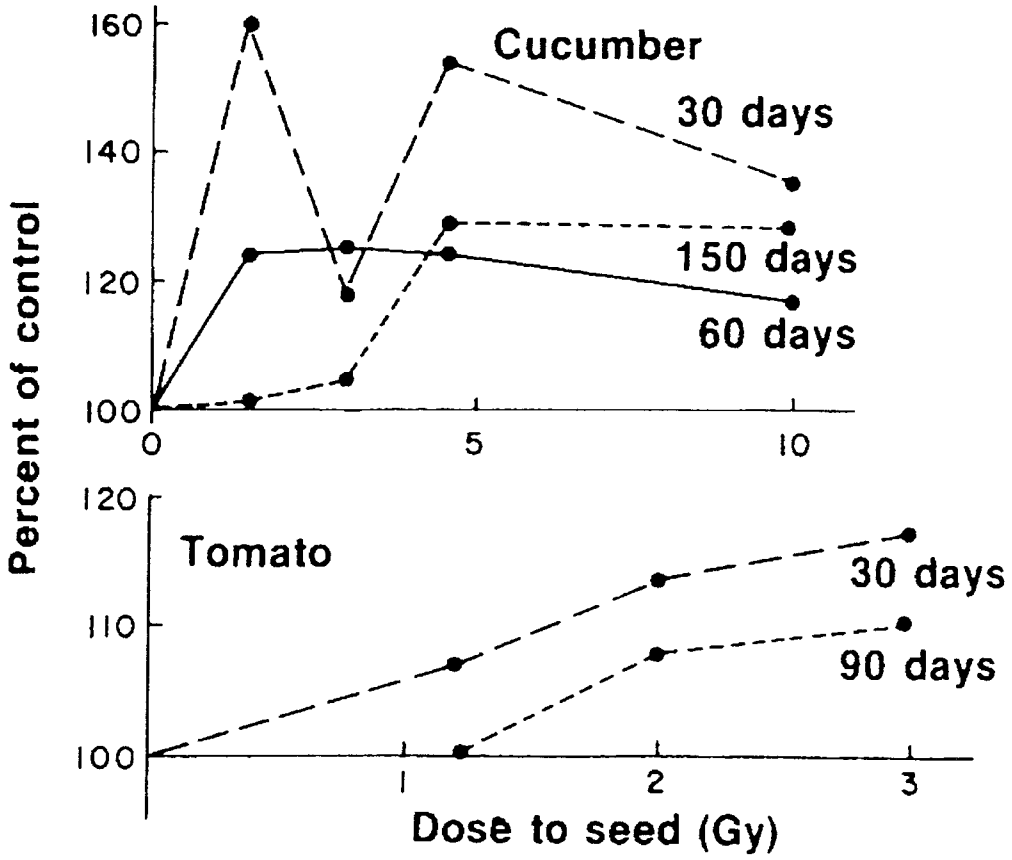

Figure 2. A significant difference in hormesis response is likely if the seeds are allowed to sit for an extended period of time following irradiation and prior to planting.

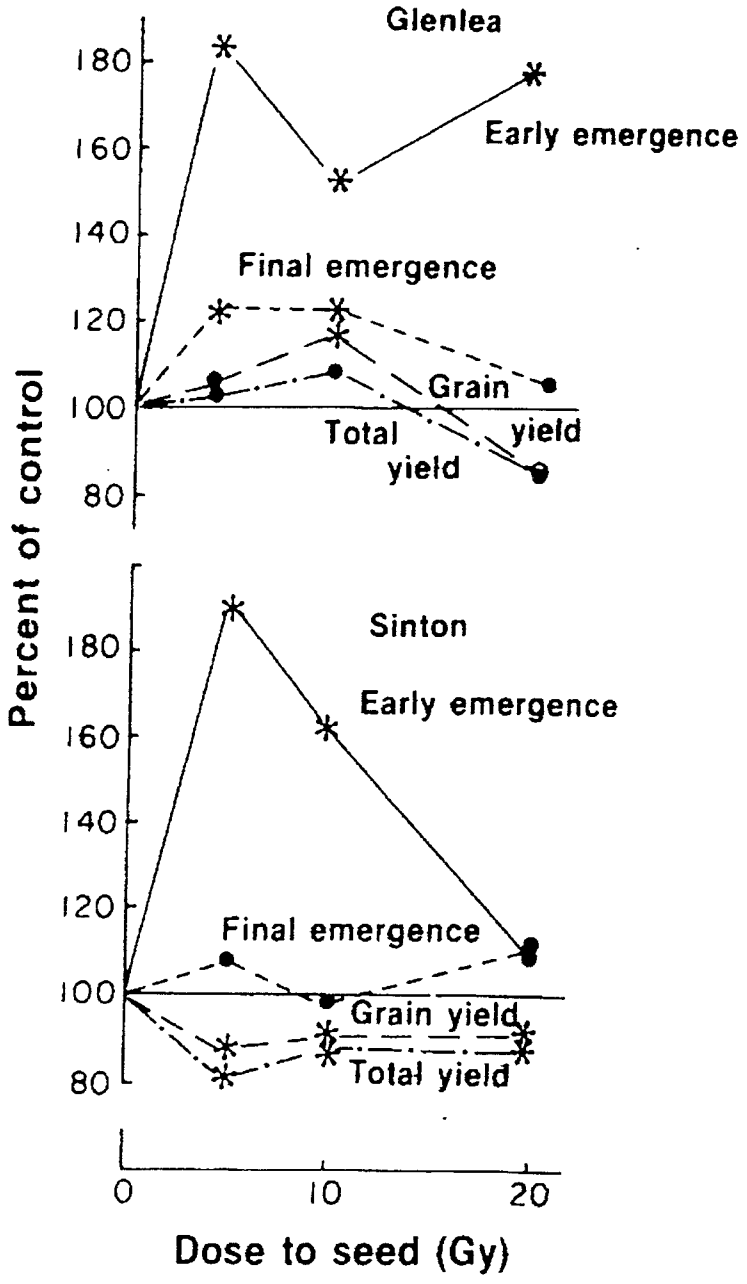

Figure 3. Measurements taken during the early stages of growth show an increased rate of emergence over control groups with no exposure.

stem. The meristem determines whether cells will be cut off for leaf and stem formation or maintain the meristem itself. The root has a meristem as well which is much more simplistic in function, it serves only two purposes, to promulgate root growth and maintain the meristem.

Development of root and stems is controlled by a growth hormone (Gordon, 1957). They are effective in very minute quantities and may either stimulate or inhibit growth. For example, the main stem apical meristem produce hormones which effect the elongation and differentiation of the cells it produces. The same hormones may inhibit the axillary meristem, holding them nearly dormant until the inhibiting hormone is either removed or the concentration is extremely low.

There are many biological parameters which may affect plant sensitivity to radiation. The most widely accepted theory deals with the relationship between the organism's interphase chromosomal volume (ICV) and biological sensitivity. Simply stated, the larger the ICV the greater the sensitivity (Sparrow, 1963). This relationship applies to a wide variety of organisms from the bacterial level to mammals and plants (Sparrow, 1967; Underbrink, 1968; Kaufman, 1970). The ICV is generally derived from a measurement of the diameter of an interphase cell nucleus, its volume and the division of the nuclear volume by the chromosome number for that species. When considering plants and ICV, typically the overall nuclear volume may be used as an indicator of overall size. Given this, a plant would be expected to be less sensitive to ionizing radiation if they contain smaller nuclei and/or are not mitotically active. This explanation

leads to the theory that systems such as seeds, which are considered to be mitotically inactive could tolerate much higher levels of ionizing radiation than a developing plant (Miller, 1987).

3. METHODS, MATERIALS AND EQUIPMENT FOR SEED IRRADIATION AND GROWTH

Numerous experiments have been conducted on the subject of radiation hormesis, both in plants and animal type systems. Results while positive are not predictable and often seem to vary between experiments and researcher. Quite possibly, these differences are from confounding variables beyond the control of the researcher which are different between locations and vary depending on statistical experimental design and implementation.

Inconsistencies in experimentation are available for review in well over 200 published articles (Miller, 1987). Using various end points for analysis such as height, fresh and/or dry weight, number of stems, number of flowers and fruits, weight of fruit, and number of leaves, results varied widely. Reports differ in the basic setup in that some did not observed a stimulation, different levels of ionizing radiation were used, no replication existed and often, no statistics were used to support conclusions. Further more, some experiments were not conducted as a single or double blind, meaning that the researcher may have had an advanced knowledge of the treatment groups prior to final analysis.

In an effort to design a repeatable experiment for observing the hormesis phenomenon , careful consideration was used in the statistical design. The location was as controlled as possible in order to eliminate potentially confounding variables. An environmentally controlled green house supplied by the Environmental Protection Agency was used as the starting point for this experiment. Two separate experiments

were conducted in order to provide a comparison of methods. A complete randomized design and a completely randomized block design were used.

3.1 Complete Randomized Design and Objectives

The first design used was the complete randomized design. This statistical experimental design assumes that there are no uncontrollable or controllable potentially confounding variables present which could adversely or uncontrollably effect the outcome of the experiment. This design is simple and straight forward and requires only a single stage of randomization. This random element ensures that if a biasing factor is present, it will be distributed evenly among all of the available treatment groups. The green house bench is divided into physical segments which are designated as available planting locations. Each plant is a numbered unit which is assigned a growth location based on numbers taken from a random number table. The distribution of units is not available.

3.2 Randomized Block Design and Objectives

In any experiment, particularly of a biological nature, there is a degree of variability that arises from a nuisance factor which can impact the results. A nuisance factor is defined as a design factor that most likely has an effect on the end point, but the effect is not of interest and actually may mask the desired end point (Montgomery, 1997). Often, a nuisance factor is unknown and uncontrolled, in other words, the presence is unknown to the researcher and may be changing the response level during the conduct of the experiment. Randomization is the usual method of attempting to eliminate possible nuisance factors in an experiment. Randomization states that both the allocation of

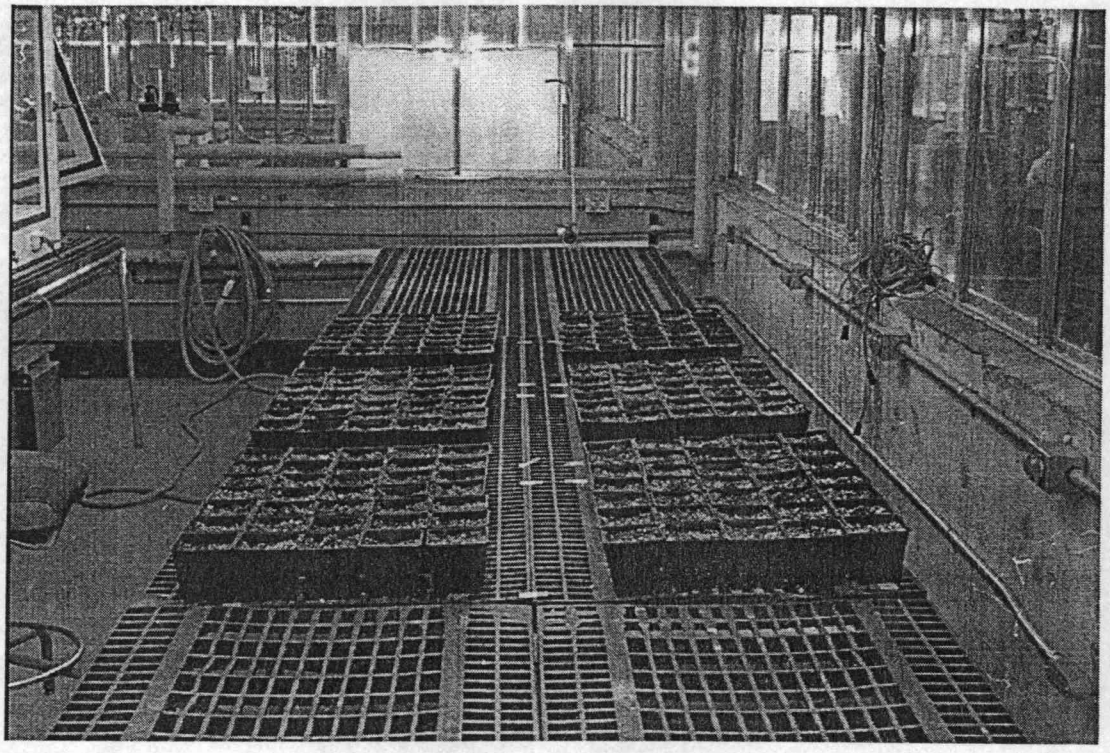

Figure 4. Physical arrangement of planters within blocks.

materials (seeds for this experiment), and the order in which the trials are performed are randomly determined. Statistical methods used for data analysis require that the observations in the experiment be independently distributed random variables. Proper randomization tends to average out the influence of a nuisance factor and provide repeatable reliable results (Montgomery, 1997).

If a nuisance factor is known and controllable, then a design known as blocking is used. Blocking retains the concept of randomization while attempting to systematically eliminate the influence of a known factor to allow the reasonable comparison of treatment means. The blocking concept is unique in that given a set number of blocks within a plot or in the case of this experiment, a green house bench, equal numbers of experimental units from each treatment group are randomly assigned to each block. Following this assignment, each block is equally divided into physical locations. The previously assigned units are then randomly assigned to a physical location within block. The randomization is typically performed using a random number table or the simple roll of a die.

3.2.1 Block Construction

The bench designed for growth located in green house #3 at the Environmental Protection Agency's Terrestrial Effects Research Facility (TERF) was approximately seven meters in length and 1.5 meters wide and consisted of three actual benches placed end to end. The center most bench was divided into six equal segments approximately 46 x 71 cm.

3.2.2 Random Assignment To Blocks and Within Blocks

The first step in successful random assignment of experimental units within blocks is to assign each of the plants to one of six blocks. In order to assign the plants to a block, the natural method was to roll a six sided die while assigning each block to its corresponding block number, the number one to block one and so forth through block number six.

To randomly assign each plant within a block to a specific location required a more deliberate mechanism. The options of choice were a random number generator or a random number table. Although extremely tedious, a random number table was generated using the random number feature within Microsoft ®Excel. Each plant within the block was located on the random number table by using the first four numbers in the listing. Using for example physical location 1-1 located in the upper left corner of block one, the first plant number listed in order was #22. This plant was then assigned to space 1-1. The remaining spaces within the block were assigned similarly. The final distribution of plants can be seen in Table 1.

Block 1		1	2	3	4	5	6	7
	1	22	158	160	115	103	88	202
	2	140	190	78	181	197	118	174
	3	132	90	3	60	18	124	85
	4	51	175	149	55	136	91	106
	5	7	89	173	208	58	57	10

Block 2		1	2	3	4	5	6	7
	1	45	65	121	125	26	36	189
	2	170	27	9	73	47	184	6
	3	61	112	198	178	63	34	157
	4	203	150	94	204	193	148	179
	5	176	28	145	42	111	98	64

Block 3		1	2	3	4	5	6	7
	1	72	128	142	23	13	133	2
	2	96	187	196	81	161	21	29
	3	167	126	49	39	200	62	192
	4	92	95	155	76	171	41	46
	5	141	185	54	93	67	99	164

Block 4		1	2	3	4	5	6	7
	1	1	169	40	48	114	11	154
	2	186	191	37	69	12	43	79
	3	113	83	146	143	123	108	147
	4	77	30	15	152	74	101	162
	5	194	166	130	183	206	32	109

Block 5		1	2	3	4	5	6	7
	1	105	168	205	138	25	207	53
	2	172	159	33	122	107	199	71
	3	8	102	195	24	86	80	100
	4	5	17	35	129	50	110	127
	5	177	188	70	38	180	66	131

Block 6		1	2	3	4	5	6	7
	1	119	44	120	16	116	20	19
	2	201	87	209	182	137	163	117
	3	82	104	151	4	56	156	75
	4	68	134	59	97	31	14	84
	5	144	153	165	52	210	135	139

Table 1. Random assignment of experimental units within blocks.

3.3 Sequential Exposure of Seeds to ^{60}Co Radiation

Using a Gammacell 220 ^{60}Co irradiator located in room 120 in the Radiation Center at Oregon State University, six treatment groups were exposed in the following manner. A group of one hundred seeds was placed in a 250 ml glass beaker and blocked in place within the central irradiation chamber using a second inverted beaker as the base. Blocking of the beaker containing the seeds allowed for central placement of the seeds in the chamber. The 100% gamma flux region of the chamber was located approximately 4" vertically from the bottom and central to the accessible area radially.

3.3.1 Calculation of Exposure Rate

The exposure rate used in calculating the time of each exposure of the treatment groups was based on an age corrected value of 2.08×10^3 Gy hr^{-1}. The expression:

$$A_f = A_o e^{-\lambda t}$$

The source age correction was performed based on a value of 2.304×10^3 Gy hr^{-1} dated February 10, 1997 provided by the Oregon State University Health Physics Department. The distribution within the cell can be seen in Appendix III.

3.3.2. Selection of Treatment Levels

In order to provide a wide spectrum of treatment groups, data from previously performed experiments were used following minor adjustments to the low and high ends of the group. Small scale experiments performed in radiation biology classes at Oregon State University used a range from a control level of 0 to 80×10^3 Gy hr^{-1}. The upper end of the scale produced virtually no useable data. Subsequently, a high end value of 30 x

10^3 Gy hr^{-1} was chosen in a class experiment performed in 1996. This particular experiment continued to yield extremely low overall end points in only the highest level treatment group. The overall mass of the plants excluding root mass was approximately 25% of the six lower treatment levels. Due to this result, a maximum treatment level of 200 Gy was chosen. A complete listing of treatment levels with corresponding exposure time and date are noted in Table 2.

Date	Time	Time of Exposure (s)	Treatment Level (Gy)	Plant #'s
10-6-97	1514	87	50	151-180
10-6-97	1517	130	75	121-150
10-6-97	1520	173	100	181-210
10-6-97	1525	216	125	31-60
10-6-97	1530	260	150	91-120
10-6-97	1536	346	200	61-90
10-6-97	Control Group	0	0	1-30

Table 2. Treatment levels with length of exposure.

3.4 Planting and Care of Seedlings

Experimental repeatability is necessary for successful defense of a given data set. In an effort to provide an easily reproducible experiment, the planting and care phase of the research were performed as simply as possible.

3.4.1 Materials

Materials necessary to conduct the growth hormesis experiment were initially seeds, seed start soil mixture and 4 x 4" plastic planters with aeration and drainage holes located in the bottom. The seed selection required significant consideration since as

previously stated, seed lot, moisture content and age of seed have a significant bearing on the overall results of a hormesis experiment.

Obtaining a large number of seeds at a relatively low cost was the number one objective to maintain a simple experiment. Seeds may be ordered in large batches from specialty brokers, however, this does not seem to simulate the seeds that an average person would obtain for crop use. Bulk seed may be obtained at nearly all large chain stores such as Cub Foods located on Walnut Boulevard in Corvallis, Oregon. This very likely a mixture of several seed lots with varying degrees of moisture content and overall age, providing very little stability in the seed choice. The statistical experimental design utilized however should have eliminated those nuisance factors from affecting the end point.

The black plastic 4 x 4" planters were chosen due to the number of days the plants would grow and the maximum expected size of the root bundle from previous experimentation. These particular planters can be purchased from any nursery, such as Shonnard's Nursery located on Philomath Boulevard between Corvallis and Philomath, Oregon. They are extremely low cost at approximately $5.00 per hundred.

Seed start mixture was used which was a combination of pumelite, spagnum moss and soil. The particular brand used was "Uncle Malcolms".

3.4.2 Seed Planting and Watering

Seeds were planted at a uniform depth of 4 cm. The depth of each seed was determined by inserting a marked wooden dowel with an approximate diameter of 2 cm into a full planter of seed start mixture. A seed from the seed corresponding to the

appropriate treatment group was placed in the bottom of the hole and left open. After each planter contained the correct seed for the treatment group, all planters were covered with seed start mixture to cover the seeds.

Due to the relative density of seed start mixture, applying a uniform pre measured amount of water to each planter would not have given an equal amount to each plant. The water has a tendency to channel through the soil and potentially bypass the seed. In an effort to remedy this discrepancy, each plant was completely soaked until water was seen coming from each of the four drainage holes located in the bottom of the planter. Watering was performed on a daily basis due to relatively warm green house conditions.

3.4.3 Green House Conditions

Green house conditions were established and verified seven days prior to the start of the experiment. 1000 watt sodium vapor lights spaced four feet above the green house bench provided supplementary light and a large portion of the heat specified in the initial setup. The lights and the hot water perimeter radiator unit coupled with a wet pad cooler and roof vents maintained the temperature 60°F during the night and 80°F during the day. Simulated day time started at 0600 each morning and completed at 2100 each night and was controlled by a mechanical timer. Conditions were verified each morning by a recordable strip chart, maintained in the immediate area of the planters, and on weekends by Fred Senneca of the EPA each weekend. During the course of the experiment, there were no notable deficiencies in the green house operation. The green house can be viewed in Figure 5.

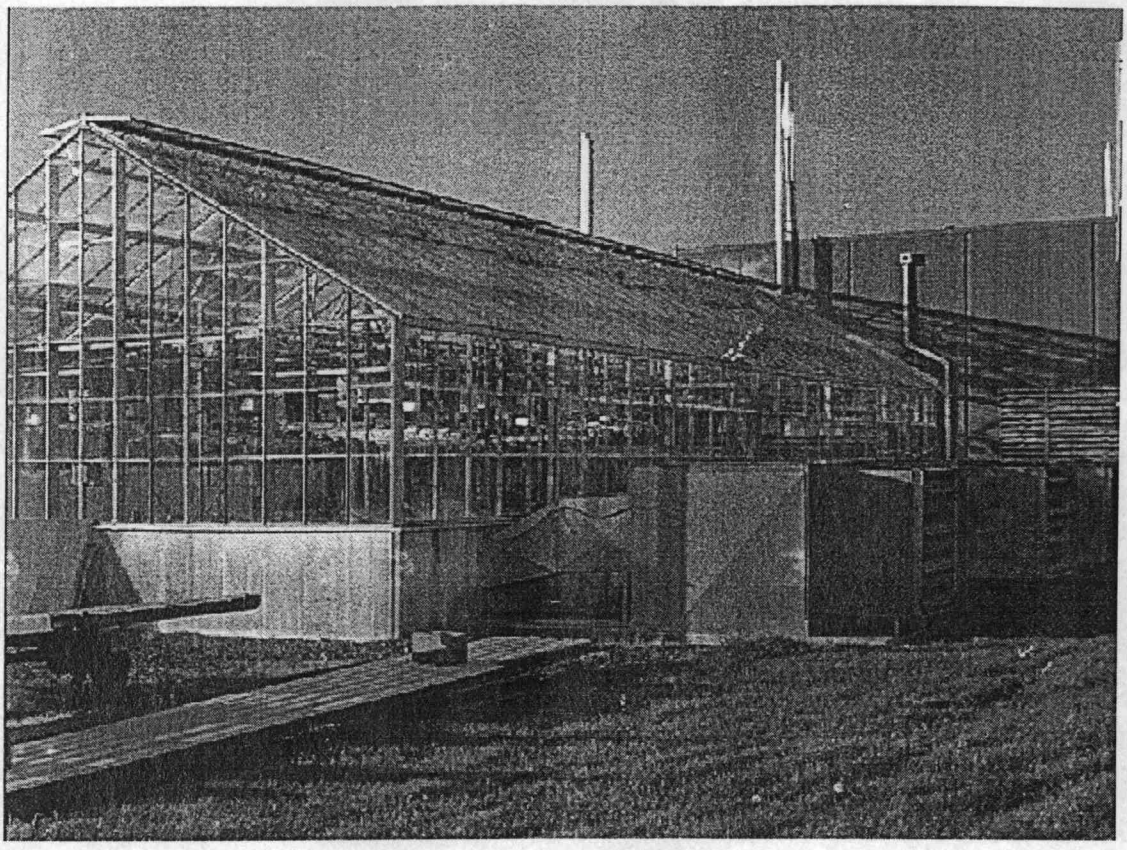

Figure 5. Glass thermostatically controlled green house located on the Corvallis, Oregon Environmental Protection Agency site.

3.5 Plant Care and Growth Cycle

Time of measurement has a definite impact on the possible detection of a hormetic effect, this was discussed in 2.2.3. In order to provide a reasonable growth cycle which would allow sufficient development of the plants simulating a mature specimen, forty days was chosen. This time started upon planting of the seeds and terminated when the plants were harvested. The particular time of forty days was not chosen at random but due to the presence of blossoms at approximately this stage in development.

There was no documentation available which specifically stated what the care of the plants should model. During the course of two experiments used to determine the possibility of a hormetic effect, two separate methods of growth were used. The first experiment, a completely randomized design, was conducted with nearly a maximum amount of human intervention. Simply stated, each plant was purposely manipulated physically so that it could not interact with surrounding units. Legumes typically intertwine with adjacent plants in a normal garden or large scale agricultural setting. The first assumption was that this was accomplished to provide structural support for each plant and would not effect the overall plant size or growth rate. This method of plant control required daily handling to unwind the tendrils from neighboring plants. Although no visible physical damage was noted, the plants were handled numerous times throughout the course of the entire cycle.

The second experiment, a completely randomized block design, was conducted with zero physical interference and human intervention. The plants were watered on a

daily basis but were allowed to intertwine and support each other in a natural manner. Figure 6 provides a visual reference for this method.

3.6 Specimen Harvest and Measurement

Following the forty day growth cycle, the plants were harvested. The harvest was completed in two distinct phases, the first was separation of the stem and leaf section above ground from the root mass below ground. The plants were cut exactly at soil level and placed in marked brown paper bags as in Figure 7. These bags were stored in the green house and exposed to the same conditions as the growing plants.

To facilitate the measurement of the root mass, all soil and debris contained within the soil must be rinsed from the roots while maintaining the root physical structure. To successfully accomplish this, an apparatus was used which was designed to catch portions of roots which break free during the rinsing process. Extreme care was taken to ensure that the nitrogen nodules were not dislodged during this phase of the harvest. A device which is used by plant biologists at the EPA was used. Figure 8. After washing, the root mass is placed carefully in the same bag as the associated plant. Care was used to ensure that the two separate portions were not allowed to touch as this would prohibit the separate measurement following drying.

The plants were allowed to dry in the green house for seven days prior to measurement. Each portion of the plants, both roots and steam and leaf combination were weighed independently on a balance calibrated to NIST traceable standards. The measurement apparatus was fully enclosed to prevent small variations in measurement due to air currents within the room due to personnel passage and the ventilation system.

Figure 6. Plants in the completely randomized block design were allowed to react naturally, intertwining and supporting adjacent plants.

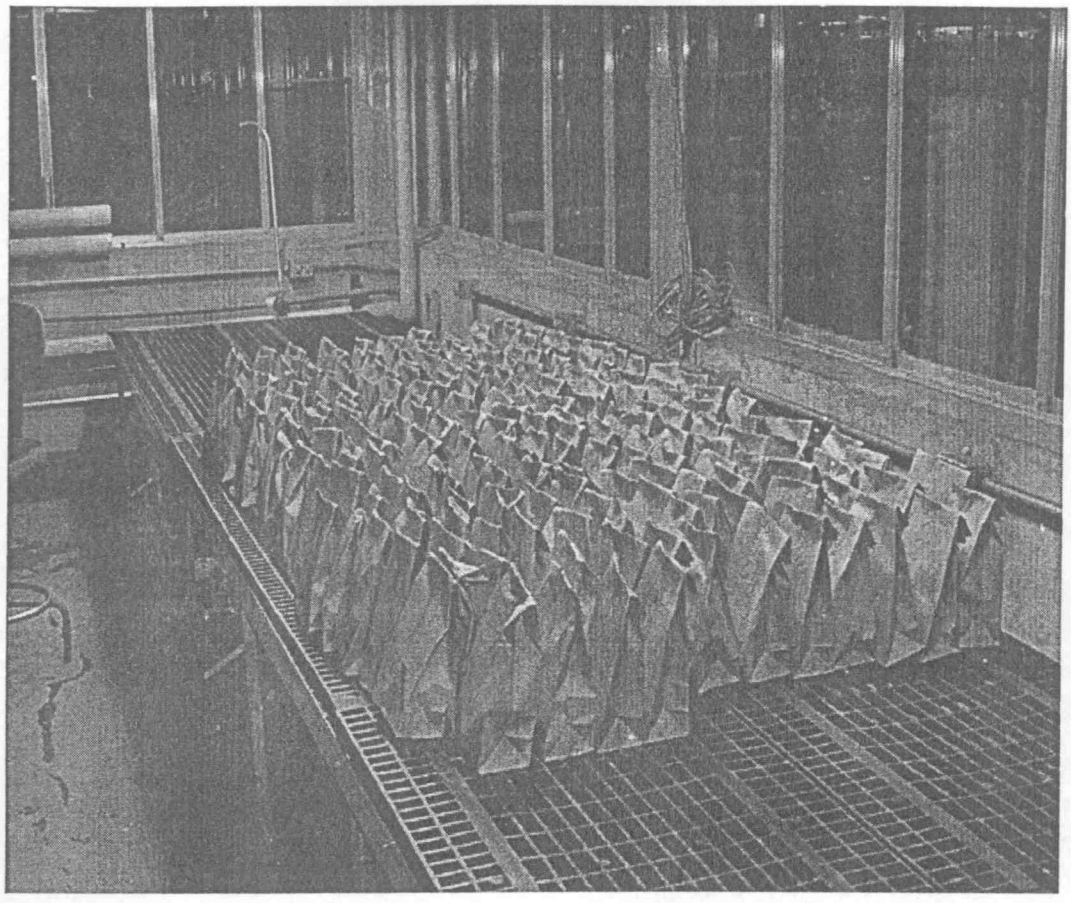

Figure 7. Harvested plants and roots were stored in brown paper bags and stored in normal green house operating conditions for seven days.

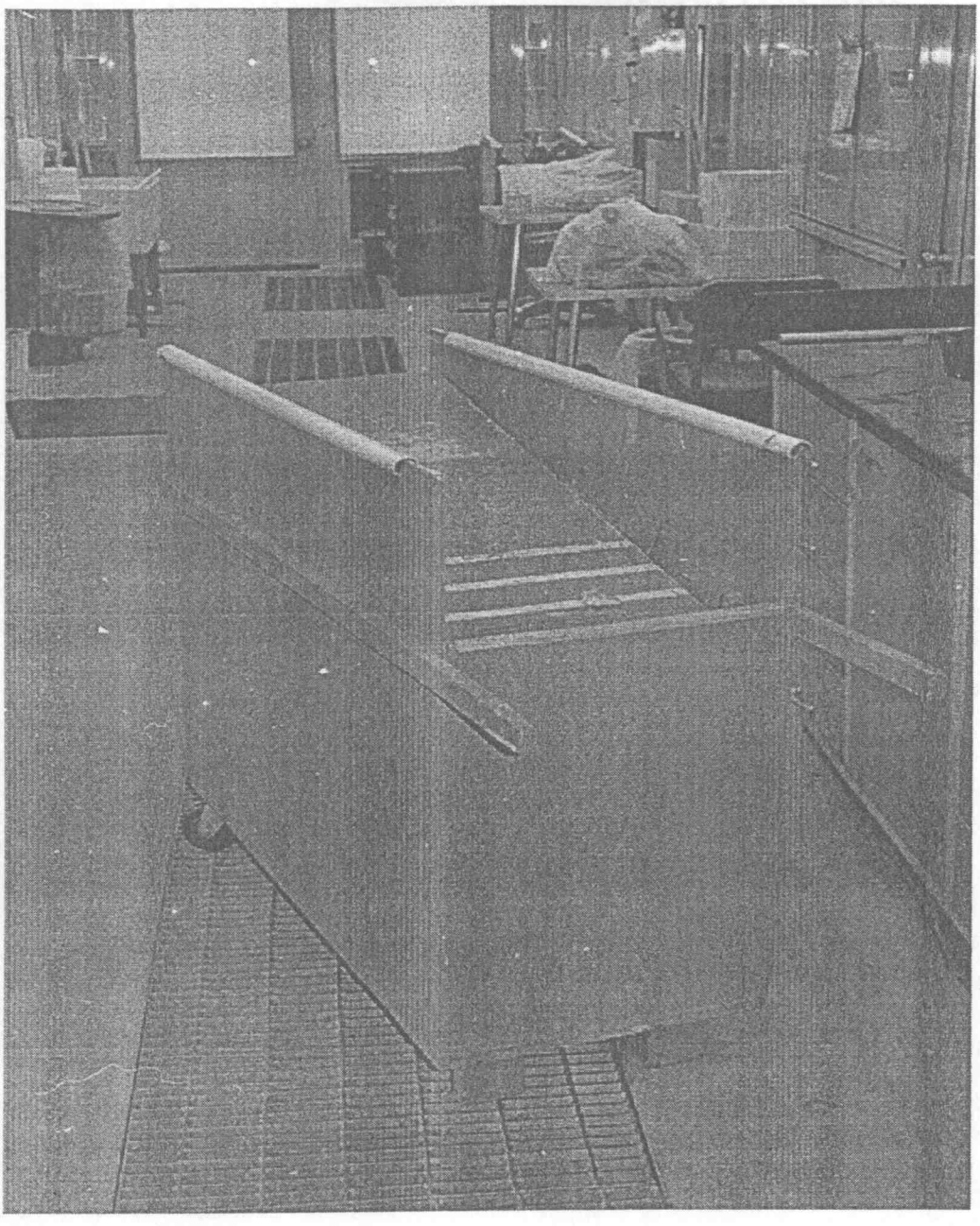

Figure 8. Device used for washing soil and debris from the root masses prior to drying and measurement.

4.0 Results

4.1 Statistical Methods

For an experiment to be credible, the results must be carefully analyzed with appropriate statistical methods. Careful experimental design and results analysis allows for statistical inference. Inference implies that the results obtained from the experiment may be applied to results obtained in future experiments and in naturally occurring environments, in this case, farm plots or gardens. The use of a randomized design assumes that the results will be nearly equivalent to the results obtained by randomly sampling the entire population.

All results contain elements of error which if improperly analyzed may cause the rejection of a null hypothesis when it is true or the a non rejection of the null hypothesis when it is false. The null hypothesis is typically the basis for examining comparisons of means from a control or untreated group to that of one or more means of a treatment group. The expression

$$H_0 : \mu_1 = \mu_2$$

is used as the qualifying statement representing the null while

$$H1 : \mu_1 \neq \mu_2$$

represents the alternative hypothesis and is said to be two sided if the inequality can be stated with either treatment mean on either side of the inequality.

The two types of error, type I and type II are given special symbols.

$$\alpha = P(\text{Type I error}) = P(\text{reject } H_0 | H_0 \text{ is true})$$

$$\beta = P(\text{Type II error}) = P(\text{fail to reject } H_0 | H_0 \text{ is false})$$

The most often performed comparison used in hypothesis testing is to specify a value of the probability of a type I error α, often called the significance level of the test, and then design the test procedure so that there is an acceptably small value for the probability of a type II error (Montgomery, 1996).

During the course of this experiment, the probability of a type I error was set at $\alpha = 0.05$. This is stated as having a 95% confidence interval. All results will be reported at the 95% confidence interval.

Determining whether differences in treatment means are significant requires two steps. The performance of an analysis of variance (ANOVA) is required to determine whether differences exist between any of the treatment means in an experiment. The ANOVA provides a comparable value which leads to the acceptance or rejection of the null hypothesis.

Following the ANOVA, assuming the null is rejected, there are three major methods for performing multiple comparisons of means, they are Scheffe's Method, Tukey's test, and the Least Significant Difference (LSD) method. Scheffe's Method is the most conservative of the three yet the least powerful. The LSD method was chosen for analysis of this experiment and is specifically valid for planned experiments. Using the LSD method, two treatment means are declared to be significantly different if

$$| \mu_i - \mu_j | > t_{\alpha/2,N-a} \sqrt{MSE\left(\frac{1}{n_i} + \frac{1}{n_j}\right)}$$

This quantity is called the least significant difference. An equivalent statement is given that for any pair of means, the null hypothesis is rejected if the absolute value of the difference between treatment means is greater than the least significant difference.

4.2 Analysis of Variance for the Completely Randomized Design

Before completing the multiple comparison of means, an analysis of variance was performed with treatments as the independent variable and total plant mass as the dependent variable. The results of the ANOVA are listed in Table 3.

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Statistic	Prob > F
Model	6	160.7415	26.7903	37.0694	0.0001
Error	688	497.2207	0.7227		
C Total	694	657.9623			

Table 3. Analysis of variance for the completely randomized design.

The ANOVA was constructed with the SAS statistical software package, the source designations represent the comparisons of between groups for the model and within groups for the error term. The value of 37.0694 for an F statistic is very high and results in a P-value of 0.0001 as listed in the ANOVA. This extremely low value provides convincing evidence that there were statistically significant differences between treatment groups at the 95% confidence interval.

Prior to the completion of data analysis, a plot of the residual values was analyzed. Residual values are the observation values minus the estimated mean for the associated treatment group. Examining a plot of residuals versus is necessary due to the difficulty often experienced when attempting to determine patterns in data within groups. This difficulty is due to the large amount of variability which can be seen within the treatment group. Scatter plots of the residuals versus the fitted values are a better tool for analysis because the linear component of variation in the responses has been removed, leaving a clearer picture for curvature and spread (Ramsey, 1997).

Along with a clear picture of trends, the residual plot dictates the necessity of a transformation in data, for example a log transformation. Transformations often allow easier visual comparisons of data across treatment groups. The residual plot is displayed in Figure 9. The residual plot for this experiment showed no irregularities which suggested the use of a transformation, the spread was nearly equivalent.

4.3 Multiple Comparison of Means Results

In an effort to provide a relevant comparison of means and provide evidence of normal trends in growth, several comparisons were made. Multiple comparisons were performed on the mean root mass, mean leaf and stem mass and the total mass consisting of roots, leaves and stems.

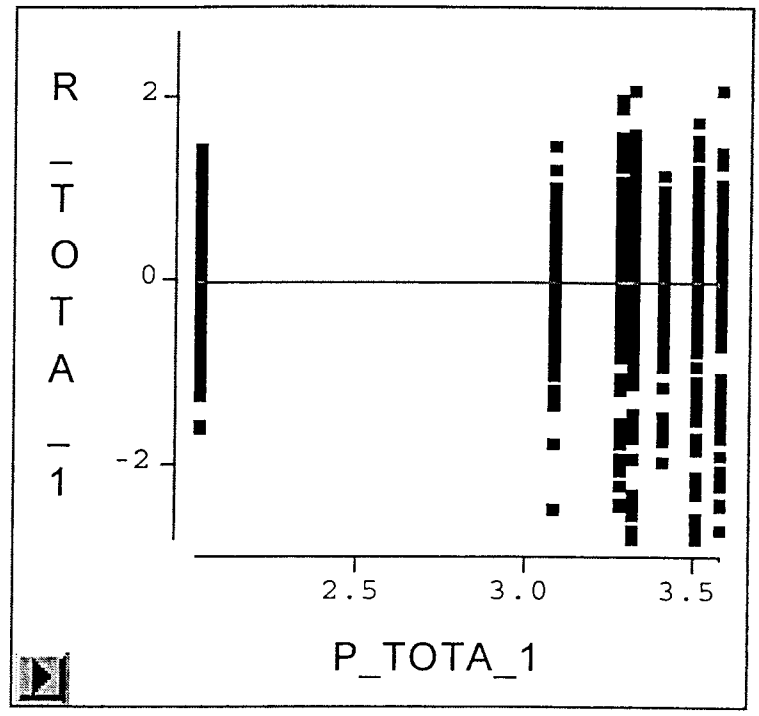

Figure 9. Residual plot from the ANOVA for the seven treatment groups

4.3.1 Root Mass Comparisons

The LSD method of multiple means comparisons was performed on the root mass data from the completely randomized design with significant results. The results of the ANOVA showed a P-value of 0.0001 which stated a significant difference between some of the treatment means between root masses. The ANOVA can be viewed in Table 4.

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Statistic	Prob > F
Model	6	14.305	2.384	41.57	0.0001
Error	688	39.454	0.057		
C Total	694	53.758			

Table 4. ANOVA from multiple comparisons of means for root masses.

Table 5 provides the results of the multiple comparison of means at the 95% confidence interval. The comparisons marked with a triple asterisk represent a statistically significant comparison at the 95% confidence interval

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result	Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
1 - 4	-0.00249	0.06418	0.13085		5 - 1	-0.23210	-0.16636	-0.10062	***
1 - 2	0.09387	0.16037	0.22688	***	5 - 4	-0.16741	-0.10218	-0.03695	***
1 - 6	0.09499	0.16199	0.22899	***	5 - 2	-0.07105	-0.00599	0.05908	
1 - 5	0.10062	0.16636	0.23210	***	5 - 6	-0.06994	-0.00437	0.06120	
1 - 7	0.13130	0.19864	0.26598	***	5 - 7	-0.03364	0.03228	0.09820	
1 - 3	0.43743	0.50587	0.57432	***	5 - 3	0.27247	0.33951	0.40656	***
4 - 1	-0.13085	-0.06418	0.00249		7 - 1	-0.26598	-0.19864	-0.13130	***
4 - 2	0.03019	0.09619	0.16220	***	7 - 4	-0.20130	-0.13446	-0.06762	***
4 - 6	0.03131	0.09781	0.16431	***	7 - 2	-0.10494	-0.03826	0.02842	
4 - 5	0.03695	0.10218	0.16741	***	7 - 6	-0.10382	-0.03665	0.03052	
4 - 7	0.06762	0.13446	0.20130	***	7 - 5	-0.09820	-0.03228	0.03364	
4 - 3	0.37374	0.44169	0.50965	***	7 - 3	0.23862	0.30724	0.37585	***
2 - 1	-0.22688	-0.16037	-0.09387	***	3 - 1	-0.57432	-0.50587	-0.43743	***
2 - 4	-0.16220	-0.09619	-0.03019	***	3 - 4	-0.50965	-0.44169	-0.37374	***
2 - 6	-0.06472	0.00162	0.06795		3 - 2	-0.41330	-0.34550	-0.27770	***
2 - 5	-0.05908	0.00599	0.07105		3 - 6	-0.41217	-0.34388	-0.27560	***
2 - 7	-0.02842	0.03826	0.10494		3 - 5	-0.40656	0.33951	-0.27247	***
2 - 3	0.27770	0.34550	0.41330	***	3 - 7	-0.37585	-0.30724	-0.23862	***

Table 5. Multiple comparison of means for root masses.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
6 - 1	-0.22899	-0.16199	-0.09499	***
6 - 4	-0.16431	-0.09731	-0.03131	***
6 - 2	-0.06795	-0.00162	0.06472	
6 - 5	-0.06120	0.00437	0.06994	
6 - 7	-0.03052	0.03665	0.10382	
6 - 3	0.27560	0.34388	0.41217	***
*** Indicates a significant comparison at the 95% confidence level.				

Table 5 continued.

The inferences drawn from these comparisons will be discussed at the end of all individual group comparisons.

4.3.2 Leaf and Stem Mass Comparisons

The LSD method of multiple means comparisons was performed on the leaf and stem mass data from the completely randomized design with significant results. The results of the ANOVA showed a P-value of 0.0001 which stated a significant difference between some of the treatment means between root masses. The ANOVA can be viewed in Table 6.

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Statistic	Prob > F
Model	6	94.197	15.700	33.38	0.0001
Error	688	323.543	0.470		
C Total	694	417.740			

Table 6. ANOVA from multiple comparisons of means for root masses.

Table 7 provides the results of the multiple comparison of means at the 95% confidence interval. The comparisons annotated with a triple asterisk represent a statistically significant comparison at the 95% confidence interval.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result	Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
6 - 5	-0.11548	0.07228	0.26004		4 - 6	-0.47383	-0.28341	-0.09298	***
6 - 7	0.08286	0.27522	0.46757	***	4 - 5	-0.39792	-0.21113	-0.02433	***
6 - 4	0.09298	0.28341	0.47383	***	4 - 7	-0.19960	-0.00819	0.18322	
6 - 1	0.24059	0.43245	0.62432	***	4 - 1	-0.04187	0.14905	0.33996	
6 - 2	0.32059	0.51055	0.70052	***	4 - 2	0.03814	0.22715	0.41615	***
6 - 3	1.03477	1.23031	1.42584	***	4 - 3	0.75230	0.94690	1.14151	***
5 - 6	-0.26004	-0.07228	0.11548		1 - 6	-0.62432	-0.43245	-0.24059	***
5 - 7	0.01417	0.20294	0.39170	***	1 - 5	-0.54843	-0.36017	-0.17191	***
5 - 4	0.02433	0.21113	0.39792	***	1 - 7	-0.35008	-0.15724	0.03561	
5 - 1	0.17191	0.36017	0.54843	***	1 - 4	-0.33996	-0.14905	0.04187	
5 - 2	0.25195	0.43827	0.62460	***	1 - 2	-0.11235	0.07810	0.26855	
5 - 3	0.96602	1.15803	1.35003	***	1 - 3	0.60184	0.79785	0.99386	***
7 - 6	-0.46757	-0.27522	-0.08286	***	2 - 6	-0.70052	-0.51055	-0.32059	***
7 - 5	-0.39170	-0.20294	-0.01417	***	2 - 5	-0.62460	-0.43827	-0.25195	***
7 - 4	-0.18322	0.00819	0.19960		2 - 7	-0.42629	-0.23534	-0.04439	***
7 - 1	-0.03561	0.15724	0.35008		2 - 4	-0.41615	-0.22715	-0.03814	***
7 - 2	0.04439	0.23534	0.42629	***	2 - 1	-0.26855	-0.07810	0.11235	
7 - 3	0.75859	0.95509	1.15159	***	2 - 3	0.52560	0.71975	0.91391	***

Table 7. Multiple comparison of means for stem and leaf masses.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
3 - 6	-1.42584	-1.23031	-1.03477	***
3 - 5	-1.35003	-1.15803	-0.96602	***
3 - 7	-1.15159	-0.95509	-0.75859	***
3 - 4	-1.14151	-0.94690	-0.75230	***
3 - 1	-0.99386	-0.79785	-0.60184	***
3 - 2	-0.91391	-0.71975	-0.52560	***
*** Indicates a significant comparison at the 95% confidence level.				

Table 7 continued.

4.3.3 Total Mass Comparison

The LSD method of multiple means comparisons was performed on the total mass data from the completely randomized design with significant results. The results of the ANOVA showed a P-value of 0.0001 which stated a significant difference between some of the treatment means between root masses. The ANOVA can be viewed in Table 8.

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Statistic	Prob > F
Model	6	160.741	26.790	37.07	0.0001
Error	688	497.221	0.723		
C Total	694	657.962			

Table 8. ANOVA from multiple comparisons of total mass.

Table 9 provides the results of the multiple comparison of means at the 95% confidence interval. The comparisons annotated with a triple asterisk represent a statistically significant comparison at the 95% confidence interval.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result	Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
6 - 5	-0.1561	0.0767	0.3094		1 - 6	-0.5083	-0.2705	-0.0326	***
6 - 4	-0.0505	0.1856	0.4217		1 - 5	-0.4272	-0.1938	0.0396	
6 - 1	0.0326	0.2705	0.5083	***	1 - 4	-0.3215	-0.0849	0.1518	
6 - 7	0.0734	0.3119	0.5503	***	1 - 7	-0.1977	0.0414	0.2805	
6 - 2	0.2734	0.5089	0.7444	***	1 - 2	0.0024	0.2385	0.4746	***
6 - 3	1.3318	1.5742	1.8166	***	1 - 3	1.0607	1.3037	1.5467	***
5 - 6	-0.3094	-0.0767	0.1561		7 - 6	-0.5503	-0.2705	-0.0734	***
5 - 4	-0.1226	0.1089	0.3405		7 - 5	-0.4692	-0.1938	-0.0012	***
5 - 1	-0.0396	0.1938	0.4272		7 - 4	-0.3636	-0.0849	0.1110	
5 - 7	0.0012	0.2352	0.4692	***	7 - 1	-0.2805	-0.0414	0.1977	
5 - 2	0.2013	0.4323	0.6633	***	7 - 2	-0.0396	0.2385	0.4338	
5 - 3	1.2595	1.4975	1.7356	***	7 - 3	1.0187	1.3037	1.5059	***
4 - 6	-0.4217	-0.1856	0.0505		2 - 6	-0.7444	-0.5089	-0.2734	***
4 - 5	-0.3405	-0.1089	0.1226		2 - 5	0.6633	-0.4323	-0.2013	***
4 - 1	-0.1518	0.0849	0.3215		2 - 4	-0.5576	-0.3233	-0.0890	***
4 - 7	-0.1110	0.0414	0.3636		2 - 1	-0.4746	-0.2385	-0.0024	***
4 - 2	0.0890	0.2385	0.5576	***	2 - 7	-0.4338	-0.1971	0.0396	
4 - 3	1.1473	1.3037	1.6298	***	2 - 3	0.8246	1.0653	1.3059	***

Table 9. Multiple comparison of means for total masses.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
3 - 6	-1.8166	-1.5742	-1.3318	***
3 - 5	-1.7356	-1.4975	-1.2595	***
3 - 4	-1.6298	-1.3886	-1.1473	***
3 - 1	-1.5467	-1.3037	-1.0607	***
3 - 7	-1.5059	-1.2623	-1.0187	***
3 - 2	-1.3059	-1.0653	-0.8246	***
*** Indicates a significant comparison at the 95% confidence level.				

Table 9 continued.

4.3.4 Overall Comparison

Before an overall comparison could be performed, the exposure levels associated with each of the treatment groups was obtained. The results can be seen in Table 10.

Treatment group	1	2	3	4	5	6	7
Exposure level (kRad)	10.0	15.0	20.0	12.5	5.0	7.5	0.0

Table 10. Exposure level by treatment group.

Comparison of the treatment group to the multiple comparison of means revealed that a positive growth effect was statistically significant among the root masses at both the 10k Rad and the 12.5k Rad level while an equivalent effect was noticeable in both the stem and leaf mass and the total mass at both the 5.0k Rad and 7.5k Rad levels. Additionally, there was a significant comparison at the 20k Rad level. Within each level of

measurement, the 20k Rad treatment group was considerably smaller than all other groups. This smaller size was evident visually and by mass comparison.

4.4 Analysis of Variance for the Completely Randomized Block Design

An ANOVA was performed with treatments and blocks as the independent variables and total plant mass as the dependent variable. The results are listed in Table 11.

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Statistic	Prob>F
Model	11	326.427	29.675	30.72	0.0001
Error	196	189.335	0.966		
C Total	207	515.762			

Table 11. Analysis of variance for the completely randomized block design.

The ANOVA was constructed with the SAS statistical software package. The designations within the table are identical to those listed in section 4.2. The relatively high F statistic is indicative of a significant difference between treatment groups with a P-value of 0.0001. This extremely low value provides convincing evidence that there were statistically significant differences between treatment groups at the 95% confidence interval.

From the same ANOVA the significance of the blocking factor can be concluded. With an F statistic of 1.584 and P value of 0.1662, this element of the experiment provided little in the way of convincing differences across the green house bench.

Prior to the completion of the data analysis, a plot of the residual values was analyzed. As stated in section 4.2.1, residual plots provide a better tool for analysis because the linear component of variation in the responses has been removed, leaving a clearer picture of curvature and spread (Ramsey, 1997). The residual plot is displayed in Figure 9.

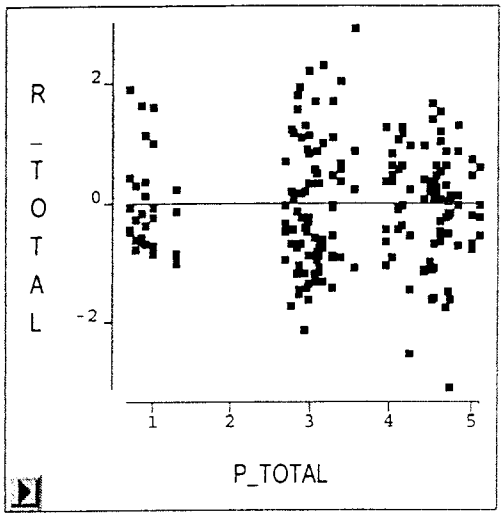

Figure 9. Residual plot from the ANOVA from the seven treatment groups.

The residual plot from this experiment although far from ideal, did not demonstrate the need for a transformation.

4.5 Multiple Comparison of Means for the Block Design

In an effort to provide a relevant comparison of means and provide evidence of normal trends in growth, several comparisons were made. Multiple comparisons were

performed on the mean root mass, mean leaf and stem mass and the total mass consisting of roots, leaves and stems.

4.5.1 Root Mass Comparisons

The LSD method of multiple comparisons was performed on the root mass data from the completely randomized block design with significant results. The results of the ANOVA showed a P-value of 0.0001 which stated a significant difference between some of the treatment means between root masses. The ANOVA can be viewed in Table 12.

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Statistic	Prob>F
Model	6	19.153	3.192	51.51	0.0001
Error	201	12.456	0.062		
C Total	207	31.61			

Table 12. ANOVA from multiple comparisons of means for root masses.

Table 13provides the results of the multiple comparison of means at the 95% confidence interval.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result	Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
1 - 3	-0.10851	0.01823	0.14497		4 - 1	-0.47543	-0.34761	-0.21978	***
1 - 2	0.00966	0.13640	0.26314	***	4 - 3	-0.45720	-0.32937	-0.20155	***
1 - 4	0.21978	0.34761	0.47543	***	4 - 2	-0.33903	-0.21121	0.08338	***
1 - 5	0.22606	0.35280	0.47954	***	4 - 5	-0.12263	0.00519	0.13302	
1 - 6	0.30630	0.43412	0.56195	***	4 - 6	-0.04239	0.08652	0.21542	
1 - 7	0.82323	0.94997	1.07671	***	4 - 7	0.47453	0.60236	0.73019	***
3 - 1	-0.14497	-0.01823	0.10851		5 - 1	-0.47954	-0.35280	-0.22606	***
3 - 2	-0.00857	0.11817	0.24491		5 - 3	-0.46131	-0.33457	-0.20783	***
3 - 4	0.20155	0.32937	0.45720	***	5 - 2	-0.34314	-0.21640	-0.08966	***
3 - 5	0.20783	0.33456	0.46131	***	5 - 4	-0.13302	-0.00519	0.12262	
3 - 6	0.28806	0.41589	0.54372	***	5 - 6	-0.04650	0.08132	0.20915	
3 - 7	0.80499	0.93173	1.05847	***	5 - 7	0.47043	0.59717	0.72391	***
2 - 1	-0.26314	-0.13640	-0.00966	***	6 - 1	-0.56195	-0.43412	-0.30630	***
2 - 3	-0.24491	-0.11817	0.00857		6 - 3	0.54372	-0.41589	-0.28806	***
2 - 4	0.08338	0.21121	0.33903	***	6 - 2	-0.42555	-0.29772	-0.16990	
2 - 5	0.08966	0.21640	0.34314	***	6 - 4	-0.21542	-0.08652	0.04239	
2 - 6	0.16990	0.29772	0.42555	***	6 - 5	-0.20915	-0.08132	0.04650	
2 - 7	0.68683	0.81357	0.94031	***	6 - 7	0.38802	0.51584	0.64367	***

Table 13. Multiple comparison of means for total masses.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
7 - 1	-1.0767	-0.94997	-0.82323	
7 - 3	-1.0585	-0.93173	-0.80499	
7 - 2	-0.9403	-0.81357	-0.68683	
7 - 4	-0.7302	-0.60236	-0.47453	
7 - 5	-0.7239	-0.59717	-0.47043	
7 - 6	-0.6437	-0.51584	-0.38802	
*** Indicates a significant comparison at the 95% confidence level.				

Table 13 continued.

The inferences drawn from these comparisons will be discussed at the end of all individual group comparisons.

4.5.2 Leaf and Stem Mass Comparisons

The LSD method of multiple means comparisons was performed on the leaf and stem mass data from the completely randomized block design with significant results. The results of the ANOVA showed a P-value of 0.0001 which stated a significant difference between some of the treatment means leaf and stem masses. The ANOVA can be viewed in Table 14.

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Statistic	Prob > F
Model	6	182.913	30.456	48.57	0.0001
Error	201	126.153	0.628		
C Total	207				

Table 14. ANOVA from multiple comparisons of means for plant and leaf masses.

Table 15 provides the results of the multiple comparison of means at the 95%

confidence interval. Comparisons annotated with a triple asterisk represent a statistically significant comparison at the 95% confidence interval.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result	Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
3 - 1	-0.2704	0.1329	0.5363		4 - 3	-1.6714	-1.2646	-0.8578	***
3 - 2	0.0628	0.4661	0.8695	***	4 - 1	-1.5384	-1.1316	-0.7248	***
3 - 4	0.8578	1.2646	1.6714	***	4 - 2	-1.2052	-0.7984	-0.3916	***
3 - 5	0.9317	1.3385	1.7453	***	4 - 6	-0.3363	0.0740	0.4842	
3 - 6	1.1192	1.5225	1.9259	***	4 - 5	-0.1488	0.2580	0.6648	
3 - 7	2.5108	2.9142	3.3175	***	4 - 7	1.2428	1.6496	2.0564	***
1 - 3	-0.5363	-0.1329	0.2704		6 - 3	-1.7453	-1.3385	-0.9317	***
1 - 2	-0.0701	0.3332	0.7365		6 - 1	-1.6124	-1.2056	-0.7988	***
1 - 4	0.7248	1.1316	1.5384	***	6 - 2	-1.2792	-0.8724	-0.4656	***
1 - 5	0.7988	1.2056	1.6124	***	6 - 4	-0.4842	-0.0740	0.3363	
1 - 6	0.9863	1.3896	1.7929	***	6 - 5	-0.2228	0.1840	0.5908	
1 - 7	2.3779	2.7812	3.1846	***	6 - 7	1.1688	1.5756	1.9824	***
2 - 1	-0.8695	-0.4661	-0.6280	***	5 - 3	-1.9259	-1.5225	-1.1192	***
2 - 3	-0.7365	-0.3332	0.0701		5 - 1	-1.7929	-1.3896	-0.9863	***
2 - 4	0.3916	0.7984	1.2052	***	5 - 2	-1.4597	-1.0564	-0.6531	***
2 - 5	0.4656	0.8724	1.2792	***	5 - 4	-0.6648	-0.2580	0.1488	
2 - 6	0.6531	1.0564	1.4597	***	5 - 6	-0.5908	-0.1840	0.2228	
2 - 7	2.0447	2.4480	2.8514	***	5 - 7	0.9883	1.3916	1.7950	***

Table 15. Multiple comparison of means for total masses.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
7 - 1	-3.3175	-2.9142	-2.5108	***
7 - 3	-3.1846	-2.7812	-2.3779	***
7 - 2	-2.8514	-2.4480	-2.0447	***
7 - 4	-2.0564	-1.6496	-1.2428	***
7 - 5	-1.9824	-1.5756	-1.1688	***
7 - 6	-1.7950	-1.3916	-0.9883	***
*** Indicates a significant comparison at the 95% confidence level.				

Table 15 continued.

4.5.3 Total Mass Comparison

The LSD method of multiple comparisons was performed on the total mass data from the completely randomized block design with significant results. The results of the ANOVA showed a P-value of 0.0001 which demonstrated significant differences between some of the total masses. The ANOVA can be viewed in Table 16.

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Statistic	Prob > F
Model	6	318.775	53.129	54.21	0.0001
Error	201	196.987	0.980		
C Total	207				

Table 16. ANOVA from multiple comparisons of total mass.

Table 17 provides the results of the multiple comparison of means at the 95% confidence interval. Comparisons annotated with a triple asterisk represent a statistically significant comparison at the 95% confidence interval.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result	Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
3 - 1	-0.3893	0.1147	0.6187		4 - 3	-2.1023	-1.5939	-1.0856	***
3 - 2	0.0803	0.5843	1.0883	***	4 - 1	-1.9876	-1.4792	-0.9709	***
3 - 4	1.0856	1.5939	2.1023	***	4 - 2	-1.5180	-1.0096	-0.5013	***
3 - 5	1.2461	1.7544	2.2628	***	4 - 6	-0.3522	0.1605	0.6731	
3 - 6	1.3531	1.8571	2.3611	***	4 - 5	-0.2452	0.2632	0.7715	
3 - 7	3.3419	3.8459	4.3499	***	4 - 7	1.7436	2.2520	2.7603	***
1 - 3	-0.6187	-0.1147	0.3893		6 - 3	-2.2628	-1.7544	-1.2461	***
1 - 2	-0.0344	0.4696	0.9736		6 - 1	-2.1481	-1.6397	-1.1314	***
1 - 4	0.9709	1.4792	1.9876	***	6 - 2	-1.6785	-1.1701	-0.6618	***
1 - 5	1.1314	1.6397	2.1481	***	6 - 4	-0.6731	-0.1605	0.3522	
1 - 6	1.2384	1.7424	2.2464	***	6 - 5	0.4057	0.1027	0.6110	
1 - 7	3.2272	3.7312	4.2352	***	6 - 7	1.5831	2.0915	2.5998	
2 - 1	-1.0883	0.5843	-0.0803	***	5 - 3	-2.3611	-1.8571	-1.3531	***
2 - 3	-0.9736	-0.4696	0.0344		5 - 1	-2.2464	-1.7424	-1.2384	***
2 - 4	0.5013	1.0096	1.5180	***	5 - 2	-1.7768	-1.2728	-0.7688	***
2 - 5	0.6618	1.1701	1.6785	***	5 - 4	-0.7715	-0.2632	0.2452	
2 - 6	0.7688	1.2728	1.7768	***	5 - 6	-0.6110	-0.1027	0.4057	
2 - 7	2.7576	3.2616	3.7656	***	5 - 7	1.4848	1.9888	2.4928	***

Table 17. Multiple comparison of means for total masses.

Treatment Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	Result
7 - 1	-4.3499	-3.8459	-3.3419	***
7 - 3	-4.2352	-3.7312	-3.2272	***
7 - 2	-3.7656	-3.2616	-2.7576	***
7 - 4	-2.7603	-2.2520	-1.7436	***
7 - 5	-2.5998	-2.0915	-1.5831	***
7 - 6	-2.4928	-1.9888	-1.4848	***
*** Indicates a significant comparison at the 95% confidence level.				

Table 17 continued.

4.5.4 Overall Comparison

As in section 4.3.4 an overall comparison could not be performed before examining the exposure levels associated with each of the treatment groups. The results can be seen in Table 18.

Treatment Group	1	2	3	4	5	6	7
Exposure Level (kRad)	0.0	7.5	5.0	12.5	10.0	15.0	20.0

Table 18. Exposure level listed by treatment group.

Comparison of the treatment means to the multiple comparison means from the LSD test revealed that there were no statistically significant differences in growth in a positive manner. There were differences which were significant at the higher levels of exposure that indicated a negative effect.

4.6 Discussion of Results

Having completed all of the necessary comparisons, a final examination of the data revealed two separate results for the completely randomized design and the completely randomized block design. While the results were similar when examined graphically, they were not similar in significance. The major difference between the two experiments was the total number of samples in each which drastically changes the degrees of freedom available in the statistical calculations.

4.6.1 Completely Randomized Design

This experiment was conducted with an initial number of 770 plants and concluded with 695 living units for sample measurement. The degrees of freedom associated with the final ANOVA were 694. The analysis of data revealed a significant difference between the control and the 5k and 7.5k Rad treatment groups. A noticeable difference was also evident at the 20k Rad treatment level. The relatively large number of experimental units in this design provided a reasonable value for the standard deviation while also providing a large measure of robustness to variations within treatment groups.

A simple graphical representation clearly depicts a difference in means in the 5k, 7.5k, 15k and 20k Rad groups. With the exception of the 12.5k Rad group, the trend is basically as would be expected if a hormetic effect was present.

4.6.2 Completely Randomized Block Design

The completely randomized block design started with 210 experimental units and provided an ANOVA with 207 degrees of freedom. The results did not reveal a hormetic

effect of a statistically significant nature at any treatment level, but did provide a significant difference at the higher treatment level as did the previous design in section 4.6.1. The standard deviation was relatively small, however, the degrees of freedom were not sufficient to overcome the within treatment group variation for a final comparison of means.

A simple graphical representation provides suggestive evidence of a difference between the control, 5.0k and the 20.0k Rad groups. These differences, however, were not significant in the statistical analysis.

4.7 Comparison of Experimental Results

Following the completion of the growth and harvest stage of the completely randomized design, the detection of a significant difference was not expected due to the belief that potentially confounding variables, or nuisance factors were present that would interfere with evidence of a hormetic effect. The purpose of the complete randomized block design was to eliminate these nuisance factors and provide convincing evidence of a difference in growth rates over a 40 day span of time.

The expected difference was evident in the completely randomized experiment and not in the blocked design. The reason for the differences is believed to be due to the relatively small number of degrees of freedom available in the statistical calculations. The standard deviation associated with each experiment was nearly the same, however, the reduced degrees of freedom masked differences between treatment groups in the blocked design due to decreased robustness to the within treatment group variations.

A significant difference was noted in each experiment at the 20.0k Rad level. The quality of the plant at this level was extremely poor and the overall mass was considerably less than the control group. This result suggests the possibility of a threshold value for reasonable survival of the pinto bean when exposed to ionizing radiation.

4.8 Suggested Further Research

While further research in the area of radiation hormesis may yield more significant results, the two experiments conducted provide fairly convincing evidence that a hormesis effect does in fact exist somewhere around the 5.0 to 7.5k Rad treatment level if using ^{60}Co as a radiation source. The true question that logically arises from these experiments deals with the possibility of an actual threshold somewhere between 15.0 and 20.0k Rad. The work necessary to determine the presence of this level would be fairly extensive, as small differences in treatment levels would have to be used in order to locate the point at which the plant experiences a true decline in the quality and overall mass.

The results which would be obtained from an outdoor plot may provide more useful evidence that would provide a more powerful inference to what the typical agricultural farmer would experience on a large scale. In order to provide meaningful results on this large scale, the experiment would best be designed such that the total mass for a pre-determined area was used as an end point.

The final stage of further experimentation should be the determination of a genetic effect in the off spring of the 5.0k Rad group. This particular experiment could be accomplished by the growth to maturity through two familial generations.

5.0 CONCLUSIONS

Using two distinct experimental designs, an investigation of the presence of a radiation hormesis effect in pinto beans (*phaseolus vulgaris L*) was conducted. The literature review provided numerous accounts of the presence of this effect in many types of crops in experiments performed by different researchers. There were not however many experiments which dealt with attempting to locate a hormetic level in a plant which provided nitrogen fixation, a legume.

Legumes provide nitrogen fixation through a symbiotic relationship with a bacteria, rhizobium. As in food sterilization, exposure to ionizing radiation will kill bacteria. Destroying this bacteria should have caused a nearly linear decrease in plant mass when compared to the control group. The fact that despite this mechanism within the pinto bean, a hormetic effect was plainly visible provides evidence of a mechanism which counteracts the reduced number of bacteria and provides increased growth rates.

The fact that a dry seed is nearly mitotically inactive explains the relatively small radiosensitivity and subsequent high survival rates. The increase in growth rate present is likely to be caused by the actuation of a stimulative growth product within the seed prior to germination. The presence of this product is however counteracted at high levels of radiation exposure.

Although current public perception concerning radiation and is not favorable and this technique is not likely to be used in farming in the near future, it should not be ruled out for a time when less crop land is available and the public is further educated on the topic of radiation.

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APPENDIX A

Table of Results for the Completely Randomized Design

Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)
1	0.156	0.399	0.555	25	1.656	2.422	4.078	49	0.917	2.305	3.222
2	1.565	2.702	4.267	26	0.426	0.524	0.950	50	1.260	2.634	3.894
3	1.497	2.736	4.233	27	0.857	2.395	3.252	51	0.943	3.341	4.284
4	1.082	2.623	3.705	28	1.200	1.158	2.358	52	1.245	2.475	3.720
5	0.868	1.705	2.573	29	0.958	1.457	2.415	53	0.836	1.659	2.495
6	1.230	3.252	4.482	30	1.521	2.317	3.838	54	0.671	1.575	2.246
7	1.300	1.693	2.993	31	0.939	2.525	3.464	55	0.905	2.602	3.507
8	1.136	2.032	3.168	32	1.326	2.962	4.288	56	1.241	1.655	2.896
9	1.224	2.423	3.647	33	1.095	2.618	3.713	57	1.024	3.013	4.037
10	1.581	1.928	3.509	34	1.017	2.672	3.689	58	0.928	2.502	3.430
11	1.042	2.820	3.862	35	0.891	2.750	3.641	59	0.771	2.316	3.087
12	1.513	3.042	4.555	36	1.349	3.262	4.611	60	1.872	3.121	4.993
13	0.283	0.532	0.815	37	1.003	2.809	3.812	61	0.996	2.794	3.790
14	1.233	2.680	3.913	38	0.914	0.745	1.659	62	0.993	2.249	3.242
15	1.282	2.390	3.672	39	1.030	2.863	3.893	63	0.738	2.102	2.840
16	1.011	2.331	3.342	40	0.342	0.672	1.014	64	0.926	2.667	3.593
17	1.209	2.064	3.273	41	0.548	1.852	2.400	65	0.903	2.638	3.541
18	1.407	2.535	3.942	42	0.748	1.657	2.405	66	0.432	1.379	1.811
19	1.124	2.355	3.479	43	1.345	2.133	3.478	67	0.565	2.330	2.895
20	1.118	2.565	3.683	44	0.874	1.865	2.739	68	0.766	2.359	3.125
21	1.130	2.646	3.776	45	1.243	2.728	3.971	69	1.127	2.145	3.272
22	1.405	2.026	3.431	46	0.889	1.786	2.675	70	0.864	3.475	4.339
23	1.646	1.737	3.383	47	1.685	3.239	4.924	71	0.957	2.293	3.250
24	0.909	1.853	2.762	48	0.942	2.498	3.440	72	1.321	3.128	4.449

Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)
73	0.102	0.567	0.669	97	0.732	2.605	3.337	121	0.888	2.450	3.338
74	0.732	2.856	3.588	98	1.011	2.843	3.854	122	0.931	3.212	4.143
75	0.747	3.993	4.740	99	0.781	2.357	3.138	123	1.007	2.285	3.292
76	0.718	2.331	3.049	100	0.989	2.645	3.634	124	0.882	2.343	3.225
77	0.784	2.789	3.573	101	0.818	2.372	3.190	125	0.987	3.096	4.083
78	1.014	3.570	4.584	102	0.803	3.556	4.359	126	0.933	1.207	2.140
79	0.690	1.733	2.423	103	1.035	2.913	3.948	127	0.610	2.511	3.121
80	0.296	0.775	1.071	104	1.114	2.446	3.560	128	1.079	1.880	2.959
81	0.639	2.352	2.991	105	1.421	2.627	4.048	129	0.926	1.828	2.754
82	0.761	1.037	1.798	106	1.313	2.718	4.031	130	1.037	1.958	2.995
83	0.707	2.491	3.198	107	1.157	3.475	4.632	131	0.683	2.721	3.404
84	0.802	2.776	3.578	108	0.851	2.109	2.960	132	1.028	2.662	3.690
85	0.976	3.302	4.278	109	0.981	3.180	4.161	133	0.834	1.912	2.746
86	0.667	2.050	2.717	110	0.862	2.546	3.408	134	0.766	1.691	2.457
87	0.447	1.473	1.920	111	0.895	1.705	2.600	135	0.882	1.961	2.843
88	0.876	2.175	3.051	112	0.744	2.137	2.881	136	0.159	0.494	0.653
89	0.985	3.825	4.810	113	1.229	2.398	3.627	137	0.714	2.221	2.935
90	0.724	2.868	3.592	114	0.877	2.752	3.629	138	0.768	2.190	2.958
91	1.882	3.591	5.473	115	0.613	2.442	3.055	139	0.672	2.262	2.934
92	0.809	3.324	4.133	116	0.633	2.490	3.123	140	0.796	2.047	2.843
93	1.456	2.609	4.065	117	0.695	2.511	3.206	141	0.878	2.015	2.893
94	0.872	2.399	3.271	118	0.958	3.031	3.989	142	0.612	1.735	2.347
95	1.707	2.867	4.574	119	0.686	3.034	3.720	143	0.522	1.604	2.126
96	0.347	1.115	1.462	120	1.034	2.521	3.555	144	0.610	2.219	2.829

Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)
145	0.621	1.834	2.455	169	0.517	1.910	2.427	193	1.367	0.881	2.248
146	0.629	2.517	3.146	170	0.347	1.028	1.375	194	0.872	2.440	3.312
147	0.682	2.344	3.026	171	1.098	2.398	3.496	195	0.749	2.328	3.077
148	0.653	2.361	3.014	172	0.686	2.227	2.913	196	0.684	2.188	2.872
149	0.555	2.025	2.580	173	0.813	1.921	2.734	197	1.155	2.706	3.861
150	0.680	2.365	3.045	174	0.899	2.821	3.720	198	0.745	2.336	3.081
151	0.623	2.193	2.816	175	0.883	2.390	3.273	199	1.006	1.699	2.705
152	0.676	2.313	2.989	176	0.785	2.271	3.056	200	1.062	2.287	3.349
153	0.747	2.212	2.959	177	0.768	2.682	3.450	201	0.901	2.225	3.126
154	0.633	2.623	3.256	178	0.761	2.208	2.969	202	0.927	1.625	2.552
155	0.889	2.589	3.478	179	0.981	0.964	1.945	203	0.360	1.267	1.627
156	0.725	2.081	2.806	180	0.535	2.071	2.606	204	0.329	1.364	1.693
157	0.446	1.353	1.799	181	1.357	2.323	3.680	205	0.643	2.498	3.141
158	0.646	2.200	2.846	182	1.051	0.878	1.929	206	0.396	1.556	1.952
159	1.030	2.858	3.888	183	0.825	2.399	3.224	207	1.005	2.201	3.206
160	1.003	2.325	3.328	184	0.948	2.320	3.268	208	0.717	2.071	2.788
161	0.590	2.019	2.609	185	0.756	2.361	3.117	209	0.543	2.022	2.565
162	0.967	2.621	3.588	186	1.502	1.066	2.568	210	0.685	2.115	2.800
163	0.802	2.219	3.021	187	0.648	2.502	3.150	211	0.546	2.293	2.839
164	0.795	3.026	3.821	188	0.621	2.325	2.946	212	0.642	1.426	2.068
165	1.158	2.213	3.371	189	0.588	1.604	2.192	213	0.321	1.126	1.447
166	0.669	2.154	2.823	190	0.723	1.718	2.441	214	0.506	1.684	2.190
167	0.619	2.178	2.797	191	0.657	1.775	2.432	215	0.632	1.995	2.627
168	0.909	2.742	3.651	192	0.801	2.537	3.338	216	0.508	1.699	2.207

Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)
289	0.262	0.919	1.181	313	1.010	2.269	3.279	337	0.679	2.194	2.873
290	0.501	1.733	2.234	314	0.956	2.348	3.304	338	0.869	2.656	3.525
291	0.488	1.669	2.157	315	0.819	2.440	3.259	339	1.029	2.202	3.231
292	0.968	2.825	3.793	316	1.031	3.043	4.074	340	0.931	3.145	4.076
293	0.684	2.223	2.907	317	0.981	2.405	3.386	341	1.107	2.699	3.806
294	0.847	2.277	3.124	318	0.925	2.664	3.589	342	0.945	3.287	4.232
295	0.717	2.349	3.066	319	1.042	2.405	3.447	343	0.949	2.402	3.351
296	1.479	2.039	3.518	320	0.683	1.875	2.558	344	1.301	2.709	4.010
297	0.977	2.117	3.094	321	1.080	2.726	3.806	345	0.877	2.857	3.734
298	1.105	1.951	3.056	322	1.088	2.625	3.713	346	1.319	2.669	3.988
299	0.739	1.961	2.700	323	0.920	2.195	3.115	347	0.918	3.264	4.182
300	1.323	2.773	4.096	324	0.809	1.035	1.844	348	0.409	1.326	1.735
301	0.838	2.768	3.606	325	0.974	2.058	3.032	349	0.799	2.464	3.263
302	0.903	2.805	3.708	326	0.945	2.526	3.471	350	0.731	2.234	2.965
303	0.725	2.517	3.242	327	1.600	3.030	4.630	351	0.806	2.511	3.317
304	0.844	2.509	3.353	328	1.236	2.852	4.088	352	0.967	3.014	3.981
305	1.218	2.782	4.000	329	0.983	2.881	3.864	353	0.771	2.117	2.888
306	1.182	3.141	4.323	330	0.896	1.409	2.305	354	1.011	3.291	4.302
307	0.868	3.119	3.987	331	1.027	2.722	3.749	355	0.843	2.686	3.529
308	1.018	2.551	3.569	332	1.133	2.894	4.027	356	0.729	2.549	3.278
309	1.003	1.539	2.542	333	0.812	2.365	3.177	357	0.631	1.267	1.898
310	1.095	2.126	3.221	334	1.011	2.512	3.523	358	0.724	1.864	2.588
311	0.971	2.511	3.482	335	1.142	2.275	3.417	359	0.903	2.406	3.309
312	0.746	2.399	3.145	336	0.992	2.316	3.308	360	1.115	3.271	4.386

Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)
361	0.668	2.257	2.925	385	1.018	2.665	3.683	409	1.012	3.197	4.209
362	0.406	1.081	1.487	386	0.920	2.616	3.536	410	0.774	2.619	3.393
363	0.893	2.565	3.458	387	0.871	2.569	3.440	411	0.935	2.630	3.565
364	0.893	2.644	3.537	388	0.813	2.127	2.940	412	1.034	2.334	3.368
365	0.834	2.568	3.402	389	0.941	2.297	3.238	413	0.707	3.108	3.815
366	0.609	1.303	1.912	390	0.973	2.716	3.689	414	0.632	2.266	2.898
367	1.040	3.355	4.395	391	0.813	2.655	3.468	415	0.981	3.182	4.163
368	0.906	2.405	3.311	392	0.783	2.464	3.247	416	0.810	2.340	3.150
369	0.812	2.397	3.209	393	1.026	2.614	3.640	417	1.286	3.692	4.978
370	1.001	2.681	3.682	394	0.996	3.042	4.038	418	0.813	2.709	3.522
371	1.137	3.261	4.398	395	1.042	3.741	4.783	419	0.508	1.221	1.729
372	0.751	2.051	2.802	396	0.965	2.397	3.362	420	1.073	2.801	3.874
373	0.842	2.657	3.499	397	0.976	2.529	3.505	421	0.808	1.847	2.655
374	1.088	3.355	4.443	398	0.351	0.896	1.247	422	0.811	2.875	3.686
375	0.897	2.536	3.433	399	1.007	2.664	3.671	423	1.059	3.453	4.512
376	0.736	1.258	1.994	400	0.677	2.760	3.437	424	1.016	2.744	3.760
377	0.550	2.208	2.758	401	0.542	2.279	2.821	425	0.902	3.085	3.987
378	0.988	2.623	3.611	402	0.151	0.852	1.003	426	0.982	3.022	4.004
379	0.944	2.507	3.451	403	1.161	3.086	4.247	427	0.719	2.132	2.851
380	0.871	2.839	3.710	404	1.111	2.924	4.035	428	0.422	1.795	2.217
381	1.054	3.084	4.138	405	1.055	2.025	3.080	429	1.123	4.179	5.302
382	0.927	2.893	3.820	406	0.704	2.495	3.199	430	0.782	3.352	4.134
383	0.979	2.455	3.434	407	0.686	1.378	2.064	431	0.697	2.440	3.137
384	0.952	2.758	3.710	408	0.717	2.203	2.920	432	0.929	3.373	4.302

Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)
433	0.843	3.576	4.419	457	0.830	2.331	3.161	481	1.020	3.362	4.382
434	0.874	1.341	2.215	458	0.886	3.498	4.384	482	0.785	3.492	4.277
435	0.556	1.213	1.769	459	0.272	1.596	1.868	483	0.766	3.050	3.816
436	0.971	2.880	3.851	460	0.915	3.106	4.021	484	1.063	3.674	4.737
437	0.892	4.058	4.950	461	0.169	0.741	0.910	485	0.887	3.088	3.975
438	0.891	2.709	3.600	462	0.805	1.570	2.375	486	0.923	3.174	4.097
439	0.731	2.739	3.470	463	0.974	4.138	5.112	487	0.913	2.546	3.459
440	0.881	3.529	4.410	464	0.799	2.896	3.695	488	0.930	3.512	4.442
441	0.773	2.248	3.021	465	0.391	2.250	2.641	489	0.956	2.731	3.687
442	0.983	3.145	4.128	466	0.895	2.143	3.038	490	0.501	1.805	2.306
443	0.351	1.797	2.148	467	0.857	2.939	3.796	491	0.827	3.049	3.876
444	0.756	1.383	2.139	468	0.912	3.267	4.179	492	0.857	3.808	4.665
445	0.799	3.181	3.980	469	0.669	2.775	3.444	493	0.789	2.369	3.158
446	0.519	0.792	1.311	470	0.616	1.854	2.470	494	0.902	2.973	3.875
447	0.459	0.984	1.443	471	1.046	3.327	4.373	495	0.122	0.637	0.759
448	0.424	2.501	2.925	472	0.691	2.675	3.366	496	1.141	3.367	4.508
449	1.037	3.412	4.449	473	1.034	3.654	4.688	497	0.836	2.413	3.249
450	0.822	2.830	3.652	474	0.927	3.531	4.458	498	1.149	2.947	4.096
451	0.708	2.377	3.085	475	0.578	2.582	3.160	499	0.361	1.447	1.808
452	1.195	3.015	4.210	476	1.465	3.249	4.714	500	0.837	2.385	3.222
453	0.859	3.549	4.408	477	0.779	2.694	3.473	501	0.551	1.544	2.095
454	0.928	3.531	4.459	478	0.925	3.657	4.582	502	0.863	2.618	3.481
455	0.918	3.669	4.587	479	0.745	2.474	3.219	503	0.563	1.386	1.949
456	0.957	2.757	3.714	480	1.126	3.295	4.421	504	0.481	1.952	2.433

Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)
505	1.160	3.817	4.977	529	0.869	2.416	3.285	553	0.874	2.961	3.835
506	0.865	3.722	4.587	530	0.806	3.492	4.298	554	0.906	2.432	3.338
507	0.885	2.952	3.837	531	0.974	2.115	3.089	555	0.699	2.729	3.428
508	0.932	2.268	3.200	532	0.639	1.968	2.607	556	0.826	3.065	3.891
509	0.722	3.007	3.729	533	1.091	3.024	4.115	557	1.239	3.720	4.959
510	0.858	3.001	3.859	534	1.043	3.545	4.588	558	0.954	2.954	3.908
511	0.965	3.437	4.402	535	0.881	2.713	3.594	559	0.936	3.125	4.061
512	0.754	3.316	4.070	536	0.692	2.434	3.126	560	0.682	2.827	3.509
513	1.047	4.013	5.060	537	0.986	3.186	4.172	561	0.962	3.133	4.095
514	0.878	2.585	3.463	538	0.374	1.051	1.425	562	0.801	2.469	3.270
515	0.679	3.090	3.769	539	1.082	2.868	3.950	563	0.779	2.173	2.952
516	0.138	0.807	0.945	540	0.544	2.502	3.046	564	0.149	1.050	1.199
517	0.899	3.646	4.545	541	0.646	2.485	3.131	565	0.962	3.188	4.150
518	0.970	3.352	4.322	542	0.975	2.740	3.715	566	0.827	2.983	3.810
519	1.174	4.585	5.759	543	0.843	2.639	3.482	567	0.888	2.384	3.272
520	0.983	2.877	3.860	544	1.268	2.981	4.249	568	0.651	2.637	3.288
521	0.652	3.042	3.694	545	1.108	3.516	4.624	569	0.811	2.519	3.330
522	0.990	3.534	4.524	546	0.989	3.372	4.361	570	0.978	3.209	4.187
523	1.001	3.061	4.062	547	0.767	2.739	3.506	571	0.886	2.855	3.741
524	0.969	3.054	4.023	548	0.836	2.228	3.064	572	0.742	2.604	3.346
525	0.735	3.044	3.779	549	0.789	3.511	4.300	573	0.457	1.286	1.743
526	0.803	2.517	3.320	550	0.937	3.382	4.319	574	0.698	1.837	2.535
527	1.026	2.570	3.596	551	0.773	2.979	3.752	575	0.721	1.477	2.198
528	0.686	1.664	2.350	552	0.906	2.487	3.393	576	0.797	3.289	4.086

Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)
577	0.912	3.494	4.406	601	1.142	3.273	4.415	625	0.956	2.966	3.922
578	0.824	3.094	3.918	602	0.808	2.619	3.427	626	0.969	2.864	3.833
579	0.932	3.549	4.481	603	0.516	2.295	2.811	627	0.491	0.834	1.325
580	0.421	1.134	1.555	604	0.897	2.012	2.909	628	1.106	2.463	3.569
581	0.663	1.458	2.121	605	0.912	2.014	2.926	629	0.643	1.904	2.547
582	0.846	3.872	4.718	606	0.440	0.829	1.269	630	0.953	2.698	3.651
583	0.771	2.634	3.405	607	0.728	2.966	3.694	631	0.817	2.640	3.457
584	0.478	1.124	1.602	608	0.816	2.489	3.305	632	0.493	0.925	1.418
585	1.028	3.902	4.930	609	1.093	3.485	4.578	633	0.495	1.081	1.576
586	0.827	2.819	3.646	610	0.792	2.661	3.453	634	1.035	2.589	3.624
587	0.370	0.858	1.228	611	0.652	2.390	3.042	635	0.784	2.382	3.166
588	0.991	2.628	3.619	612	0.846	3.213	4.059	636	0.857	3.526	4.383
589	0.824	2.997	3.821	613	1.013	2.521	3.534	637	0.642	2.483	3.125
590	0.813	3.563	4.376	614	0.914	2.918	3.832	638	0.468	1.289	1.757
591	1.078	3.133	4.211	615	0.559	1.136	1.695	639	0.772	2.981	3.753
592	0.970	3.457	4.427	616	0.898	3.834	4.732	640	0.593	2.190	2.783
593	0.941	3.359	4.300	617	0.742	3.303	4.045	641	0.554	2.757	3.311
594	0.835	3.371	4.206	618	1.086	3.638	4.724	642	0.923	2.838	3.761
595	0.805	2.618	3.423	619	0.885	2.880	3.765	643	0.925	3.343	4.268
596	0.813	3.429	4.242	620	1.065	2.772	3.837	644	1.035	2.519	3.554
597	1.033	3.643	4.676	621	0.912	3.055	3.967	645	0.889	2.398	3.287
598	0.954	3.156	4.110	622	1.024	3.154	4.178	646	0.797	3.115	3.912
599	0.853	2.125	2.978	623	0.828	3.158	3.986	647	0.852	2.283	3.135
600	0.726	2.593	3.319	624	0.798	2.734	3.532	648	0.999	3.932	4.931

Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)
649	0.820	2.474	3.294	673	0.391	0.931	1.322
650	0.764	1.023	1.787	674	0.810	2.881	3.691
651	0.705	2.851	3.556	675	0.678	1.515	2.193
652	0.722	1.989	2.711	676	0.780	2.326	3.106
653	1.028	3.856	4.884	677	1.128	3.544	4.672
654	1.001	3.827	4.828	678	0.478	1.686	2.164
655	0.562	2.395	2.957	679	0.707	1.591	2.298
656	0.969	2.048	3.017	680	0.779	2.722	3.501
657	0.832	2.457	3.289	681	0.821	2.815	3.636
658	1.120	4.209	5.329	682	0.914	2.625	3.539
659	1.011	3.425	4.436	683	0.203	0.902	1.105
660	0.744	2.691	3.435	684	0.732	2.716	3.448
661	0.892	2.795	3.687	685	0.768	2.255	3.023
662	1.050	3.124	4.174	686	0.812	2.880	3.692
663	0.693	2.601	3.294	687	1.004	1.980	2.984
664	0.283	1.057	1.340	688	0.905	2.643	3.548
665	1.310	3.932	5.242	689	0.891	2.242	3.133
666	0.484	1.186	1.670	690	0.902	2.358	3.260
667	0.567	1.931	2.498	691	0.679	2.439	3.118
668	0.829	3.161	3.990	692	0.241	0.634	0.875
669	0.235	0.669	0.904	693	0.670	2.036	2.706
670	0.845	2.268	3.113	694	0.856	2.377	3.233
671	0.708	2.665	3.373	695	0.599	2.071	2.670
672	0.954	2.446	3.400				

APPENDIX B

Table of Results for the Completely Randomized Block Design

Plant # Number	Root Ma (g)	Plant Mass (g)	Total Mass (g)	Block Number	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Block Number
1	1.307	4.133	5.440	4	25	1.208	4.043	5.251	5
2	1.194	3.094	4.288	3	26	0.815	3.452	4.267	2
3	1.115	3.056	4.171	1	27	1.397	3.185	4.582	2
4	1.294	3.619	4.913	6	28	1.188	3.433	4.621	2
5	1.285	3.548	4.833	5	29	1.322	4.497	5.819	3
6	0.810	2.473	2.473	2	30	1.361	3.523	4.884	4
7	1.583	4.651	6.234	1	31	0.781	2.402	3.183	6
8	1.145	3.741	4.886	5	32	0.836	3.518	4.354	4
9	1.106	3.705	4.811	2	33	1.192	3.547	4.739	5
10	1.040	3.003	4.043	1	34	0.364	1.411	1.775	2
11	0.957	2.389	2.389	4	35	1.163	2.919	4.082	5
12	0.814	2.513	2.513	4	36	0.831	4.451	5.282	2
13	1.075	4.461	5.536	3	37	1.208	2.343	3.551	4
14	1.243	3.603	4.846	6	38	1.023	3.038	4.061	5
15	0.740	3.783	3.783	4	39	1.216	3.724	4.940	3
16	1.358	3.506	4.864	6	40	1.026	2.314	3.340	4
17	0.651	1.783	1.783	5	41	1.091	3.584	4.675	3
18	0.992	3.208	3.208	1	42	0.610	2.264	2.874	2
19	0.885	2.696	2.696	6	43	1.117	4.155	5.272	4
20	1.562	3.223	4.785	6	44	1.110	3.431	4.541	6
21	1.249	3.608	4.857	3	45	1.065	2.710	3.775	2
22	1.316	3.414	4.730	1	46	0.795	2.735	3.530	3
23	0.955	3.425	3.425	3	47	0.850	3.698	4.548	2
24	0.662	1.891	1.891	5	48	0.939	2.013	2.952	4

Plant # Number	Root Ma (g)	Plant Mass (g)	Total Mass (g)	Block Number	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Block Number
49	0.904	2.108	3.012	3	73	0.730	2.374	3.104	2
50	0.921	2.795	3.716	5	74	0.882	3.911	4.793	4
51	1.201	4.291	5.492	1	75	1.159	3.191	4.350	6
52	0.973	3.952	4.925	6	76	1.330	4.458	5.788	3
53	1.453	3.772	5.225	5	77	1.319	4.662	5.981	4
54	1.200	3.712	4.912	3	78	1.359	3.563	4.922	1
55	1.253	2.911	4.164	1	79	0.615	2.352	2.967	4
56	1.204	3.258	4.462	6	80	1.390	3.999	5.389	5
57	1.089	4.289	5.378	1	81	1.207	3.445	4.652	3
58	0.998	2.817	3.815	1	82	1.400	4.318	5.718	6
59	1.158	3.559	4.717	6	83	1.217	5.035	6.252	4
60	1.240	3.616	4.856	1	84	0.981	3.116	4.097	6
61	1.077	3.954	5.031	2	85	1.008	3.605	4.613	1
62	1.371	3.268	4.639	3	86	0.579	2.411	2.990	5
63	1.413	3.447	4.860	2	87	1.481	3.732	5.213	6
64	1.314	4.451	5.765	2	88	0.694	2.457	3.151	1
65	1.092	3.099	4.191	2	89	1.391	3.449	4.840	1
66	1.116	4.501	5.617	5	90	0.617	1.051	1.668	1
67	1.351	3.799	5.150	3	91	0.620	1.994	2.614	1
68	0.951	4.924	5.875	6	92	1.345	5.211	6.556	3
69	0.967	2.505	3.472	4	93	0.601	1.923	2.524	3
70	1.057	3.999	5.056	5	94	0.801	2.461	3.262	2
71	1.439	3.048	4.487	5	95	1.198	3.302	4.500	3
72	1.119	3.823	4.942	3	96	1.264	2.573	3.837	3

Plant # Number	Root Ma (g)	Plant Mass (g)	Total Mass (g)	Block Number	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Block Number
97	1.039	2.634	3.673	6	121	0.627	2.122	2.749	5
98	1.024	4.016	5.040	2	122	0.66	1.720	2.380	4
99	0.537	1.969	2.506	5	123	0.758	1.487	2.245	1
100	0.456	1.127	1.583	4	124	0.709	2.075	2.784	2
101	0.642	1.457	2.099	5	125	0.714	1.717	2.431	3
102	0.956	3.282	4.238	1	126	0.634	1.507	2.141	5
103	0.954	2.496	3.450	6	127	0.877	2.906	3.783	3
104	0.711	1.322	2.033	5	128	1.098	3.368	4.466	5
105	0.398	1.514	1.912	1	129	0.634	2.049	2.683	4
106	0.687	1.618	2.305	5	130	0.422	1.286	1.708	5
107	0.49	2.232	2.722	4	131	0.837	1.870	2.707	1
108	0.716	1.813	2.529	4	132	1.175	3.269	4.444	3
109	0.936	2.575	3.511	5	133	0.364	0.720	1.084	6
110	0.748	2.539	3.287	2	134	1.374	2.677	4.051	6
111	0.521	1.375	1.896	2	135	1.002	3.029	4.031	1
112	1.144	2.779	3.923	4	136	0.571	1.559	2.130	6
113	0.626	2.005	2.631	4	137	1.164	3.525	4.689	5
114	1.485	4.051	5.536	1	138	0.66	1.731	2.391	6
115	0.454	1.339	1.793	6	139	0.734	1.518	2.252	1
116	0.664	1.859	2.523	6	140	0.846	1.936	2.782	3
117	0.897	1.581	2.478	1	141	0.772	1.668	2.440	3
118	1.132	3.675	4.807	6	142	1.082	2.341	3.423	4
119	0.613	1.316	1.929	6	143	0.862	2.138	3.000	6
120	0.635	1.532	2.167	2	144	1.037	3.156	4.193	2

Plant # Number	Root Ma (g)	Plant Mass (g)	Total Mass (g)	Block Number	Plant Number	Root Mass (g)	Plant Mass (g)	Total Mass (g)	Block Number
145	0.561	1.703	2.264	4	169	0.615	1.905	2.520	3
146	0.534	1.233	1.767	4	170	1.037	3.249	4.286	5
147	0.535	0.896	1.431	2	171	0.575	2.131	2.706	1
148	0.986	2.109	3.095	1	172	0.867	2.988	3.855	1
149	1.455	3.798	5.253	2	173	0.610	2.112	2.722	1
150	0.492	1.359	1.851	6	174	0.830	3.175	4.005	2
151	0.775	2.106	2.881	4	175	0.255	0.611	0.866	5
152	0.702	1.667	2.369	4	176	0.608	1.586	2.194	2
153	1.547	3.916	5.463	3	177	0.893	2.757	3.650	2
154	0.476	0.981	1.457	6	178	0.445	2.128	2.573	5
155	0.899	3.125	4.024	2	179	0.208	0.851	1.059	1
156	0.365	1.308	1.673	1	180	0.031	0.026	0.057	6
157	0.740	2.453	3.193	5	181	0.671	1.991	2.662	4
158	0.654	2.719	3.373	1	182	0.305	0.682	0.987	2
159	1.147	2.846	3.993	3	183	0.232	1.249	1.481	3
160	0.662	1.475	2.137	4	184	0.148	0.496	0.644	4
161	0.306	1.086	1.392	6	185	0.130	0.355	0.485	3
162	1.121	2.974	4.095	3	186	0.152	0.355	0.507	5
163	1.087	3.762	4.849	6	187	0.557	0.549	1.106	2
164	0.592	2.400	2.992	4	188	0.291	2.114	2.405	1
165	0.804	2.989	3.793	3	189	0.069	1.026	1.095	4
166	0.454	1.357	1.811	5	190	0.208	0.181	0.389	3
167	1.010	2.985	3.995	4	191	0.128	0.994	1.122	2
168	0.582	1.743	2.325	2	192	0.214	0.211	0.425	4

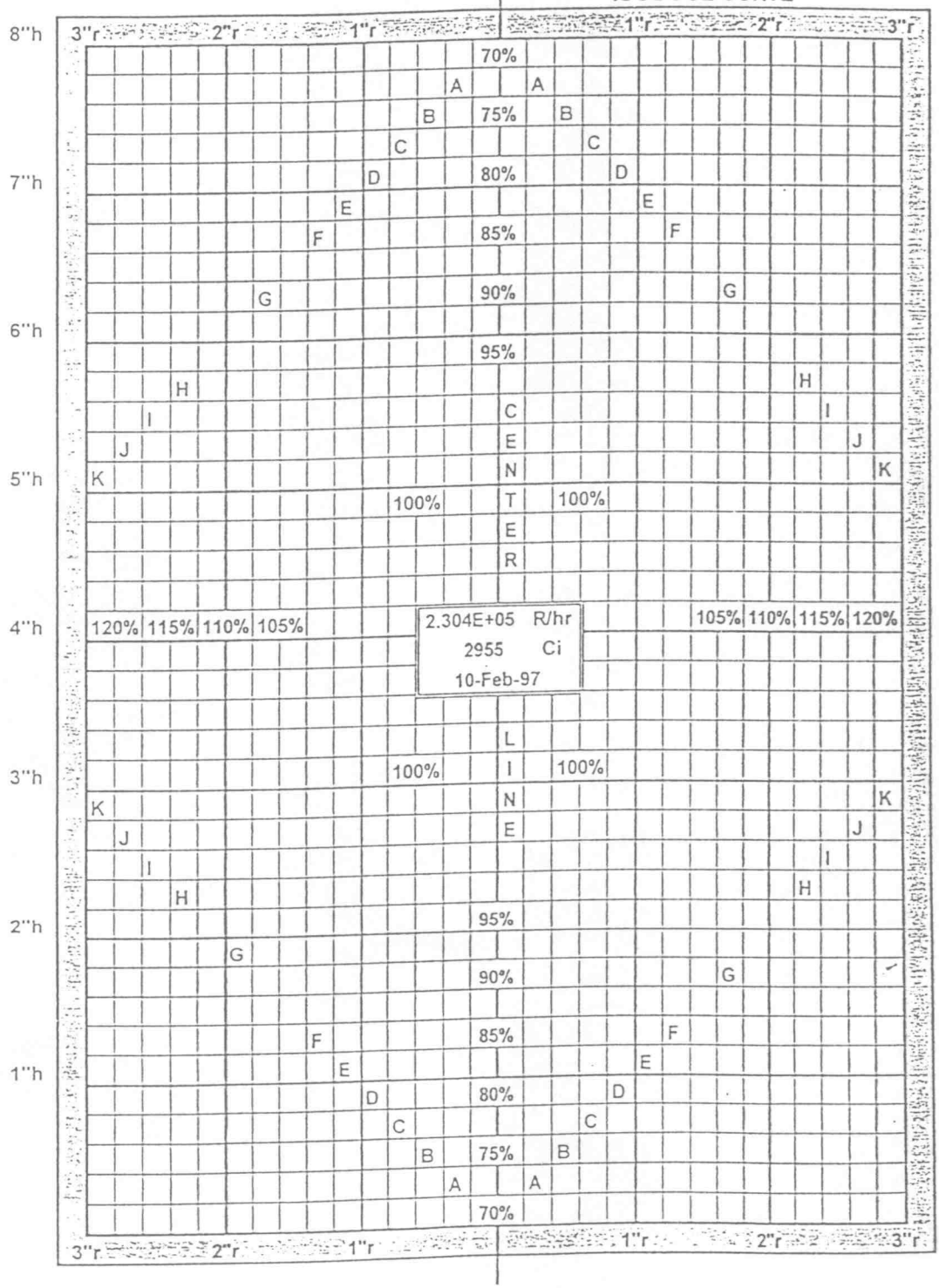
APPENDIX B

Gammacell 220 Chamber Cross section Isodose Curve

APPENDIX A

OREGON STATE UNIVERSITY RADIATION CENTER

GAMMACELL 220 CHAMBER CROSS SECTION ISODOSE CURVE



REGION:

A =	1.613E+05 R/hr	E =	2.073E+05 R/hr	I =	2.534E+05 R/hr
B =	1.728E+05 R/hr	F =	2.189E+05 R/hr	J =	2.649E+05 R/hr
C =	1.843E+05 R/hr	G =	2.304E+05 R/hr	K =	2.765E+05 R/hr
D =	1.958E+05 R/hr	H =	2.419E+05 R/hr		

Revised 10/94