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PREDICTING THE LONG-TERM RADIOLOGICAL AND AGRONOMIC IMPACTS OF HIGH RATES OF PHOSPHOGYPSUM APPLIED TO SOILS UNDER BAHIAGRASS PASTURE

Part One

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PREDICTING THE LONG-TERM RADIOLOGICAL AND AGRONOMIC IMPACTS OF HIGH RATES OF PHOSPHOGYPSUM APPLIED TO SOILS UNDER BAHIAGRASS PASTURE

FINAL REPORT

PART ONE

PREDICTING THE LONG-TERM IMPACT ON RADIOACTIVITY IN SOIL, GROUNDWATER, AND BAHIAGRASS FORAGE, AND ON RADON EMISSIONS

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PERSPECTIVE

The Florida Institute of Phosphate Research, through its "Strategic Research Priorities," currently is stressing six program areas, three that are technology oriented and three that are more environmental in nature. A major focus is on phosphogypsum, a technology area but with significant environmental aspects. The objective is to reduce the accumulation of phosphogypsum produced by the industry. A significant approach toward that objective lies in developing and demonstrating environmentally acceptable uses for the material. This project addresses one aspect of potential use.

Phosphogypsum is composed mostly of calcium sulfate and is a by-product of the reaction between sulfuric acid and phosphate rock in the production of phosphoric acid. Currently almost one billion tons of the material are stockpiled on the ground in central and north Florida, and about thirty million tons are being added each year. A priority of the Institute since virtually its inception has been to find ways to use phosphogypsum. Any proposed use, however, must meet three criteria: it must be technically feasible, economical, and protective of the environment and the public health. A major use could be as a soil amendment. Phosphogypsum would be an excellent source of calcium and especially sulfur on agricultural lands, many of which, especially those in the Southeast, are deficient in sulfur. EPA has determined that phosphogypsum can be used in unlimited quantities in agriculture as long as its radium-226 content does not exceed ten picocuries per gram (pCi/g). While this limit generally permits the use of gypsum from North Florida and elsewhere in the country, it does not allow the use of central Florida gypsum. Material from central Florida generally contains about twenty five pCi/g.

A first environmental field study of the impacts of using phosphogypsum on forage crops was done by the University of Florida in the 1980's at their Ona research and teaching center, and sponsored by the Institute (FIPR #89-01-085). Nominal rates of application were used, typical of what would be applied to a pasture by the rancher. Results showed that the gypsum application increased forage yield and made it more digestible. However, at the application rates used, data on radiological impacts to the environment or to the forage were not conclusive. No statistically valid differences in radium-226 or radon-222 levels could be found in soils, groundwater, air radon, aboveground gamma, or the forage. Thus a question remained: "Does the application of phosphogypsum to forage affect the radionuclide levels in the environment or crop?"

To answer this question a second study was conducted. The objective of that study was to establish relationships between gypsum application and environmental/ forage quality. To do this, very high quantities of phosphogypsum were applied to the crops in the hope of finding measured differences that were statistically significant. Meaningful differences were found in this second study. Results were presented in light of such variables as environmental parameter, rate of application, soil depth, type of forage, elapsed time after application, crop sequence, and type of radionuclide, i.e., radium, lead, or polonium. Dose evaluations were included. It would appear that, while differences were detectable, radiation levels were still too low to be of significance. It follows that normal rates of phosphogypsum application, which would be much lower than rates in this study, also would be too low to be of significance.

The third question that arose concerned the persistence of the radionuclides in the forage and environment. Over the long term, do they accumulate, dissipate, or remain at about the same levels? This third and final study addressed that issue by continuing the monitoring for over five additional years. Changes were mixed but generally minimal. Transfer factors relating the measured values to phosphogypsum amounts applied were calculated as predictive tools. Radiation doses and associated risks after 100 years of annual applications of phosphogypsum to forages were estimated for various pathways from soil to humans.

Gordon D. Nifong, Ph.D.
Research Director, Environment & Public Health

ABSTRACT

This study developed data to support assessments of the radiological impacts of long-term application of phosphogypsum (PG) to agricultural lands. PG containing 21.4, 22.6, and 20.1 pCi g^{-1} ^{226}Ra, ^{210}Pb, and ^{210}Po, respectively, was applied at 10 and 20 Mg PG ha^{-1} in 1993 (FIPR Publ. No. 05-038-141) to two Florida soils cropped to bahiagrass. Radiological parameters were measured periodically for 5 ½ years. Levels of ^{226}Ra, ^{210}Pb, and ^{210}Po in the top 5-cm soil layer increased with PG, and there was developing evidence of appearance in the 5-10 cm layer. Radon flux also increased and levels persisted. Effects on gamma radiation levels were slight and decreased after the first year. Effects on ^{226}Ra, ^{210}Pb, and ^{210}Po in groundwater down to 90 cm were minimal and on ambient airborne ^{222}Rn levels were inconclusive. The PG had a strong effect on ^{226}Ra, ^{210}Pb, and ^{210}Po in the first post-treatment regrowth harvest at one site. PG-attributable ^{226}Ra was observed in both mature hay and regrowth with no measurable decrease in uptake through the 6^{th} growing season; PG-attributable ^{210}Pb and ^{210}Po was observed in mature hay only during the first two seasons. Mature hay generally had higher levels of radionuclides than the regrowth. Transfer factors (TFs), relating the measured radiological values to PG rate or radioactivity applied per unit area were calculated for use as predictive tools. Radiation doses and associated risks after 100 years of annual PG application at 0.4 Mg ha^{-1} to cattle-grazed bahiagrass pasture were estimated for various pathways from soil to humans.

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EXECUTIVE SUMMARY

INTRODUCTION

A field study was conducted at the University of Florida Range Cattle Research and Education Center to support the radiological assessment of the impact of applying phosphogypsum (PG) to agricultural lands. PG was applied on a one-time basis to Pensacola bahiagrass (*Paspalum notatum* Flugge) pastures and periodic measurements were made of ^{226}Ra, ^{210}Pb, and ^{210}Po in soil, ground water, and forages and of levels of ^{222}Rn (hereafter identified as simply Rn) flux, gamma radiation, and airborne Rn. In addition, an assessment was performed of the projected effects of long-term repetitive annual applications.

METHODS

Parallel field experiments were conducted on two Florida soils: Malabar, a loamy, non-spodic soil and Myakka, a sandy, spodic soil. PG containing ^{226}Ra, ^{210}Pb, and ^{210}Po at concentrations of 21.4, 22.6, and 20.1 pCi g^{-1}, respectively, was broadcast to the surface of established Pensacola bahiagrass pastures in May/June 1993. Treatments consisted of 10.0 and 20.0 Mg ha^{-1} with no applied PG as a control. These high PG levels, ranging up to 50 times the agronomically optimum annual application, were selected to enhance the likelihood of obtaining significant data providing quantitative relationships to PG treatment rates.

Post-treatment observations were taken over a period of 5+ years (May 1993-October 1998). Concentrations of ^{226}Ra, ^{210}Pb, and ^{210}Po were measured in the soil profile, in runoff water, in ground water collected at 45-cm and 90-cm depths, in regrowth forage, and in mature hay. Rn flux was measured typically four times per year. Gamma radiation and airborne Rn, both at 1 m above the surface, were measured through August 1997.

The measurement results were examined for PG-treatment effects and for trends with time. In addition, transfer factors (TFs), relating the respective radiological values to PG (or, alternatively, to radioactivity) applied per unit area, were calculated for use as tools to predict radionuclide and radiation levels when assessing future PG use scenarios.

FIELD STUDY RESULTS AND CONCLUSIONS

Radionuclides in Soil

The effect of PG application was seen in the surface (0-5 cm) layer for all three radionuclides throughout the study at both sites. No overall time trends were observed for the surface layer. Although the analyses were not sensitive enough to directly detect or estimate the rate of losses from the surface layer, there was developing evidence for the appearance of these radionuclides in the second (5-10 cm) layer. There were no indications of significant transport of these radionuclides to layers deeper than 10 cm during the approximately 5-year observation period.

Soil Surface Rn Flux

Application of PG was clearly reflected as additions to soil surface Rn flux values at both sites. Rn flux values from these sites followed a general cyclic pattern with winter peaks and spring-summer valleys. An unexplained midsummer peak was superimposed on this pattern in June 1997, but not repeated in June 1998. Time-trend analysis did not indicate any unidirectional trend with time; the environmental loss rate for PG-attributable Rn flux following application of PG to Florida lands cropped to bahiagrass is too slow to be estimated from the approximately five years of observations in this study.

The results of the atmospheric Rn measurements were inconclusive.

Gamma Radiation

Barely detectable increases in gamma radiation levels at 1 m above the surface were observed during the first year following the surface application of PG at rates up to 20 Mg ha^{-1}. In the subsequent three years (measurements were terminated after the fourth year), the effects were less--the overall average values for treated plots were higher than for control plots, but the differences were significant for only some of the various measurement campaigns. The reduced effect after the first year is probably due to weathering of the PG with time, removal of the applied radionuclides with forage harvests, and/or penetration of the radionuclides into the upper layer of the soil.

Radionuclides in Groundwater

During the first two years following PG treatment, the rainfall seldom exceeded the soil infiltration capacity and only one runoff sample was collected, thus limiting the basis for evaluating runoff during the early post-treatment period. While not observed consistently or in a systematic pattern, there is some probability of PG-attributable radionuclides occurring in runoff water following PG treatment at levels up to 20 Mg ha^{-1}. PG-related ^{210}Po appeared to be more mobile in the early years than subsequently. Results from the wells were highly variable for the various depths, radionuclides, and sites; PG-attributable radionuclides were neither consistently detected nor totally absent.

In summary, the one-time PG applications had very limited impacts on surface and groundwater quality. However, this study provides only limited information for projecting the effects and time-dependent behavior of PG-attributable radionuclides in surface and shallow groundwater following surface application of PG. It will be necessary to make liberal use of estimated upper bounds in environmental assessment.

Radionuclides in Bahiagrass Forages

Concentrations of ^{226}Ra, ^{210}Pb, and ^{210}Po in the first post-treatment regrowth harvest at the Myakka site were strikingly in excess of those in subsequent Myakka-site and all Malabar-site regrowth harvests. It was hypothesized that for the Malabar site, PG deposited on the surface of the grass during land treatment was washed off by the rainfall that followed promptly (within four days), but for the Myakka site, the radionuclides gradually underwent foliar absorption or became fixed in the 20-day interval to the first major rainfall following treatment at that site. Thus the first-harvest radionuclide concentrations at Myakka included an extra component (probably retained surface contamination) in addition to the "basic" root-uptake component responsible for concentrations at the other Myakka harvests and all the Malabar harvests.

If the special Myakka first-harvest effect is excluded, the mature forage is generally characterized by higher concentrations (for both control and treated plots), larger concentration vs. treatment level slopes, and higher tissue/soil concentration ratios than for regrowth forage. This difference is especially pronounced for ^{210}Pb and ^{210}Po.

PG treatments at levels up to 20 Mg ha^{-1} were reflected in measurable ^{226}Ra in both mature hay and regrowth (even with the exclusion of the Myakka first-harvest effect) at both sites. There was no measurable overall decrease in ^{226}Ra uptake through the 6th post-treatment growing season. PG-attributable ^{226}Ra concentrations in mature hay were two to three times as high as those in regrowth forages (Myakka first harvest excluded).

PG-attributable ^{210}Pb and ^{210}Po were observed in mature hay during the first two post-treatment seasons, but not in subsequent seasons. The effects for ^{210}Pb and ^{210}Po were more pronounced for the Myakka site than for the Malabar site. This suggests that these radionuclides are less available from the Malabar soil than from the Myakka soil, perhaps due to the higher organic material content in the surface layer of the Malabar soil. The short persistence of detectable PG-attributable ^{210}Pb and ^{210}Po in the mature hay, with a decrease more rapid than the rate of loss from the root zone (top 15 cm) of the soil, suggests that initially there is a small, more readily available fraction that disappears through transport and/or removal, or, alternatively, that the PG-associated radionuclides become fixed in the soil with time. If the first-harvest effect is excluded, any effects on ^{210}Pb and ^{210}Po in regrowth forage could not be detected for either radionuclide at either site.

ASSESSMENT OF RADIOLOGICAL IMPACT FOR A SCENARIO OF PG USE

An assessment was performed of the potential radiological impact for a scenario of Central Florida PG applied annually to bahiagrass pastures at the agronomically recommended rate of 0.4 Mg ha^{-1} for 100 years with the land then becoming available for a variety of purposes, including residential construction. Radioactivity additions to the surface soil layers were calculated from the projected PG application rate and the specified radionuclide content of the PG. Future values of Rn flux, gamma radiation, and radionuclide concentrations in groundwater and forage were projected using selected TFs from the field study. Environmental radiation and radioactivity levels were compared to baseline values and to environmental radiation standards (where available). Radiation doses to humans were projected and compared to the recommendation that doses from a single practice or exposure pathway not exceed some fraction of the dose limit for members of the general public of 100 mrem y^{-1} above background for all exposure pathways combined. Risks were estimated also.

Radionuclides in Soil

While the radioactivity contributed by a one-time treatment at agronomic rates cannot be detected for sampling layers of 5 cm or more, increased radionuclide concentrations would be detectable in the surface soil layer following the proposed 100-year practice. However, the increased concentration of ^{226}Ra averaged over the first Rn modeling layer (61 cm or 24 in) would be only about 20%, a value that is considerably less than the typical variations in soil ^{226}Ra concentrations in nonenhanced Florida soils.

Rn Flux and Indoor Rn

The long-term practice would result in Rn flux contributions that are detectable for low background areas (such as the Ona Research Center), but well within the range of variations seen in the state. The PG-attributable Rn flux contribution was projected to be 0.072 pCi m^{-2} s^{-1}, an addition of about 290% of the baseline value for the Ona Research Center and about 35% of the statewide average for undisturbed nonmineralized lands in Florida.

PG-attributable contributions to indoor Rn concentrations in structures built directly over the treated land without any special Rn-resistant features were projected to be about 0.11 pCi L^{-1} (in the range of 0.02 to 0.5 pCi L^{-1}), a small increment relative to the variations in levels normally seen among Florida houses. Added to general indoor Rn concentrations on the order of 1 to 2 pCi L^{-1}, the projected total concentrations of 1.1 to 2.1 pCi L^{-1} are in the range of 28 to 53% of the U. S. Environmental Protection Agency (EPA) Action Level of 4 pCi L^{-1}. The calculated PG-attributable contribution represents an increased effective dose of 7.2 mrem y^{-1}. Risks from the PG-attributable Rn were calculated to be on the order of 5.4×10^{-6} from one year of exposure and on the order of 4.0×10^{-4} for a lifetime (75.2-year) exposure.

External Gamma Radiation

The PG practice was projected to contribute 0.4 μR h^{-1} to gamma radiation levels; this addition is about 6% of the baseline value for the research site and is small relative to existing background radiation levels and variations. Adding this increment to the typical background of 5.7 µR h^{-1} gives a total external radiation exposure rate of 6.1 µR h^{-1}, a value that is about 30% of the Florida Department of Health 20 µR h^{-1} standard for indoor radiation.

The PG-attributable gamma radiation would contribute 3.2 mrem y^{-1} to the effective dose, meeting the criterion of being a small fraction of 100 mrem y^{-1} above background. Risks from this source were estimated to be on the order of 1.8 x 10^{-6} from one year of exposure and on the order of 1.4 x 10^{-4} for a lifetime exposure. The dose calculation was conservative on the high side: it assumed 100% occupancy over the treated lands and no attenuation of the indoor radiation field by the building floor.

Surface and Ground Water, and the Water-to-Human Pathway

Assessment for water was based on use as drinking water by humans. Concentrations were compared to drinking water standards and dose and risk estimates were based on the assumption that this water is the exclusive drinking water source for humans.

The projected PG-attributable ^{226}Ra concentration of 0.79 pCi L^{-1} in surface and/or groundwater would be measurable (2.6 times the 0.30 pCi L^{-1} baseline) but the resulting total concentration of 1.09 pCi L^{-1} would be only a fraction (22%) of the drinking water standard of 5 pCi L^{-1}. The projected PG-attributable ^{210}Pb concentration of 1.72 pCi L^{-1} would be measurable (2.9 times the 0.59 pCi L^{-1} baseline); the resulting total concentration of 2.31 pCi L^{-1} would be on the order of 60% of a derived criterion of 4 pCi L^{-1} (at the present time there is no explicit drinking water standard for ^{210}Pb). The projected PG-attributable ^{210}Po concentration of 0.58 pCi L^{-1} would be measurable (1.1 times the 0.53 pCi L^{-1} baseline) but the resulting total concentration of 1.10 pCi L^{-1} would be only a small fraction (7%) of the gross alpha standard of 15 pCi L^{-1}.

The three radionuclides in combination represent a PG-attributable increased effective dose of 3.1 mrem y^{-1}, again meeting the criterion of being a small fraction of 100 mrem y^{-1} above background. The PG-attributable risks were calculated to be 8.1 x 10^{-7} for one year of consumption and on the order of 6.2 x 10^{-5} from a lifetime usage. The dose and the risk calculated for the water (drinking water) pathway are dominated by ^{210}Pb. The various projections for radionuclides in water are probably overestimates as “high-side” conservatism was used in assigning TFs for projecting concentrations.

Forage and the Forage-Beef-Human Pathway

The PG-attributable ^{226}Ra concentration in forages as a result of the long-term practice was predicted to be 0.34 pCi g^{-1}, 5.7 times the 0.06 pCi g^{-1} baseline. Lower uptake was projected for ^{210}Pb and ^{210}Po with respective PG-attributable concentrations of 0.40 pCi g^{-1} (0.4 times the 1.12 pCi g^{-1} baseline) and 0.13 pCi g^{-1} (0.5 times the 0.26 pCi g^{-1} baseline).

Estimates of radiation dose and risk from the forage-beef-human pathway were based on the assumptions that humans would ingest 50 kg y^{-1} of beef from animals consuming 10 kg d^{-1} (dry matter) of forage and/or hay from the PG-treated lands. The combined three-nuclide annual radiation dose was projected to be 2.0 mrem y^{-1}. This value is low and a small fraction of 100 mrem y^{-1} above background. The PG-attributable risks from the three radionuclides in combination were calculated to be 7.1 x 10^{-7} for one year of beef consumption and on the order of 5.4 x 10^{-5} for lifetime exposure. Radionuclide intakes, doses, and risks are likely to be overestimated in this analysis--concentrations in forages were based on mature hay data, and it was assumed that all feed was derived from the PG-treated grasslands, that grass-fed animals would go directly to slaughter without being fed out on grain and concentrate, and that beef from this type of animal would constitute a high percentage of the consumers' diets. While ^{226}Ra was projected to have the greatest enhancement of radioactivity in forages, under the assumptions and factors used ^{210}Pb was the major contributor to projected dose and calculated risk.

Overall Doses and Risks

Of the four pathways considered, and for the scenarios and assumptions used, indoor inhalation exposure to Rn originating in the treated soil was the major contributor (7.2 mrem y^{-1}, 46% of the combined, four-pathway dose). Next in ranking were external irradiation by gamma radiation from radionuclides in the treated soil (3.2 mrem y^{-1}, 21%), ingestion of drinking water containing radionuclides attributable to the soil treatment (3.1 mrem y^{-1}, 20%), and ingestion of beef fed with forages grown on the treated land (2.0 mrem y^{-1}, 13%).

According to this analysis, the treatment of grassland with PG and the consumption of beef grazing or consuming hay from these lands does not present a radiological health concern for humans; and thus the effect on radionuclides in forage is not a major concern in the application of PG to forage land.

For the maximum exposed individual, the PG-attributable annual effective dose from all the listed pathways combined was estimated to be 16 mrem y^{-1} or 16% of 100 mrem y^{-1} above background. The risks to this individual from the combined PG-attributable radiation exposure pathways are estimated to be on the order of 8.7 x 10^{-6} from one year of exposure and on the order of 6.6 x 10^{-4} for a lifetime exposure.

RECOMMENDATIONS

Three elements of further study at these plots are recommended; 1) continue soil sampling and analysis to better document movement of the radionuclides applied with the PG, 2) continue to track Rn flux in order to gain additional information about any overall long-term change with time and further insight into possible variations in addition to the annual cycle, and 3) continue to follow ^{226}Ra in forage in order to determine its persistence and define the rate at which concentrations decrease. It is also recommended that, for any program of sampling Rn flux to establish average values for land areas, measurements be performed at least quarterly for at least a year because of the annual cyclic pattern. It was recommended that further exploration of the feasibility of PG application to agricultural lands include additional effort to refine the various factors identified as likely to be overestimates in the risk and dose assessment and that this screening-level assessment be followed up with a probabilistic risk assessment.

INTRODUCTION

PHOSPHOGYPSUM

Phosphogypsum (PG) is primarily gypsum ($CaSO_4.2H_2O$). Mined gypsum and PG have been used in agriculture as (1) sources of S and Ca for crops, (2) soil ameliorants for Al toxicity and subsoil acidity and infertility, (3) soil ameliorants for sodic and nonsodic dispersive soils,(4) soil conditioners for hard-setting clay soils and hardpans, (5) bulk carriers for micronutrients or fillers in low analysis fertilizers, (6) soil additives to modify cation-to-Ca ratios such as Mg:Ca ratio, and (7) absorbents for NH_3-N in urea and other volatiles in manures (Shainberg and others 1989; Alcordo and Rechcigl 1993; Alcordo and Rechcigl 1995).

Over the years, approximately 600 to 700 million tons of phosphogypsum (PG) have accumulated in Florida with an additional 20 to 30 million tons being generated annually as a by-product of wet process phosphoric acid production (McFarlin 1992). The continued stockpiling of the material, apart from being unsightly, also raises questions of potential adverse environmental impact on the immediate surrounding community.

RADIONUCLIDES AND OTHER IMPURITIES IN PHOSPHOGYPSUM

Naturally-occurring U (uranium) and its radioactive decay series are associated with phosphate mineral deposits. Consequently, the U-series member ^{226}Ra (radium-226), its gaseous decay product ^{222}Rn (radon-222, hereafter designated as simply Rn), and particulate progeny, ^{210}Pb (lead-210) and ^{210}Po (polonium-210), appear in the PG. Radionuclide levels vary depending upon the source of the phosphate rock; PG derived from Central Florida rock contains ^{226}Ra and its progeny at concentrations on the order of 21-33 pCi g^{-1} (EPA, 1978). Because of the radionuclide content, the EPA allows only limited uses of PG (Federal Register, 1992; EPA, 1992). Distribution for agricultural use is permitted if the certified average ^{226}Ra concentration does not exceed 10 pCi g^{-1}. This limit is intended to prevent unacceptable risks from indoor airborne Rn and direct gamma radiation exposure in residences constructed on land previously treated with PG. Distribution of quantities up to 700 pounds for research and development (R&D) is also permitted. In addition, the EPA may grant approval for other uses on a case-by-case basis if the proposed use will be at least as protective of public health as disposal of the PG in a stack or mine. The application for such approval must be accompanied by a proposed control program description and a risk assessment. Each of these uses has requirements for measuring the ^{226}Ra content of the PG and certification by the distributor; R&D and specifically-permitted uses also require record keeping by the end user.

The presence of these radiological impurities is one of the reasons that PG has been treated by the phosphate industry and the EPA as a waste product without much economic value. The concern is that PG application, even at a moderate rate of 1.0 Mg

PG ha^{-1} annually, may result in ^{226}Ra accumulation in the soil due to its long half-life of 1620 years. Thus, there is a need to know the fate or rate of PG radionuclides accumulation and/or dissipation in soils at various PG rates.

Phosphogypsum also contains heavy metals, especially the so-called EPA "toxicity characteristic" metals such as Ag, As, Ba, Cd, Cr, Hg, Pb, and Se as well as F. However, environmental studies by May and Sweeney (1980 and 1983) established that Central Florida PG is not a hazardous waste under the EPA's "toxicity characteristic" criterion, and results from agro-environmental studies by Rechcigl and others at low rates (1996) and at very high rates (1998) have shown that the concentrations of these impurities in PG are rather small to be of environmental concern to soil, groundwater, or crop tissue.

PREVIOUS STUDIES

The first comprehensive field study conducted in Florida on the radiological impact of applying PG as a source of S and Ca (conducted 1990-92) used low agronomic rates (0.4, 2.0, and 4.0 Mg PG ha^{-1}) on a bahiagrass (*Paspalum notatum* Flugge) pasture (Rechcigl and others 1996). The relationships between the measured radiological parameters and PG rates were inconclusive, hence no definite radiological transfer factors were determined. With no strong radiological data that relate PG rates significantly to radioactivity measurements, risk analysis is necessarily speculative.

A second two-year study (1993-94 and 1994-95), using higher PG application rates (10 and 20 Mg PG ha^{-1}) was conducted with EPA approval at the Range Cattle Research and Education Center at Ona, Florida (Rechcigl and others 1998). Two field experiments were conducted on established bahiagrass pastures, one growing on a Myakka soil (Spodosol) and the other on a Malabar soil (Alfisol). Radionuclide concentrations were determined in soil, groundwater, and forage, and soil surface Rn flux, ambient atmospheric Rn, and gamma radiation were measured. The most important results of the study that are relevant to the current project were:

1. The applications of PG at 10 and 20 Mg ha^{-1} gave statistically measurable increases in soil ^{226}Ra at the top 5 cm in all four (4) determinations made over a period of two years,
2. The same PG rates also gave statistically measurable increases in soil surface Rn flux in all eight (8) determinations made over the 2-year period,
3. The increases in soil ^{226}Ra and soil surface Rn flux were linear with PG rates of application, and
4. Because of the short time period, the study yielded no definitive indication of the rate at which the contaminants would be reduced to lower levels.

OBJECTIVES OF THIS STUDY

The initial observation period of the 1993-95 higher PG-application rate study was too short to establish any rate of change of the PG-attributable radiological characteristics with time. Furthermore, the 2-year observation period was not sufficient to provide a comfortable conclusion about whether there might be a gradual mobilization of radionuclides with time. Consequently, a continuation phase was initiated in September 1995 to extend the time for observing the fate of radionuclides and other related radiological parameters attributable to PG applied in 1993 at levels up to 20 Mg ha^{-1} to Spodosol and Alfisol soils cropped to bahiagrass. The continuation was intended to provide validation of the original observations and to determine changes with time. This document is a comprehensive report of the overall study involving the 1993-95 phase as well as the 1995-98 continuation phase.

Overall Objectives

The general objective of the overall study was to develop data that would assist in the comprehensive assessment of the environmental radiological impacts of PG application to soils with established bahiagrass pastures. Four potential exposure routes and associated measurements were of interest:

1. Airborne radon progeny inhalation--measurements of soil ^{226}Ra (the radon production source), soil surface Rn flux, and ambient airborne Rn;
2. External gamma radiation exposure--direct measurement;
3. Radionuclide ingestion via the water pathway--measurements of ^{226}Ra and its two long-lived decay products, ^{210}Pb, and ^{210}Po, in soil and water; and
4. Radionuclide ingestion via the forage-to-beef-to-human pathway--measurements of ^{226}Ra, ^{210}Pb, and ^{210}Po in soil and forage.

Thus the study was directed at determining the levels, and describing the rates of any observed loss, of ^{226}Ra, ^{210}Pb, and ^{210}Po in soil, forage, and groundwater, of soil surface Rn flux, of gamma radiation, and of other environmental characteristics important to predicting the long-term radiological impacts of PG applications to agricultural land.

Objectives of the Continuation Phase

Specific objectives of the continuation phase included:

1. Continue to measure Rn flux, gamma radiation levels above the soil surface, and airborne Rn concentrations and to determine concentrations of radionuclides in soil, surficial groundwater, and bahiagrass forage at the two field experimental sites previously treated with PG;
2. Provide further validation of the factors quantitatively relating radiological parameters to PG application rate;
3. Determine the rate of loss over time of each radiological parameter;
4. Apply the data to predict future values of these radiological parameters as a result of long-term application of PG to Florida spodosol and alfisol soils; and
5. Use the radiological data for radiation dose and risk determinations.

METHODOLOGY

EXPERIMENTAL FIELD AND TREATMENT DESIGN

Two parallel field experiments were conducted on established Pensacola bahiagrass (*Paspalum notatum* Flugge) pastures, one on a Malabar soil (loamy, siliceous, hyperthermic, Grossarenic Ochraqualfs), a nonspodic soil representing the Alfisols, and the other on a Myakka soil (sandy, siliceous, hyperthermic Aeric Alaquods), a spodic soil representing the Spodosols. GPR (ground-penetrating radar) analysis indicated a very consistent argillic (Bt) horizon starting between 120 and 130 cm at the Malabar location and a spodic (Bh) horizon starting between 50 to 100 cm throughout the Myakka site.

The study involved three PG application rates (0, 10, and 20 Mg ha^{-1}) and 12 replicates per treatment level in a randomized complete block design for a total of 36 plots each measuring 6 m x 6 m.

CULTURAL PRACTICE

PG containing ^{226}Ra, ^{210}Pb, and ^{210}Po at average concentrations of 21.4, 22.6, and 20.1 pCi g^{-1}, respectively (Rechcigl and others, 1998), was broadcast by hand in 1993 at the beginning of the growing season (May-June) after the grasses on the plots were mowed down to 2.5 cm. Fertilizers N (ammonium nitrate), P (triple superphosphate), K (potassium chloride) and a commercial micronutrient mix (2.4% B, 2.4% Cu, 14.4% Fe, 6.0% Mn, 0.06% Mo, and 5.6% Zn) were applied at the beginning of the growing season (March-May) each of the first two years at the rates of 180, 45, 67.5, and 28.0 kg ha^{-1}, respectively.

For the continuation study, replicates 1 through 6 (18 plots) were fertilized and maintained as they were previously. No fertilizers were applied to replicates 7 through 12, but the grasses were mowed to control the growth each time that the other plots were harvested.

SAMPLING DESIGN

The original sampling and measurement design was initiated in 1993. Data from a previous (1990-92) study on bahiagrass pasture (Rechcigl and others 1996) were used to estimate variance components and compute standard errors of PG effects estimates as functions of PG application levels, numbers of replications, numbers of collections over time, and numbers of samples per plot per replication (O’Brien and Muller 1993; Littell and Kundu 1993). Calculated minimum detectable effects (Lynch 1993) were used to fix the PG-application, replication, and sampling frequency plan to yield the desired probability of getting significant effects of PG applications on the critical radiological parameter, soil surface Rn flux.

For the 1995-98 continuation phase, all measurement types were continued but sampling and measurement conventions were adjusted to improve data resolution or for cost containment. Replication for some media was reduced at the beginning of or during the continuation phase; and gamma radiation and airborne radon measurements were discontinued in 1997 when it appeared that further measurements would contribute little new information.

Radionuclides in Soil

In the initial design, samples from three depths were designated for radiological analysis: 0-5 cm, 30-60 cm, and 90-120 cm for the Malabar site and 0-5 cm, 5 cm to the top of the spodic layer, and the upper 10 cm of the spodic layer for the Myakka site.

In order to improve the depth resolution near the soil surface for the continuation phase, the sampling design was modified in March 1995 by discontinuing the original intermediate layer and adding collections of the 5-10 cm and the 10-15 cm layers. (During the transition period in March 1995, a one-time-only sampling was also conducted of the 15-30 cm layer.) Soil samples were collected once before and once several months after the PG application in 1993, twice in 1994, and annually for 1995-1998. The original design called for sampling of six plots (replicates 1 through 6) for each treatment level at each site. For cost-containment purposes, replicates were reduced from six to four for 1996 and 1998.

Radon Flux

The experimental design called for Rn flux sampling shortly before and shortly after PG application and then approximately quarterly thereafter. All 12 replicate plots at each treatment level were sampled throughout the study.

In addition to the measurements at the contiguous treatment array of plots, external control (C_{ext}) measurements were made over untreated soil outside of the treatment arrays at each of the two experimental sites.

Gamma Radiation and Airborne Rn

The experimental design called for a set of measurements over control plots prior to the PG application and then quarterly measurements over all plots for roughly 60-day periods following PG application. Sampling was terminated in August 1997. Initially, all 12 replicate plots were sampled at each treatment level; beginning in November 1995, replication was reduced to six plots per treatment level. Measurements were discontinued in August 1997 when it appeared that little new information would be contributed by further sampling.

In addition to measurement over the contiguous plots, measurements were made at external control stations 50 to 100 m from the edge of the nearest treated plots at each experimental site. For the external controls, the replication was initially six measurement arrays per site and then was reduced to four beginning in November 1995.

Runoff and Surficial Groundwater

The sampling design called for water collection from three depths: surface runoff, 35-45 cm below the surface, and 80-90 cm below the surface; at least annually for 1993-1998. The original design called for sampling from six replicate plots at each treatment level; in 1995, this was reduced to four replicates. The actual numbers of samples collected depended upon the occurrence of runoff and whether or not there was water present at the designated depths at the time of sampling.

Forage

Sampling included both periodic collection of regrowth forage during the growing season and a single sampling of uncut, mature forage near the end of the season. Radionuclide analyses were performed on samples from the 1st, 2nd, 4th, 5th, and 6th growing seasons following PG treatment (1993, 1994, 1996, 1997, and 1998). Three or four individual regrowth collections were submitted for analysis for each of the first two seasons; a single weighted composite of the first three regrowth harvests was analyzed for each of the last three seasons. Initially, replication involved six plots per treatment level; this was reduced to four replicates for 1997 and 1998.

SAMPLING, MEASUREMENT, AND ANALYSIS PROCEDURES

To achieve the desired accuracy under field conditions and/or to prevent uneven PG application becoming a variable, specific sampling areas within each plot were assigned for soil, Rn flux, ambient Rn, and forage sampling. These sampling areas were then marked off and special attention was given to delivering the exact amount of PG according to the treatment rate assignment. The remaining PG assigned to the plot was then applied over the rest of the plot. Sampling was always performed at the designated subarea.

Soil Sampling and Preparation

Soil samples were collected with an auger and depth increments were separately packaged according to the assigned depth scheme. The holes were back-filled with sand mixed with kaolin (9:1) and packed to the original soil surface level. During the fifth year after treatment, the bulk density of the 0-5 cm layer was determined using the core method (Blake 1965).

All soil samples collected for radionuclide analysis were air-dried and crushed to pass a 2-mm sieve before sending them to a commercial laboratory for analysis.

Runoff and Shallow Groundwater Sampling and Preparation

To collect runoff, 30-cm wide ditches were constructed around each plot with the cut sloping outward from ground level to a depth of 10 cm. Collectors consisted of 2-liter plastic containers, capped to prevent direct rainfall collection, and provided with flow holes 2 cm below the rim. The containers were buried in the ditch bottoms to the levels of the holes at the lowest elevation of the ditches. Containers were emptied by siphon pump.

For subsurface water samples, wells were installed at two depths and located 1.5 m apart near the center of the plots. Each well consisted of a 10.8-cm inside diameter PVC pipe with the lower end capped tight to hold water and with a 10-cm collection zone to allow percolating and/or standing subsurface water to flow into the pipes. Each collection zone consisted of a series of parallel fine slits distributed around the pipe; the lower end of the zone was located 30 cm above the bottom of the pipe. The upper ends of the pipes extended 10 cm above the ground and were capped to prevent rain and surface water from entering the pipes. The shallower wells had collection zones at 35 to 45 cm below the surface and the deeper wells had collection zones between 80 and 90 cm below the surface.

The wells were sampled or emptied using a siphon pump. Four-liter samples were collected for analysis. The samples were filtered and prepared for storage according to the American Public Health Association/American Water Works Association/Water Pollution Control Federation (APHA/AWWA/WPCF) procedure for wastewater (Standard Methods 1985) before sending them to a commercial laboratory for analysis.

Forage Sampling and Preparation

The first harvests for regrowth forage samples were taken 30 to 35 days after PG and fertilizer application from designated sampling sections measuring 0.6 x 1.2 m. The grasses were allowed to regrow for another 30 to 35 days before each subsequent sampling. Hay or mature forage samples, representing the accumulated growth for the whole season, were taken near the end of the growing period (November-December) from sections of the plots which had been left uncut since the application of the PG and fertilizers. All samples were oven-dried at 60^{o} C and ground to pass a 0.84-mm sieve before sending the individual samples, or the designated composites, to a commercial laboratory for analysis.

Radionuclide Analysis

All PG, soil, plant tissue, and water samples were sent to a commercial laboratory for ^{226}Ra, ^{210}Pb, and ^{210}Po analysis according to procedures in use in the laboratory contracted for such analysis. Samples collected during 1993-95 and 1998 were analyzed by Core Laboratories, Casper, Wyoming; samples collected during 1996 and 1997 were analyzed by Environmental Science & Engineering, Inc., Gainesville, Florida.

Rn Flux Measurements

Large-area activated charcoal canisters (LAACC) (Hartley and Freeman 1985) were used to measure Rn fluxes. The guidelines established by EPA for sampling (Federal Register, Vol 54, No. 240, 1989) were observed. On each plot, the grass on a 30-cm x 30-cm area was cut down to the ground, a groove having the same diameter as the canister was etched over a clean spot to a depth of 1 cm, and the canister was set into the groove. The canisters were exposed for 24 hours; then the exposed charcoal was transferred to plastic containers which were sealed and taken to Pembroke Laboratory at Fort Meade, Florida for Rn analysis and Rn flux calculation in accordance with the EPA-accepted procedure.

Airborne Rn and Gamma Radiation Measurements

Both atmospheric Rn concentrations and gamma radiation were monitored using electret ion chambers (EIC) (Kotrappa and others 1988; Matuszek 1990; Hopper and others 1990; Rechcigl and others 1992; Fjeld and others 1994; Price and others 1994). The EICs were positioned 1 m above the surface of each plot inside open-ended 1.2-m tall by 0.6-m diameter chimneys consisting of circular wire cage frames wrapped with transparent plastic sheet. The chimneys were intended to simulate the atmosphere directly over a large emanating plane surface by eliminating the dilution from lateral atmospheric mixing. The chimneys were set over wooden posts at the center of each experimental plot. Wooden stakes anchored the lower ends to the ground. The shapes of the upper ends were maintained by wooden crossbars at the top of these posts.

Four or five EIC units were hung on these crossbars. Three of the EIC units were exposed to the atmosphere for Rn gas measurements. One or two EIC units were designated for gamma radiation measurements and were placed inside a Rn-proof plastic bag to be sealed off from the Rn in the atmosphere. The results from the gamma detectors was used to report gamma radiation levels and to correct for gamma radiation contribution to the signal from the Rn-reporting units.

Exposure time was on the order of 60 to 90 days. The EICs are integrating devices, consequently the results were divided by the deployment time in order to express the measurements in terms of average gamma radiation exposure rate (μR h^{-1}) and average Rn concentration (pCi L^{-1}) over the deployment period.

At the external control sites, EIC units were deployed both inside the chimneys (designated $C_{ext,\,I}$) and outside them (designated $C_{ext,\,o}$).

DATA ANALYSIS

In general, data were analyzed by individual collections and then averaged over meaningful combinations of collections or years. Treatment effects were analyzed using analysis of variance (ANOVA) using SAS procedures (SAS 1985). Tests for linear and nonlinear trends of effect vs. treatment level were also made. Estimates of the intercepts and slopes for the linear regression of radiological parameter level vs. PG treatment level were determined.

As a screening test for time trends, simple linear regressions of PG-attributable radiological parameters vs. time after PG application were performed. For this test, "PG-attributable" was defined as the values observed for treated plots (T = 10 or 20 Mg ha^{-1}) minus the values observed for the control plots (T = 0 Mg ha^{-1}). It should be noted that the linear regression was used as a tool for screening purposes; this does not imply that a linear form is necessarily the best model to describe environmental behavior of the radionuclides over time.

RESULTS AND DISCUSSION OF THE FIELD STUDY

This report presents the cumulative observations and discusses the overall results since the application of PG to these test plots in 1993 (Malabar 5/25/93; Myakka 6/01/93). These results incorporate the data and extend the interpretations previously reported for the initial phase of this study (Rechcigl and others 1998). The cumulative data and statistical testing are presented in Appendix A and summarized in the following sections.

RADIONUCLIDES IN SOIL

The cumulative soil data are presented in Appendix Tables A-1 and A-2. In May 1993, prior to the application of the PG, samples were collected from three depths at each plot of each site. Following application of the PG, samples were collected seven times during the period September 1993 through August 1998. The full seven collections were performed for the surface layer at each site; as a result of the changes in sampling protocol in 1995 and 1998, collections at deeper depths ranged from one to five.

Data were examined for evidence of treatment effects in the various layers. Data were also examined for evidence of downward migration of PG-attributable radionuclides during the first 5+ years following the PG application as indicated by losses from the surface layer or appearance in deeper soil layers.

Baseline Radioactivity

In order to evaluate the effect of PG application, it is important to have an understanding of the baseline radioactivity and its variations. Average baseline soil radionuclide concentrations for the two sites (two soil types) are presented in Table 1, both in terms of the entire series of measurements at the control plots and the single set of preapplication measurements for all plots.

The natural radioactivity of this soil is low (generally <1 pCi g^{-1}). The average baseline ^{226}Ra concentrations at the Malabar site are on the order of 0.5 pCi g^{-1} in the upper 5 cm, in the range of 0.2-0.3 pCi g^{-1} for the depths between 5 and 30 cm, and on the order of 0.5 pCi g^{-1} from there to 1 m. At the Myakka site, ^{226}Ra concentrations are on the order of 0.3 pCi g^{-1} at the surface, about 0.2 pCi g^{-1} for the next 10 cm, and then on the order of 0.3-0.4 pCi g^{-1} down to 1 m. Thus the two sites have qualitatively similar baseline ^{226}Ra profiles through the first 1-m depth; near the surface, levels are about 1½ times as high at the Malabar site as at the Myakka site, and between 10 cm and 1 m levels are comparable between the two sites.

Baseline ^{210}Pb and ^{210}Po concentrations at any soil depth are determined by a) formation from the locally-present ^{226}Ra precursor, b) formation from the decay of ^{222}Rn that has migrated following formation from ^{226}Ra at deeper depths, c) deposition from the atmosphere following formation from airborne ^{222}Rn, and d) relocation by downward transport of Pb and Po in the soil column. At both sites, the average baseline ^{210}Pb and ^{210}Po concentrations were highest in the surface layer (0.8 to 1.4 pCi g^{-1}). These concentrations were in excess of radioactive equilibrium with the soil ^{226}Ra; probably due to the surface deposition of ^{210}Pb and ^{210}Po formed in the atmosphere from Rn. Below 5 cm at the Malabar site, ^{210}Pb and ^{210}Po are initially near equilibrium with ^{226}Ra. For ^{210}Pb, the equilibrium persists down to 1 m while ^{210}Po tends toward subequilibrium with depth and at 1 m is about 50% of equilibrium with ^{226}Ra. At the Myakka site, ^{210}Pb and ^{210}Po occur in excess of ^{226}Ra equilibrium down to 15 cm and 10 cm, respectively, and then rapidly decrease in concentration relative to ^{226}Ra; at 1 m both appear at approximately 50% of equilibrium with ^{226}Ra.

Table 1. Baseline Radionuclide Concentrations in Two Florida Soils.

Site and Depth	NC	Concentration, pCi g^{-1}		
		^{226}Ra	^{210}Pb	^{210}Po
Nonspodic Soil (Malabar)				
Surface Layer; 0-5 cm	8	0.47 (0.56)	1.03 (1.36)	0.81 (0.81)
Intermediate Layer A; 5-10 cm	4	0.29	0.27	0.34
Intermediate Layer B; 10-15 cm	4	0.23	0.08	0.26
Intermediate Layer C; 15-30 cm	1	0.28	0.20	0.28
Intermediate Layer D; 30-60 cm	4	0.45 (0.50)	0.50 (0.49)	0.20 (0.23)
Lower (Clayey) Layer; ~90-120 cm	5	0.32 (0.73)	0.43 (0.61)	0.16 (0.35)
Spodic Soil (Myakka)				
Surface Layer; 0-5 cm	8	0.31 (0.26)	0.79 (0.54)	0.69 (0.56)
Intermediate Layer A; 5-10 cm	4	0.19	0.66	0.46
Intermediate Layer B; 10-15 cm	4	0.21	0.55	0.22
Intermediate Layer C; 15-30 cm	1	0.28	0.20	0.08
Intermediate Layer D; 5 cm to spodic	4	0.37 (0.32)	0.31 (0.12)	0.23 (0.25)
Lower (Spodic) Layer; 10 cm of spodic	6	0.45 (0.33)	0.24 (0.11)	0.22 (0.22)

Notes:

- NC = Number of collections for control plots.
- Values are multiple-collection averages for control plots (typically 6 plots).
- Values in ( ) are single-collection pre-PG averages for all plots (typically 18 plots).
- The spodic horizon at the Myakka site occurs at depths ranging from 50 to 100 cm.
- Myakka site lower layer = first 10 cm of the spodic horizon (typically 25 cm thick).

As an overall picture for the upper 1-m soil column, ^{210}Pb and ^{210}Po appear in excess of equilibrium with ^{226}Ra at the surface (effect of deposition from the atmosphere), and decrease with depth to equilibrium and then to subequilibrium concentrations. The excess of equilibrium persists to a deeper depth at the Myakka site than at the Malabar site and the progression from equilibrium to subequilibrium occurs at shallower depths for ^{210}Po than for ^{210}Pb. This suggests that Pb and Po are less mobile in the Malabar soil than in the Myakka soil and that Po is more mobile than Pb.

PG-Attributable Radium-226

Figure 1 presents ^{226}Ra concentrations in the surface layer (0-5 cm) for all collections. Statistical analyses for the overall post-treatment sampling are presented in Table 2. Except for the possible migration to the 5-10 cm layer (see discussion below), there was generally no evidence of an overall time trend during the 5+ years of observation; therefore, the post-treatment results are presented as an overall analysis for the seven samplings. The profiles of ^{226}Ra concentrations with depth based on the averages of collections #6 and #7 are shown in Figure 2.

At both sites there was an overall treatment effect (statistically significant) in the upper (0-5 cm) layer. For individual collections, the data at both sites show some fluctuations with time that are not readily explained. There were limited indications of an effect in the second (5-10 cm) layer but not in the other subsurface layers.

For the second (5-10 cm) layer, individual collections (#4-#7) are presented in Figure 3. The data suggest a developing appearance of PG-attributable ^{226}Ra in this layer; the effect was statistically significant for collections #4 and #5 and the overall combined data at the Myakka site (Appendix Tables A-3 and A-4). It is unknown exactly when a treatment effect could first be detected at this depth since it was not sampled for earlier collections. Appearance in this layer suggests downward migration during the first several years after PG application to the soil However, analysis of the time trend of the ^{226}Ra concentration in the upper layer using the linear model did not show any significant trends. The analyses are not sensitive enough to document losses from the upper layer or to estimate a rate of any such loss.

PG-Attributable Lead-210

Concentrations in the surface layer (0-5 cm) for all collections are presented in Figure 4. Statistical analyses for the overall post-treatment samplings are presented in Table 2. Except for the possible migration to the 5-10 cm layer (see discussion below), there was generally no evidence of an overall time trend during the 5+ years of observation; therefore, the post-treatment results are presented as an overall analysis for the seven samplings. The profiles of ^{210}Pb concentrations with depth based on the averages of collections #6 and #7 are shown in Figure 5.

At both sites there was an overall treatment effect (statistically significant) in the upper layer. For individual collections, the data at both sites show some fluctuations with time that are not readily explained. This radionuclide appeared in the second (5-10 cm) layer in the fifth year; no treatment effects were observed in the deeper layers.

For the second (5-10 cm) layer, individual collections (#4-#7) are presented in Figure 6. The significant effects for collection #7 (8/98) suggest a developing appearance of PG-attributable ^{210}Pb in this layer and possible downward migration during the first several years after PG application to the soil. However, time-trend analysis for ^{210}Pb in the upper layer did not show any significant decrease. Thus the analyses are not sensitive enough to document losses from the upper layer or to estimate a rate of any such loss.

PG-Attributable Polonium-210

Concentrations in the surface layer (0-5 cm) for all collections are presented in Figure 7. Statistical analyses for the overall post-treatment samplings are presented in Table 2. Except for the possible migration to 5-10 cm layer (see discussion below), there was generally no evidence of an overall time trend during the 5+ years of observation; therefore, the post-treatment results are presented as an overall analysis for the seven samplings. The profiles of ^{210}Po concentrations with depth based on the averages of collections #6 and #7 are shown in Figure 8.

At both sites there was an overall treatment effect (statistically significant) in the upper layer. For individual collections, the data at both sites show some fluctuations with time that are not readily explained. There was some evidence of appearance of this radionuclide in the second (5-10 cm) layer, but not in any of the other subsurface layers.

For the second layer (5-10 cm), individual collections (#4-#7) are presented in Figure 9. The data suggest a developing appearance of PG-attributable ^{210}Po in this layer at the Malabar site where the effects were statistically significant for the overall combined data. These results suggest downward migration during the first several years after PG application to the soil; however, time-trend analysis for ^{210}Po in the upper layer did not show any significant loss. The analyses are not sensitive enough to document losses from the 5-cm surface layer or to estimate a rate of any such transfer.

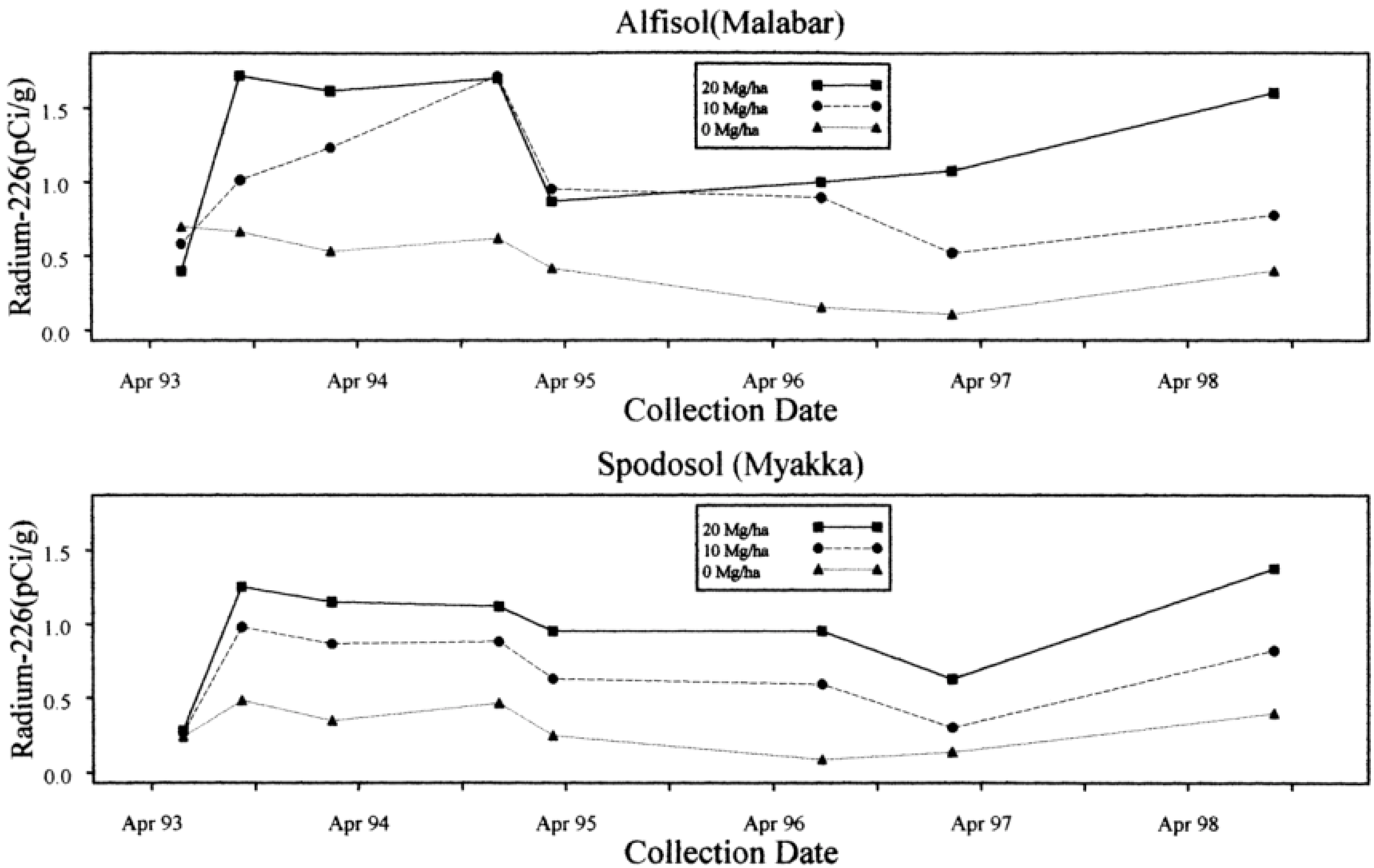

Figure 1. Radium-226 in the Surface (0-5 cm) Soil Layer of PG-treated Florida Land Cropped to Bahiagrass.

Table 2. Radionuclides in Soil from PG-Treated Florida Land Cropped to Bahiagrass (Page 1 of 4).

	Malabar Site			Myakka Site		
	^{226}Ra	^{210}Pb	^{210}Po	^{226}Ra	^{210}Pb	^{210}Po
	Surface Layer, 0-5 cm; 7 Collections (#1-#7), 9/93-8/98					
Conc., pCi g^{-1}						
At 0 Mg ha^{-1}	0.43 c	0.95 b	0.84 b	0.32 c	0.82 b	0.70 c
10	1.03 b	1.69 a	1.49 a	0.72 b	1.10 b	1.01 b
20	1.37 a	2.09 a	1.69 a	1.05 a	1.79 a	1.30 a
LSD, pCi g^{-1}	0.22	0.52	0.27	0.14	0.39	0.23
ANOVA P's:						
Treat. Effect	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Treat. Trends:						
Linear	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Nonlinear	NS	NS	0.06	NS	NS	NS
Linear Eqn:						
Intercept	0.477	1.012	0.912	0.332	0.747	0.708
Slope	0.0474	0.0570	0.0427	0.0365	0.0497	0.0307
Slope Std Error	0.0055	0.0129	0.0068	0.0038	0.0102	0.0058
	5-10 cm Layer; 4 Collections (#4-#7) 3/95-8/98					
Conc., pCi g^{-1}						
At 0 Mg ha^{-1}	0.29 a	0.25 a	0.34 b	0.19 b	0.66 a	0.43 a
10	0.31 a	0.39 a	0.52 a	0.31 ab	0.74 a	0.44 a
20	0.38 a	0.53 a	0.49 ab	0.38 a	0.88 a	0.53 a
LSD, pCi g^{-1}	0.59	0.34	0.16	0.18	0.76	0.18
ANOVA P's:						
Treat. Effect	NS	NS	0.07	0.09	NS	NS
Treat. Trends:						
Linear	NS	0.10	0.06	0.03	NS	NS
Nonlinear	NS	NS	NS	NS	NS	NS
Linear Eqn:						
Intercept	0.282	0.260	0.370	0.199	0.648	0.421
Slope	0.0042	0.0117	0.0079	0.0083	0.0110	0.0045
Slope Std Error	0.0044	0.0083	0.0043	0.0043	0.0205	0.0045

Continued...

Table 2. Radionuclides in Soil from PG-Treated Florida Land Cropped to Bahiagrass (Page 2 of 4).

	Malabar Site			Myakka Site		
	^{226}Ra	^{210}Pb	^{210}Po	^{226}Ra	^{210}Pb	^{210}Po
	10-15 cm Layer; 4 Collections (#4-#7), 3/95-8/98					
Conc., pCi g^{-1}						
At 0 Mg ha^{-1}	0.23 a	0.07 a	0.26 a	0.21 a	0.55 a	0.22 a
10	0.30 a	0.19 a	0.32 a	0.19 a	0.56 a	0.22 a
20	0.22 a	0.15 a	0.32 a	0.29 a	0.70 a	0.24 a
LSD, pCi g^{-1}	0.12	0.27	0.13	0.17	0.67	0.08
ANOVA P's:						
Treat. Effect	NS	NS	NS	NS	NS	NS
Treat. Trends:						
Linear	NS	NS	NS	NS	NS	NS
Nonlinear	NS	NS	NS	NS	NS	NS
Linear Eqn:						
Intercept	--	--	--	--	--	--
Slope	--	--	--	--	--	--
Slope Std Error	--	--	--	--	--	--
	15-30 cm Layer; 1 Collection (#4), 3/95					
Conc., pCi g^{-1}						
At 0 Mg ha^{-1}	0.28 a	0.20 a	0.28 a	0.28 a	0.20 a	0.08 a
10	0.33 a	0.14 a	0.22 a	0.25 a	0.25 a	0.06 a
20	0.27 a	0.24 a	0.12 a	0.26 a	0.27 a	0.10 a
LSD, pCi g^{-1}	0.16	0.15	0.39	0.24	0.22	0.09
ANOVA P's:						
Treat. Effect	NS	NS	NS	NS	NS	NS
Treat. Trends:						
Linear	NS	NS	NS	NS	NS	NS
Nonlinear	NS	NS	NS	NS	NS	NS
Linear Eqn:						
Intercept	--	--	--	--	--	--
Slope	--	--	--	--	--	--
Slope Std Error	--	--	--	--	--	--

Continued...

Table 2. Radionuclides in Soil from PG-treated Florida Land Cropped to Bahiagrass (Page 3 of 4).

	Malabar Site			Myakka Site		
	^{226}Ra	^{210}Pb	^{210}Po	^{226}Ra	^{210}Pb	^{210}Po
	30-60 cm Layer 3 Collect's (#1-#3); 9/93-12/94			5 cm to Spodic Layer 3 Collect's (#1-#3); 9/93-12/94		
Conc., pCi g^{-1}						
At 0 Mg ha^{-1}	0.44 a	0.49 a	0.21 a	0.37 a	0.36 a	0.20 a
10	0.51 a	0.48 a	0.23 a	0.53 a	0.28 a	0.13 b
20	0.53 a	0.51 a	0.16 a	0.46 a	0.38 a	0.18 ab
LSD, pCi g^{-1}	0.68	0.30	0.11	0.17	0.18	0.07
ANOVA P's:						
Treat. Effect	NS	NS	NS	NS	NS	NS
Treat. Trends:						
Linear	NS	NS	NS	NS	NS	NS
Nonlinear	NS	NS	NS	NS	NS	0.05
Linear Eqn:						
Intercept	--	--	--	--	--	--
Slope	--	--	--	--	--	--
Slope Std Error	--	--	--	--	--	--
	Lower (Clayey) Layer, ~90-120 cm 6 Collections (#1-#6); 9/93-2/97			Lower (Spodic) Layer, top 10 cm of spodic 5 Collections (#1-#3, #5-#6); 9/93-2/97		
Conc., pCi g^{-1}						
At 0 Mg ha^{-1}	0.30 a	0.24 a	0.13 a	0.49 a	0.27 a	0.21 a
10	0.34 a	0.26 a	0.14 a	0.54 a	0.18 a	0.20 a
20	0.20 a	0.27 a	0.14 a	0.50 a	0.29 a	0.23 a
LSD, pCi g^{-1}	0.18	0.39	0.07	0.23	0.28	0.13
ANOVA P's:						
Treat. Effect	NS	NS	NS	NS	NS	NS
Treat. Trends:						
Linear	NS	NS	NS	NS	NS	NS
Nonlinear	NS	NS	NS	NS	NS	NS
Linear Eqn:						
Intercept	--	--	--	--	--	--
Slope	--	--	--	--	--	--
Slope Std Error	--	--	--	--	--	--

Continued...

Table 2. Radionuclides in Soil from PG-treated Florida Land Cropped to Bahiagrass (Page 4 of 4).

Notes:

- PG application: Malabar 5/25/93; Myakka 6/01/93
- Concentrations are means of six replicates per treatment unless indicated otherwise by number in ( ).
- Means with the same letter code (a, b, or c) are not significantly different at the $P \leq 0.05$ level.
- NS = Not significant at the $P \leq 0.10$ level.
- Linear equation: $C_R = a + bT$; where radionuclide concentration, C_R, and intercept, a, are in pCi g^{-1}, and T = treatment level, Mg ha^{-1}.
- Coefficients for regression equations are generally presented with one more decimal place than the reported data and with at least two significant digits.

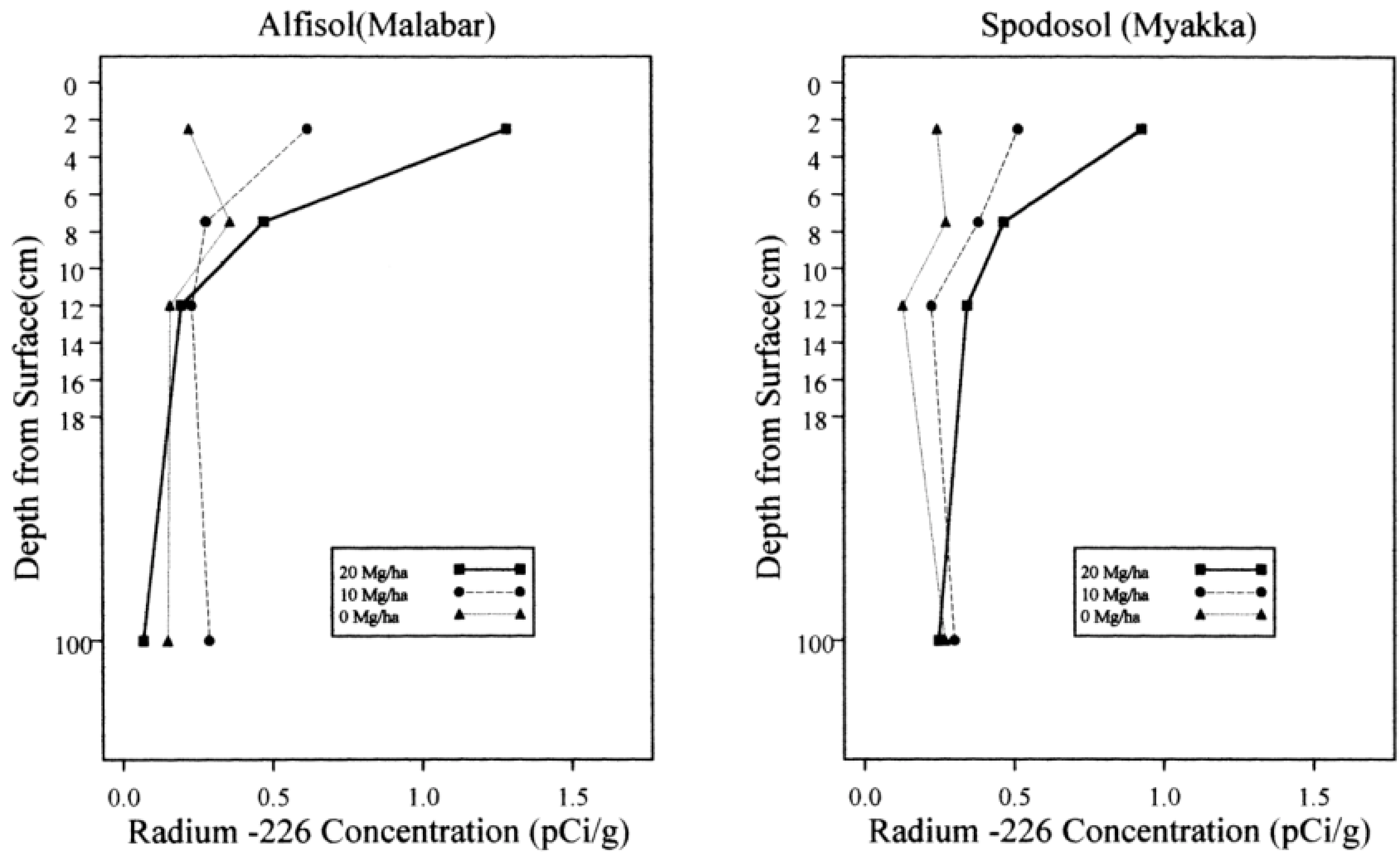

Figure 2. Depth Profile of Radium-226 in the Soil of PG-treated Florida Land Cropped to Bahiagrass--Four-five Years after Treatment.

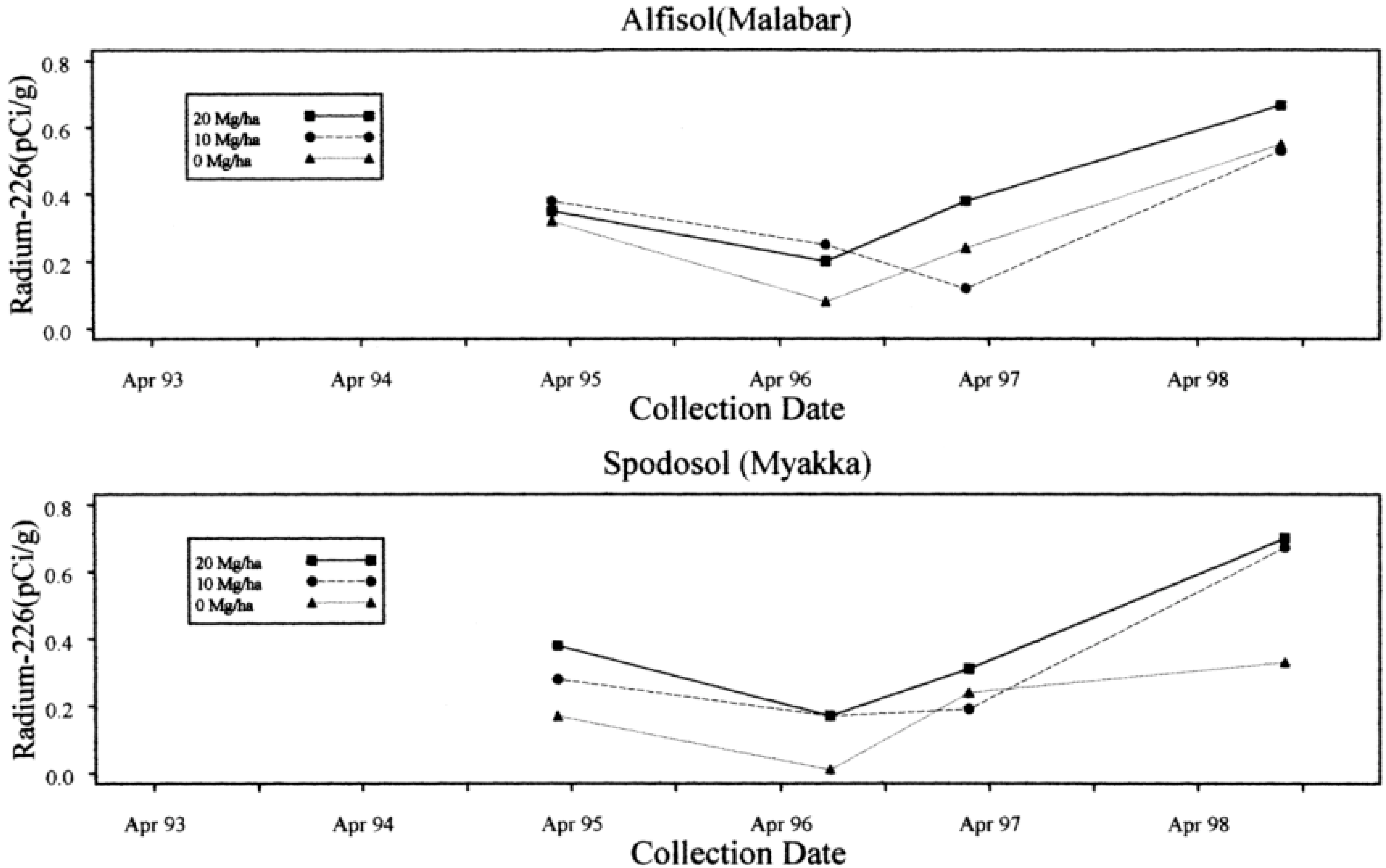

Figure 3. Radium-226 in the 5-10 cm Soil Layer of PG-treated Florida Land Cropped to Bahiagrass.

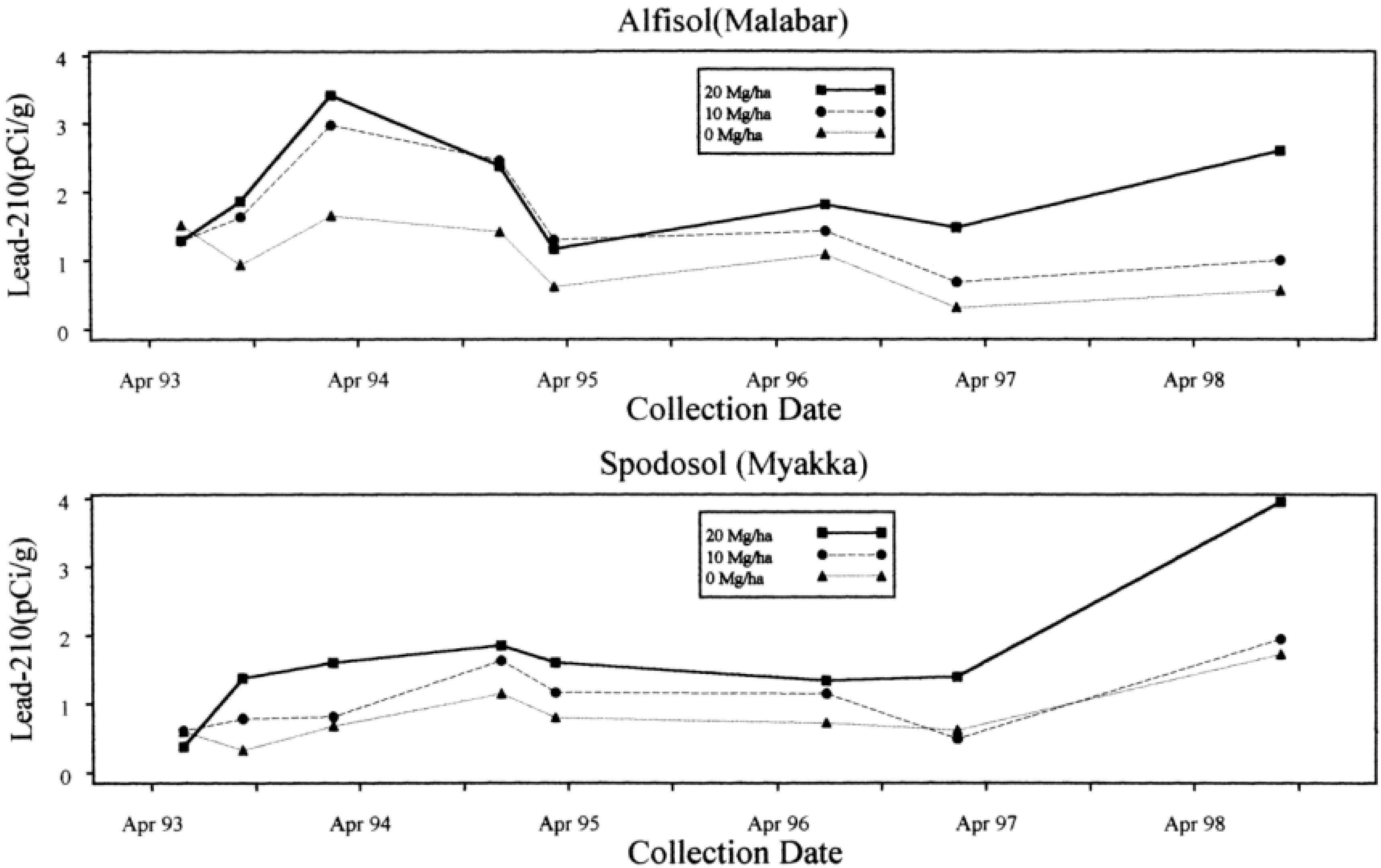

Figure 4. Lead-210 in the Surface (0-5 cm) Soil Layer of PG-treated Florida Land Cropped to Bahiagrass.

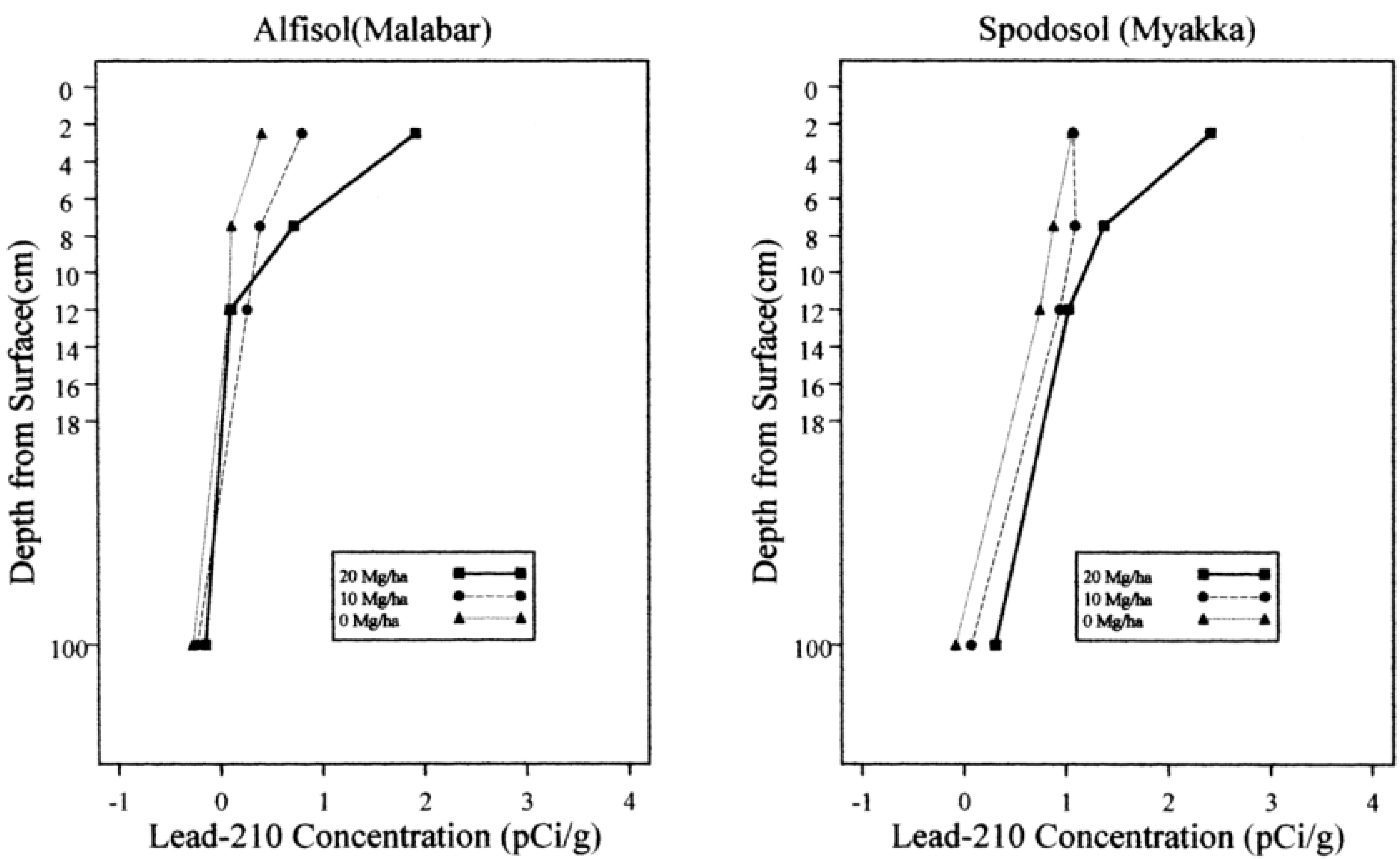

Figure 5. Depth Profile of Lead-210 in the Soil of PG-treated Florida Land Cropped to Bahiagrass--Four-five Years after Treatment.

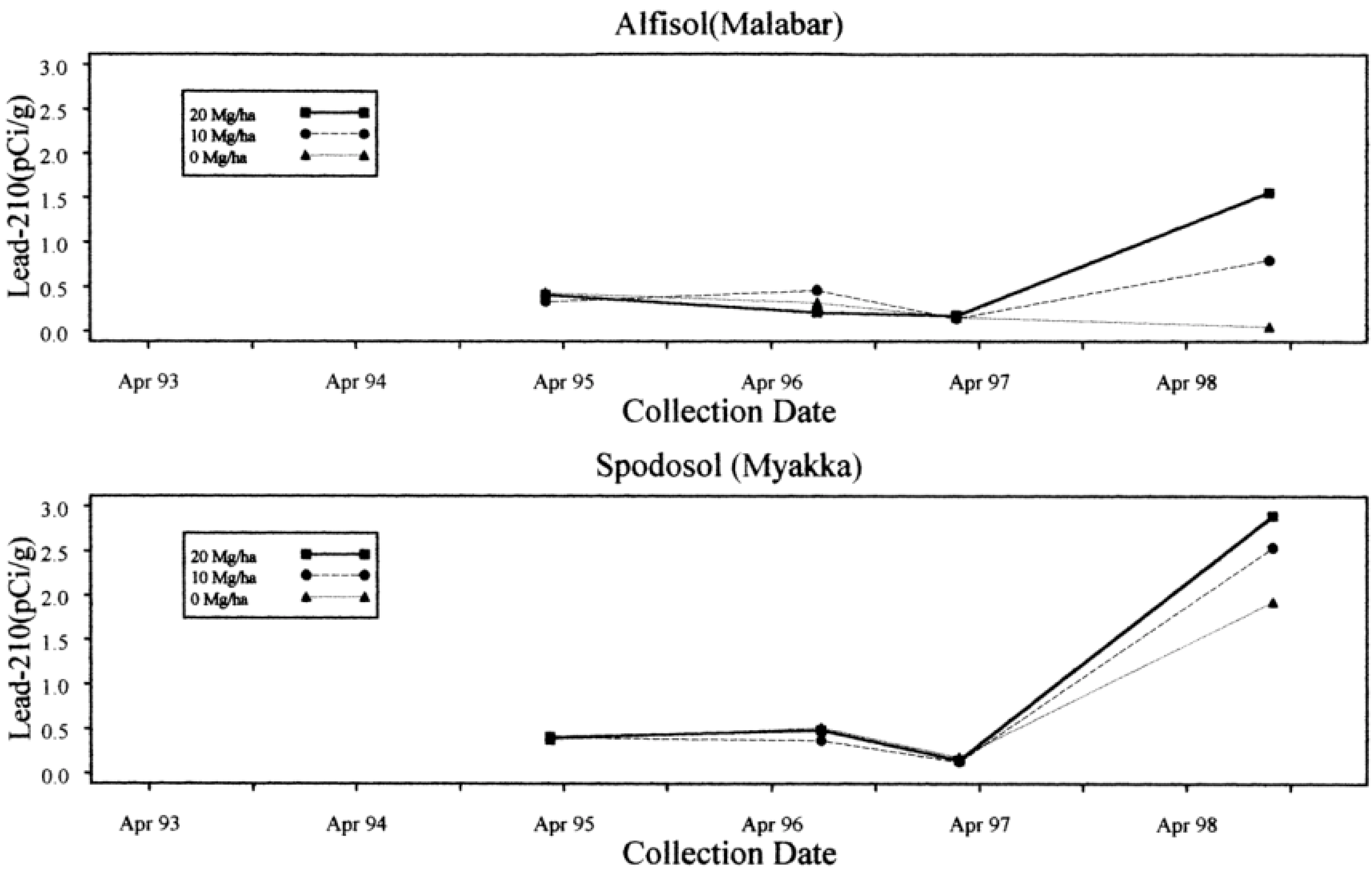

Figure 6. Lead-210 in the 5-10 cm Soil Layer of PG-treated Florida Land Cropped to Bahiagrass.

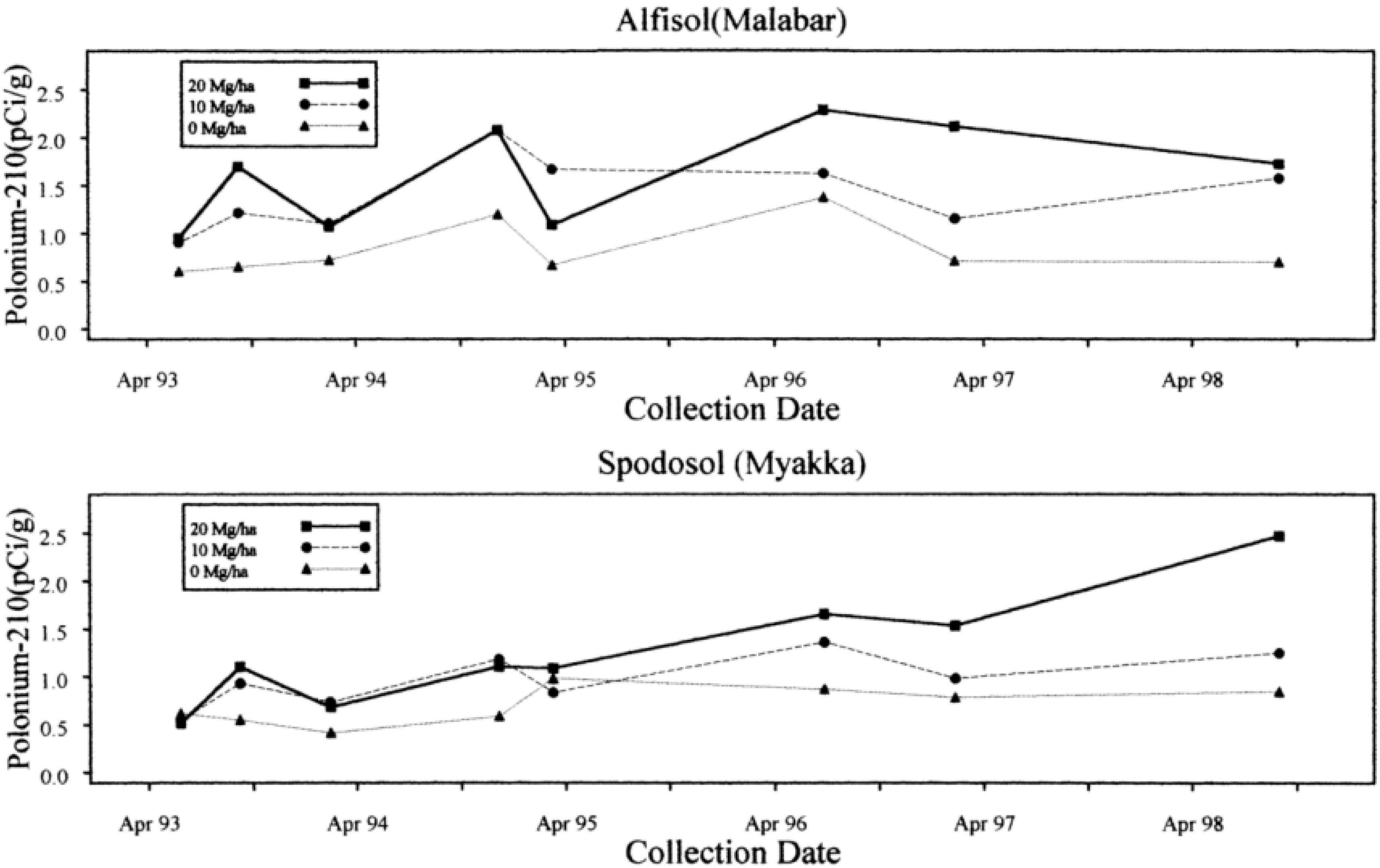

Figure 7. Polonium-210 in the Surface (0-5 cm) Soil Layer of PG-treated Florida Land Cropped to Bahiagrass.

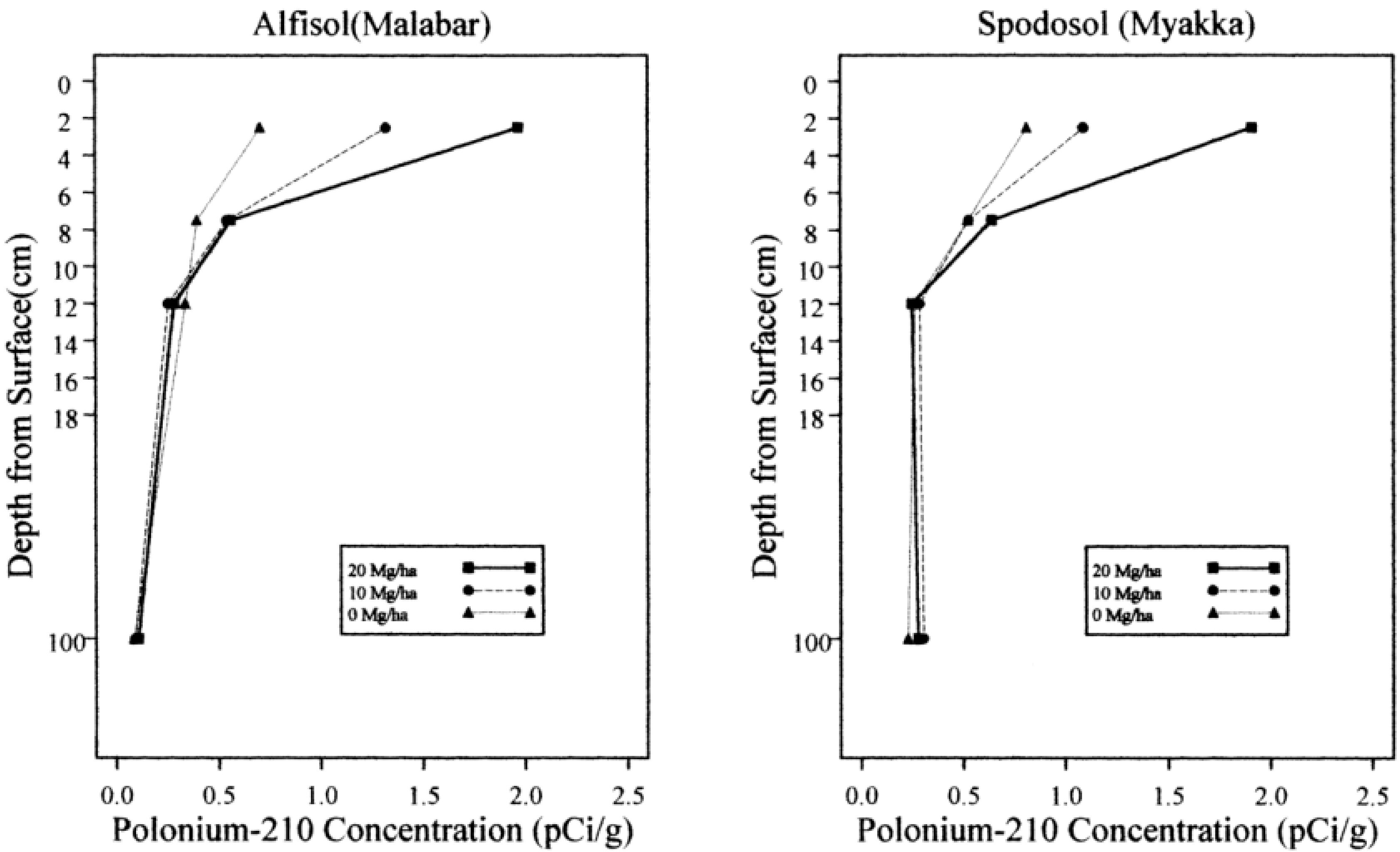

Figure 8. Depth Profile of Polonium-210 in the Soil of PG-treated Florida Land Cropped to Bahiagrass--Four-five Years after Treatment.

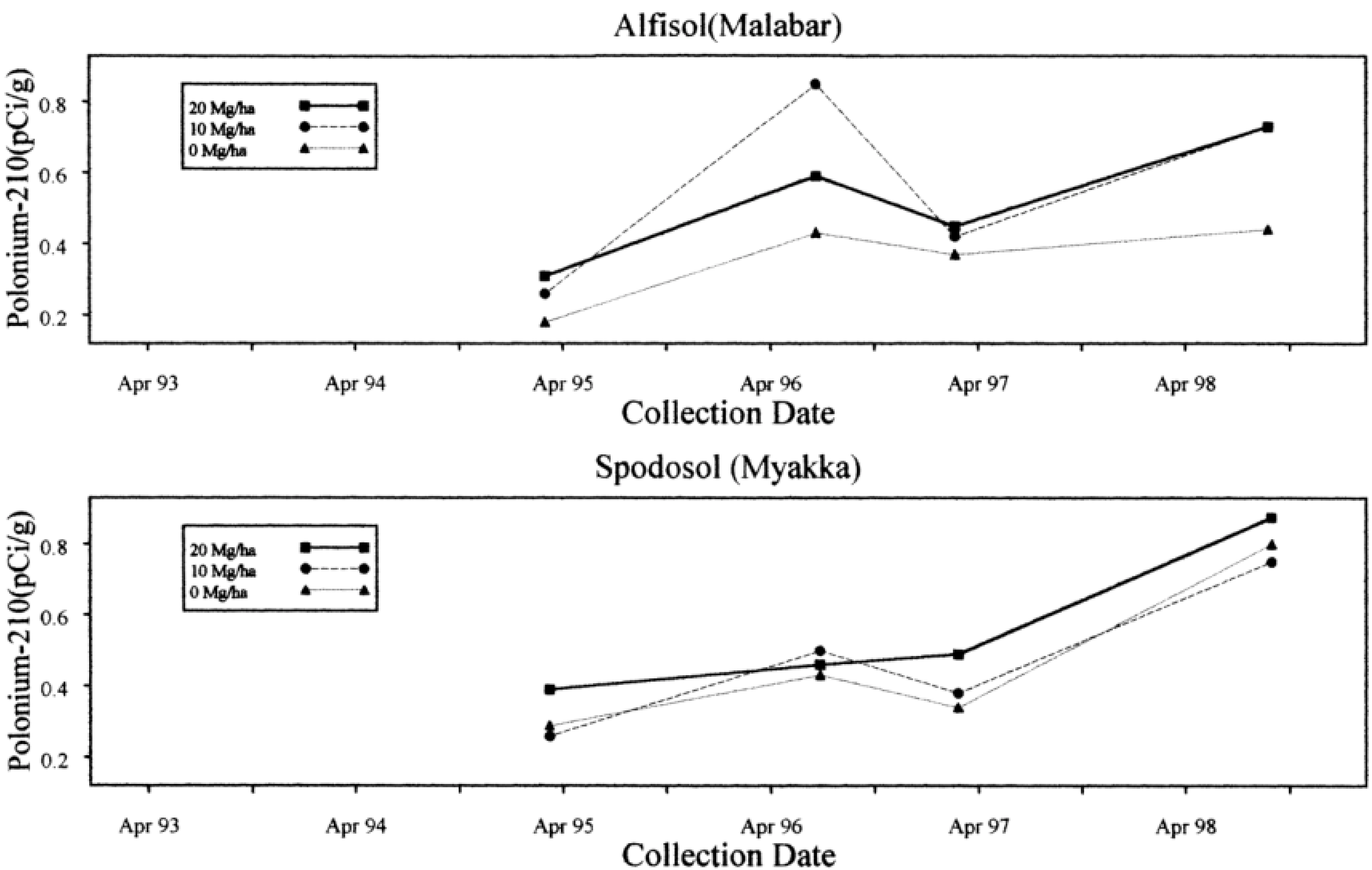

Figure 9. Polonium-210 in the 5-10 cm Soil Layer of PG-treated Florida Land Cropped to Bahiagrass.

Material Balance

Since the PG was applied to the surface without tilling, initially all the PG-attributable radioactivity should be contained in the surface soil layer. The measured surface layer soil bulk densities of 750 kg m^{-3} for the loamy Malabar soil and 970 kg m^{-3} for the sandy Myakka soil and the concentrations of radionuclides in the PG were used to calculate initial post-treatment concentrations of PG-attributable radionuclides per unit PG application for the surface soil layer (Table 3). These concentrations were compared to the observed slopes of the linear regressions of increased radionuclide concentration vs. PG treatment level. The ratios of these quantities give radioactivity recovery factors for the surface layer, as averaged over the entire study.

Table 3. Material Balance for Added Radioactivity in the Surface (0-5 cm) Soil Layer.

Radio-nuclide	Conc. in PG (pCi g^{-1})	Malabar Site ρ = 750 kg m^{-3}			Myakka Site ρ = 970 kg m^{-3}		
		Conc. in Soil pCi g^{-1} per Mg ha^{-1}		Recovery %	Conc. in Soil pCi g^{-1} per Mg ha^{-1}		Recovery %
		Added*	Meas-ured**		Added*	Meas-ured**	
^{226}Ra	21.4	0.0571	0.0474	83.0	0.0441	0.0365	82.8
^{210}Pb	22.6	0.0603	0.0570	94.5	0.0660	0.0497	75.0
^{210}Po	20.1	0.0536	0.0427	79.7	0.0414	0.0307	74.1

*Calculated from PG characteristics and soil density.
**Slope of linear regression of radionuclide concentration vs. PG treatment level.

Recoveries were on the order of 74-94%. Recoveries of less than 100% may be due to sampling and analytical inconsistencies and/or to weathering, cropping, and leaching losses from the surface layer during the observation period of 5+ years. The recoveries for the Malabar site were greater than for the Myakka site for all three radionuclides (although the difference is likely not significant for ^{226}Ra). The difference is most striking for ^{210}Pb. Some of the site difference may be due to the fact that the Malabar soil surface layer has a higher organic matter content than for the Myakka; this may have resulted in greater complexing with the organic matter and a lower removal by plants and/or downward migration from the surface layer for this soil. The observations of a tendency for movement to the second layer supports at least some of the deficit in recovery from the surface layer as averaged over the observation period; however, the soil type differences are not clearly supported.

SOIL SURFACE RN FLUX

Measurements were performed prior to the application of the PG, immediately after PG treatment, and then an additional 18 (Myakka site) or 19 times (Malabar site) during the following five years. The data are presented in Figure 10, tabulated in Appendix Tables A-9 and A-10, and summarized in Table 4. Data points represent the means of 12 replicates for each treatment. Figure 11 presents PG-attributable Rn flux (treated plot means minus the respective control plot means) normalized to unit PG application (PG-attributable values divided by treatment level).

Table 4. Rn Flux from PG-Treated Florida Land Cropped to Bahiagrass.

	Malabar Site	Myakka Site
No. of Collections	20	19
Rn flux, pCi m^{-2} s^{-1}:		
At 0 Mg ha^{-1}	0.027 c	0.016 c
10	0.043 b	0.038 b
20	0.060 a	0.053 a
LSD, pCi m^{-2} s^{-1}	0.006	0.004
ANOVA P Values :		
Treatment Effects	<0.01	<0.01
Treatment Trends:		
Linear	<0.01	<0.01
Nonlinear	NS	0.07
Linear Equation:		
Intercept	0.027	0.017
Slope	0.0017	0.0019
Slope Std Error	0.0002	0.0001

Notes:

- PG Application: Malabar, 5/25/93; Myakka, 6/01/93.
- Flux values are means of the indicated number of collections of 12 replicates each per treatment.
- Means with the same letter code (a, b, or c) are not significantly different at the $P \leq 0.05$ level.
- NS = Not significant at the $P \leq 0.10$ level.
- Linear equation: $J = a + bT$; where Rn flux, J, and intercept, a, are in pCi m^{-2} s^{-1}, and T = treatment level, Mg ha^{-1}.
- Coefficients for regression equations are generally presented with one more decimal place than the reported data and with two significant digits.

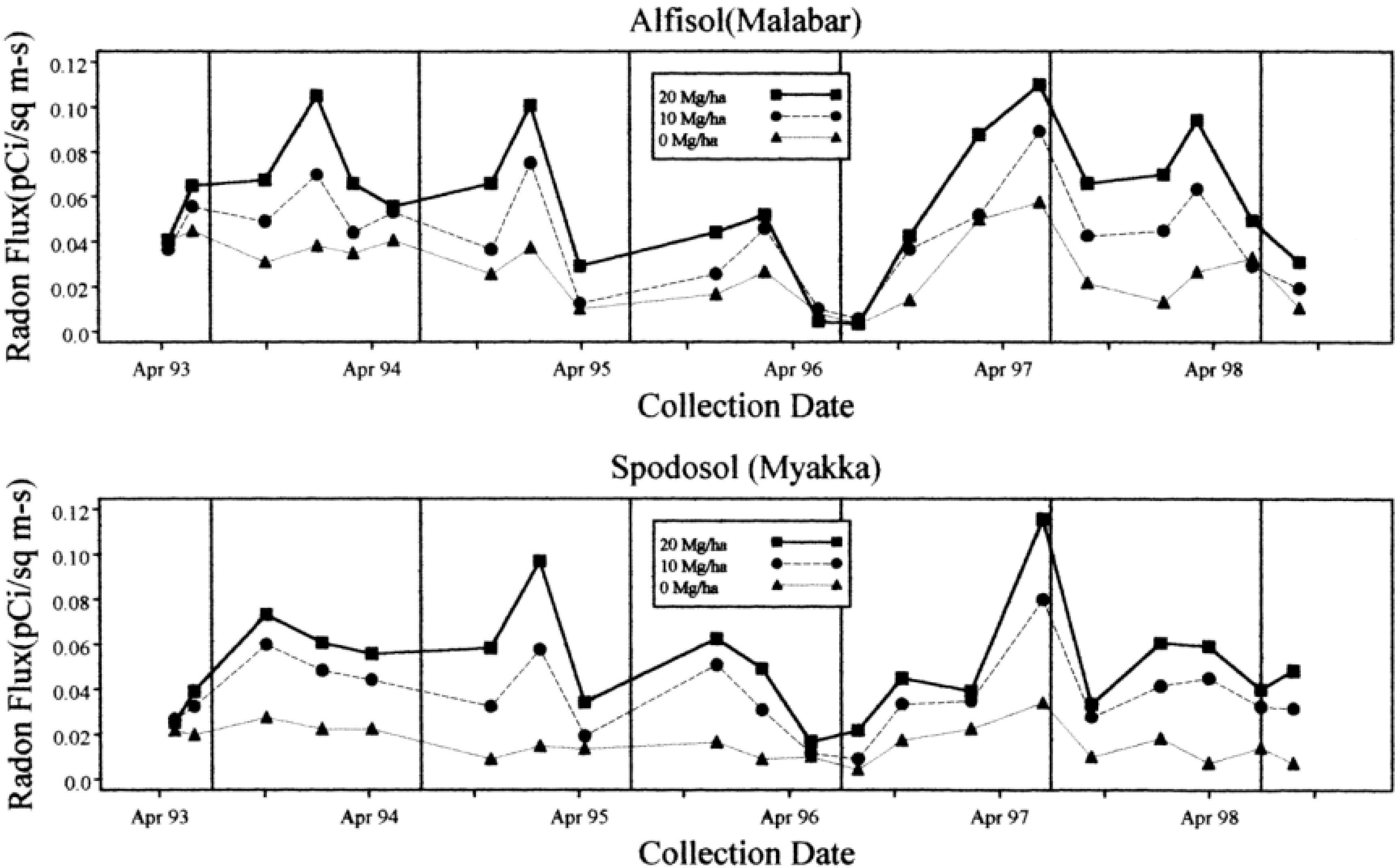

Figure 10. Rn Flux from PG-treated Florida Land Cropped to Bahiagrass.

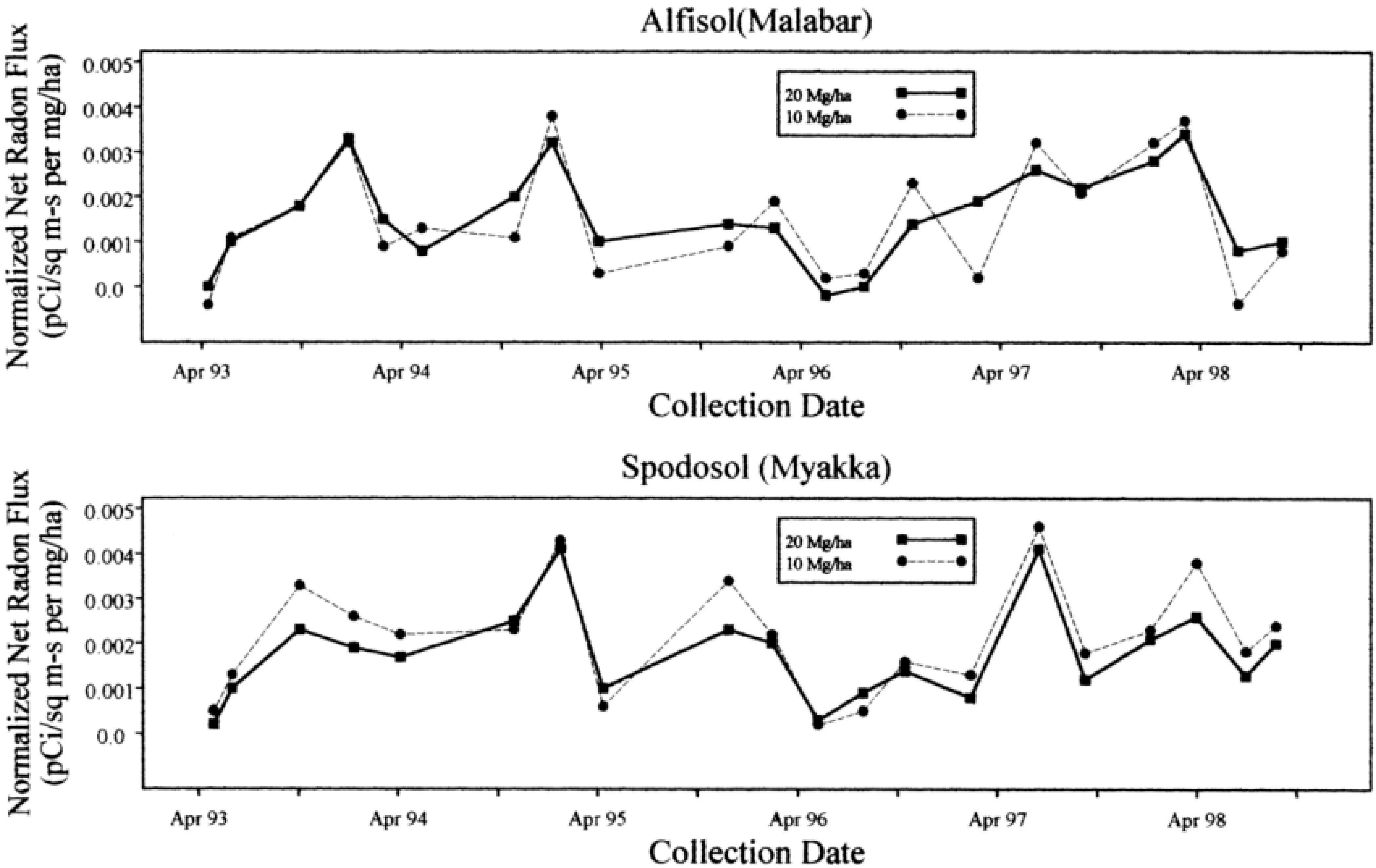

Figure 11. Net PG-attributable Rn Flux from PG-treated Florida Land Cropped to Bahiagrass--Normalized to Unit PG Rate.

The figures indicate a persistent treatment effect and a general cyclic pattern with winter peaks (October-February time window) and spring-summer valleys (March-September time window). This pattern was modified in 1997 in that rather than decreasing after the October 1996-February 1997 increases, the values continued to rise to reach an all-time peak in June 1997 followed by a more typical decrease to August-September 1997. A peak was not observed in the June 1998 measurements. The June 1997 peak may represent a singular event occurring only once during the period 1993-1998. Alternatively, it may represent a more frequent occurrence formerly unobserved because that month had not been sampled since the June 1, 1993 sampling at the Myakka site; however, it would not have been predicted from the spring and late summer samplings that “bracketed” June in previous years. The June 1997 peak poses the possibility that, in addition to the annual cycle, Rn flux may also be affected by variations of a longer period. Time-trend analysis did not indicate any unidirectional trend with time. Therefore, the entire complement of post-treatment results were analyzed for overall average effects during this time period. As indicated in Table 4, there was a significant effect of PG application on soil surface Rn flux and this response was linear with respect to treatment level.

The environmental loss rate for PG-attributable Rn flux following application of PG to Florida lands cropped to bahiagrass is slow relative to the approximately five years of observations and cannot be estimated from the data collected to date.

GAMMA RADIATION

Gamma radiation measurements were performed over the control plots for an approximately 30-day period beginning about seven weeks prior to application of the PG. After the PG application, measurements were conducted over all plots for roughly 60-day periods. After August 1997, gamma radiation measurements were discontinued. During the 4+ post-application years, measurements were performed 16 times at the Myakka site and 17 times at the Malabar site. The data are presented in Figure 12 and tabulated in Appendix Tables A-13 and A-14. Data points represent the average gamma-radiation exposure rate over the measurement period and are the means from 12 replicate plots per treatment during the first two years and from six replicate plots beginning in November 1995.

Data were grouped by years to test for treatment effects (Appendix Tables A-15 and A-16). There was some indication of a meaningful treatment effect the first year but there were no meaningful differences or trends in any of the subsequent individual years. Therefore, for final analysis, the data were grouped into two time periods: Year 1, and Years 2-4. As indicated in Table 5, a slight treatment effect is suggested during the first year after PG application. At the Malabar site, the exposure rate for the 20 Mg ha^{-1} treatment level was significantly greater than for the other treatment levels; at the Myakka site, the mean values for the first year suggest a treatment effect, but the differences are not statistically significant. The data are more equivocal for subsequent years. If these years are considered in aggregate, the average values for treated plots are higher than for control plots and some of the differences are significant.

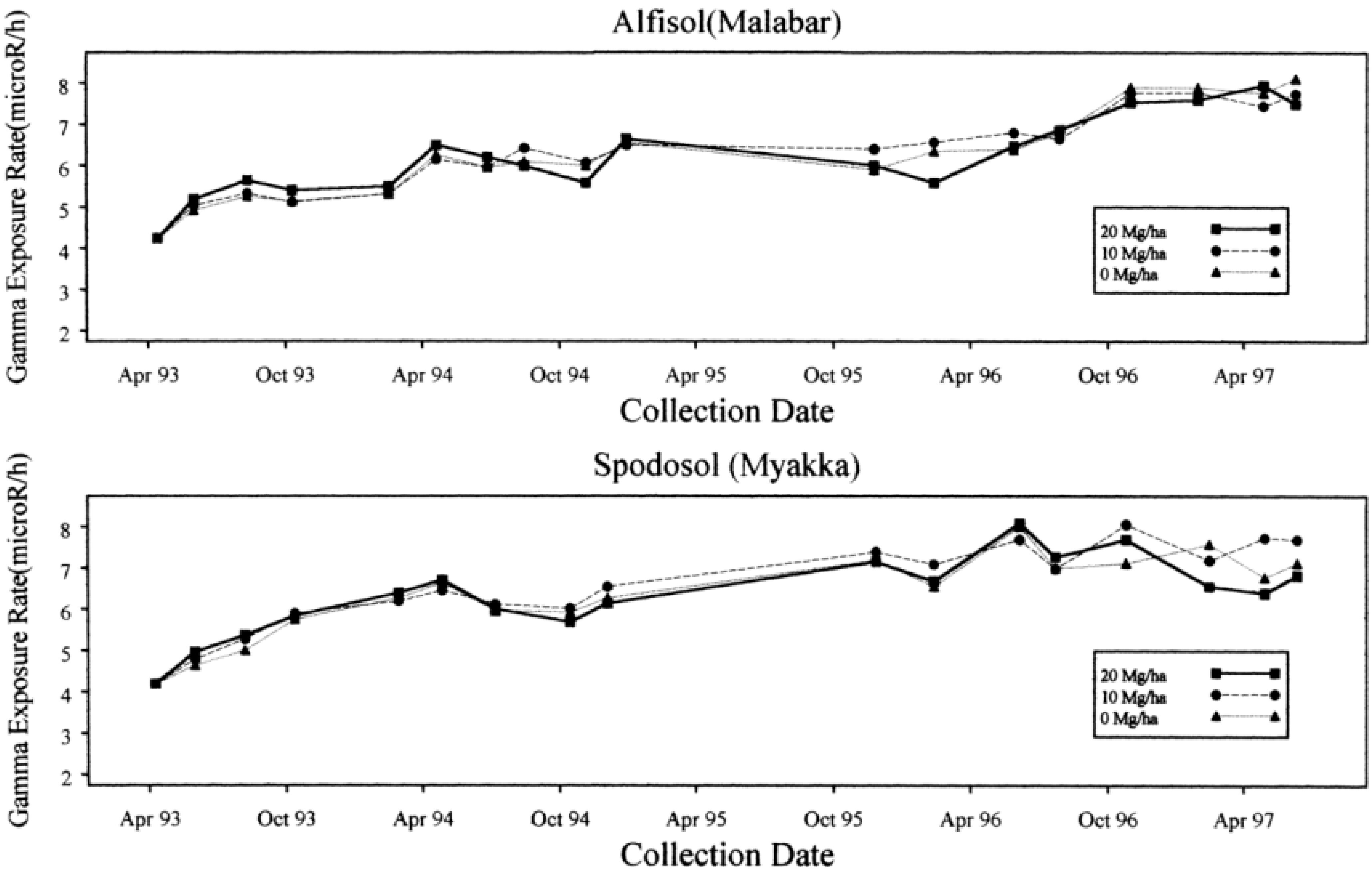

Figure 12. Gamma Radiation Exposure Rate over PG-treated Florida Land Cropped to Bahiagrass.

Table 5. Gamma Radiation over PG-Treated Florida Land Cropped to Bahiagrass.

	Malabar Site		Myakka Site	
	Year 1 1993-94	Years 2-4 1994-97	Year 1 1993-94	Years 2-4 1994-97
No. of Measurements	4	13	4	12
Exposure Rate, μR h^{-1}				
External Control Stations	5.1	7.0	5.3	6.1
Treatment Plots:				
At 0 Mg ha^{-1}	5.2 b	6.5 b	5.4 a	6.5 b
10	5.2 ab	6.8 a	5.6 a	7.0 a
20	5.4 a	6.7 ab	5.7 a	6.7 b
LSD,μR h^{-1}	0.2	0.3	0.3	0.3
ANOVA P Values:				
Treatment Effects	<0.01	0.08	NS	<0.01
Treatment Trends:				
Linear	<0.01	NS	0.10	NS
Nonlinear	0.13	0.08	NS	<0.01
Linear Equation:				
Intercept	5.32	6.58	5.42	6.65
Slope	0.013	0.009	0.012	0.007
Slope Std Error	0.004	0.007	0.007	0.008

Notes:

- PG Application: Malabar, 5/25/93; Myakka, 6/01/93.
- Exposure rate values are means of the indicated number of collections. Each collection involved 12 replicates per treatment for the first two years and six replicates beginning November 1995. (External Controls involved six replicate plots.)
- Means with the same letter code (a, b, or c) are not significantly different at the P≤0.05 level.
- NS = Not significant at the P≤0.10 level.
- Linear equation: $\dot{X} = a + bT$; where exposure rate, $\dot{X}$, and intercept, a, are in μR h^{-1}, and T = treatment level, Mg ha^{-1}.
- Coefficients for regression equations are generally presented with one more decimal place than the reported data and with two significant digits.

The PG applied to the ground surface initially had a barely detectable effect on the gamma-radiation field at 1 m above the surface. For subsequent years, the detection of an effect was more uncertain, perhaps due to weathering of the PG with time, removal of the applied radionuclides with forage harvests, and/or penetration of the radionuclides into the soil. There is no immediate explanation for the general gradual increase with time of levels over all plots, including the control plots (Figure 12).

The Myakka/Malabar ratio of the baseline gamma radiation levels, as estimated by control plot measurements and intercepts of the linear regression equations, are in the range of 1.00 to 1.04; this difference does not reflect the significantly higher ^{226}Ra content in the surface soil at the Malabar site. The soil ^{226}Ra concentrations at these sites are low and the gamma radiation measurement method is not sensitive enough to detect the influence of the soil radioactivity differences in the total background radiation field which is due to cosmic radiation and to terrestrial radiation originating in the atmosphere and biota as well as from terrestrial radiation originating in the soil and minerals.

RADIONUCLIDES IN GROUNDWATER

Water samples were collected seven times at each site: about a month after PG application in 1993, twice each in the second (1994-95) and the third (1995-96) post-treatment years, and once each in the fourth (1996-97) and the fifth (1997-98) post-treatment years. The cumulative data for radionuclides in water are presented in Appendix Tables A-17 and A-18 for the Malabar and Myakka sites, respectively. During the first two post-PG treatment years, the rainfall seldom exceeded the soil infiltration capacity and only one runoff sample was collected (Malabar site, January 1995). Runoff samples were available more consistently in the four collections during subsequent years (three times at the Malabar site and four times at the Myakka site).

The following approach, assumptions, and/or guidelines were used for grouping and analyzing the water data:

- Each radionuclide was treated separately.
- It is possible for radioactivity concentrations in the wells to behave differently than in the runoff, with a likelihood of a lesser and more delayed effect for the wells.
- Data could be grouped across collections to improve the power of the statistical tests, if this was not likely to obscure time trends.
- A change with time was considered possible – for the runoff, there could be an initial effect that diminishes with time as the available fraction becomes depleted and the PG and radionuclides become more incorporated in the soil.
- It was assumed that for a given radionuclide, there would be a similar behavior at the Malabar and Myakka sites but that there might be a difference between sites in degree of effect or rate of change with time due to differences such as content of organic matter in the surface layer and presence or absence of the spodic layer.
- Patterns may be further influenced by short-term effects such as rainfall/drought conditions.

Radium-226

Results are plotted by collection in Figure 13, data analyses are presented in Appendix Tables A-19 and A-20, and results are summarized in Table 6.

Runoff. For runoff, the figure suggests a PG treatment effect, particularly for the second and third years at the Myakka site and the fifth year at the Malabar site. For statistical analysis, the data were grouped in two time periods, Years 2-3 and Years 4-5. At the Malabar site, the effect of PG treatment was not statistically significant for the Years 2-3 period, but for the subsequent period, the effect was significant and there was a significant linear trend with a significant positive slope for concentration vs. treatment level. For the initial time period at the Myakka site, a treatment effect was suggested but not statistically significant, but there was a significant linear trend with treatment level, and the concentration vs. treatment slope was positive. For the subsequent time period, average concentrations were greater for the treated plots than for the control plots, but there were no significant differences or trends.

Wells. The ^{226}Ra concentrations for the wells at both depths at both sites were more equivocal than for the runoff and the data from all collections were combined for statistical analysis. Individual collections occasionally suggested a treatment effect, but the overall means increased only slightly with PG treatment level and overall there was no statistically-significant effect.

Lead-210

Results are plotted by collection in Figure 14, data analyses are presented in Appendix Tables A-21 and A-22, and results are summarized in Table 7.

Runoff. The figure presents little evidence of a PG treatment effect, with the possible exception of a single episode at the Myakka site in Year 3 (4/96). Again the data were grouped in the two time periods, Years 2-3 and Years 4-5. At the Myakka site, for the initial period, a treatment effect was suggested but not statistically significant, there was a significant linear trend with treatment level, and the concentration vs. treatment slope was positive. Otherwise, no effect was detected at either site (in fact, slopes were negative).

Wells. The ^{210}Pb concentrations for the wells at both depths at both sites were quite variable and the data from all collections were combined for statistical analysis. For the 35-45 cm wells, the overall combined data indicated a treatment effect with a linear trend at the Malabar site, but no treatment effect at the Myakka site (negative slope). For the 80-90 cm wells, while the overall mean values showed increasing concentrations with treatment level, there were no statistically-significant effects, trends, or slopes.

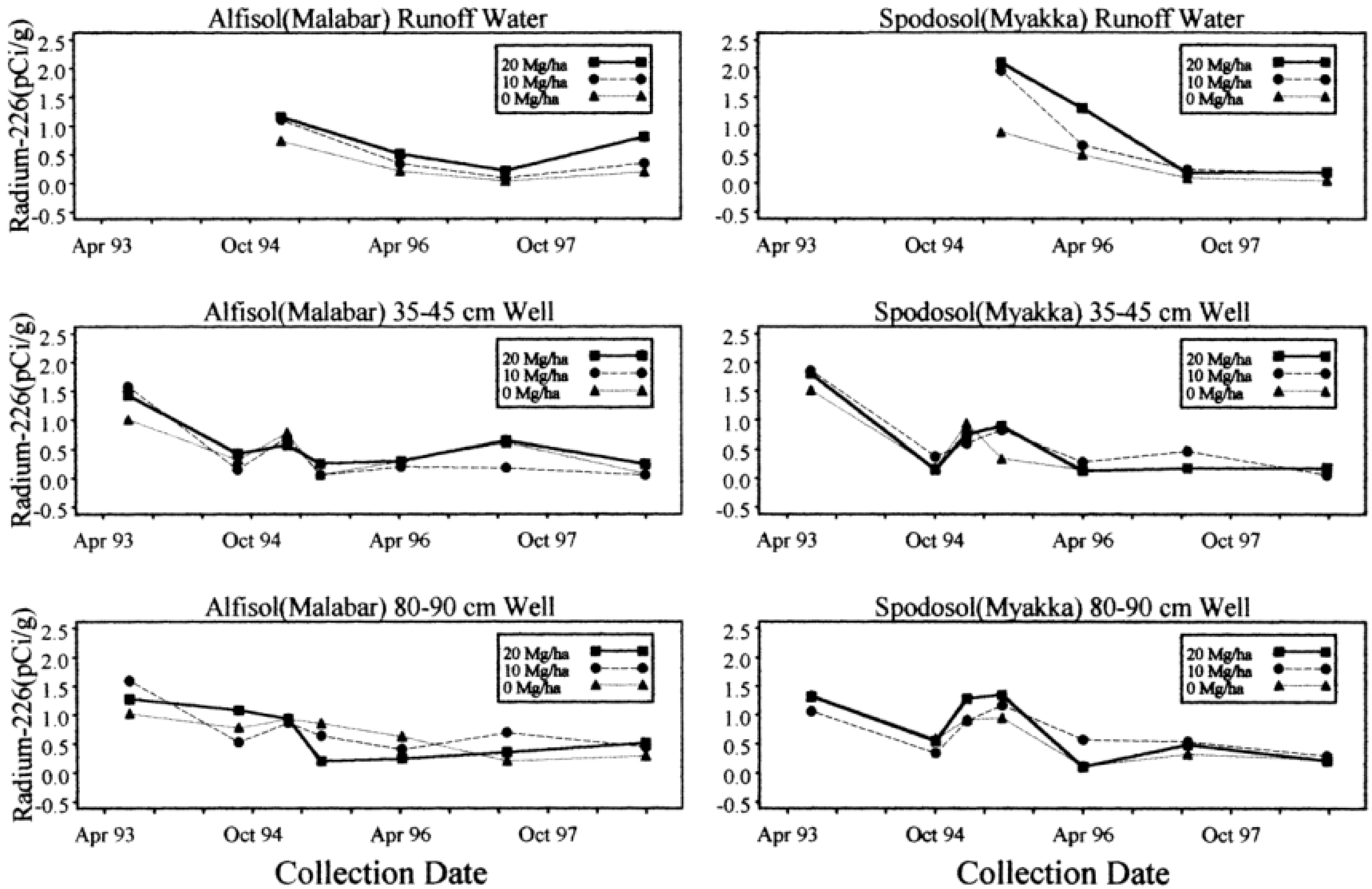

Figure 13. Radium-226 in Groundwater of PG-treated Florida Land Cropped to Bahiagrass.

Table 6. Summary of ^{226}Ra in Groundwater from PG-Treated Florida Land Cropped to Bahiagrass (Page 1 of 2).

	Malabar Site		Myakka Site	
A. Runoff*	Years 2-3 (#3a & 5)	Years 4-5 (#6 & #7)	Years 2-3 (#4 & 5)	Years 4-5 (#6 & #7)
Concentration, pCi L^{-1}:				
At 0 Mg ha^{-1}	0.60 a	0.07 b	0.68 a	0.08 a
10	0.91 a	0.19 ab	1.31 a	0.22 a
20	0.94 a	0.42 a	1.76 a	0.18 a
LSD, pCi L^{-1}	0.68	0.31	1.18	0.20
ANOVA P Values:				
Treatment Effect	NS	0.11	NS	NS
Treatment Trends:				
Linear	NS	0.05	0.08	NS
Nonlinear	NS	NS	NS	NS
Linear Equation:				
Intercept	0.643	0.037	0.446	0.087
Slope	0.0169	0.0183	0.0704	0.0060
Slope Std Error	0.0167	0.0064	0.0267	0.0047

B. 35-45 cm Well	Overall (Years 1-5, Collections #1 - # 7)	
Concentration, pCi L^{-1}:		
At 0 Mg ha^{-1}	0.48 a	0.52 a
10	0.45 a	0.64 a
20	0.60 a	0.61 a
LSD, pCi L^{-1}	0.26	0.32
ANOVA P Values:		
Treatment Effect	NS	NS
Treatment Trends:		
Linear	NS	NS
Nonlinear	NS	NS
Linear Equation:		
Intercept	0.450	0.542
Slope	0.0066	0.0047
Slope Std Error	0.0068	0.0080

Continued...

Table 6. Summary of ^{226}Ra in Groundwater from PG-Treated Florida Land Cropped to Bahiagrass (Page 2 of 2).

	Malabar Site	Myakka Site
C. 80-90 cm Well	Overall (Years 1-5; Collections #1-#7)	
Concentration, pCi L^{-1}:		
At 0 Mg ha^{-1}	0.80 a	0.69 a
10	0.80 a	0.70 a
20	0.82 a	0.81 a
LSD, pCi L^{-1}	0.28	0.30
ANOVA P Values:		
Treatment Effect	NS	NS
Treatment Trends:		
Linear	NS	NS
Nonlinear	NS	NS
Linear Equation:		
Intercept	0.799	0.685
Slope	0.0009	0.0064
Slope Std Error	0.0079	0.0077

Notes:

* No Runoff samples obtained during Year 1.

- PG Application: Malabar, 5/25/93; Myakka, 6/01/93.
- Experimental design called for sampling six replicate plots per treatment for collections #1-#3 and four replicates for collections #4-#7. Not all designated plots yielded a sample for each collection. See Appendix Tables A-17 and A-18 for exact numbers of samples for each.
- Means with the same letter code (a, b, or c) are not significantly different at the $P \leq 0.05$ level.
- NS = Not statistically significant at the $P \leq 0.10$ level.
- Linear equation: $C_R = a + bT$; where concentration, C_R, and intercept, a, are pCi L^{-1}, and T = treatment level, Mg ha^{-1}.
- Coefficients for regression equations are generally presented with one more decimal place than the reported data and with two significant digits.

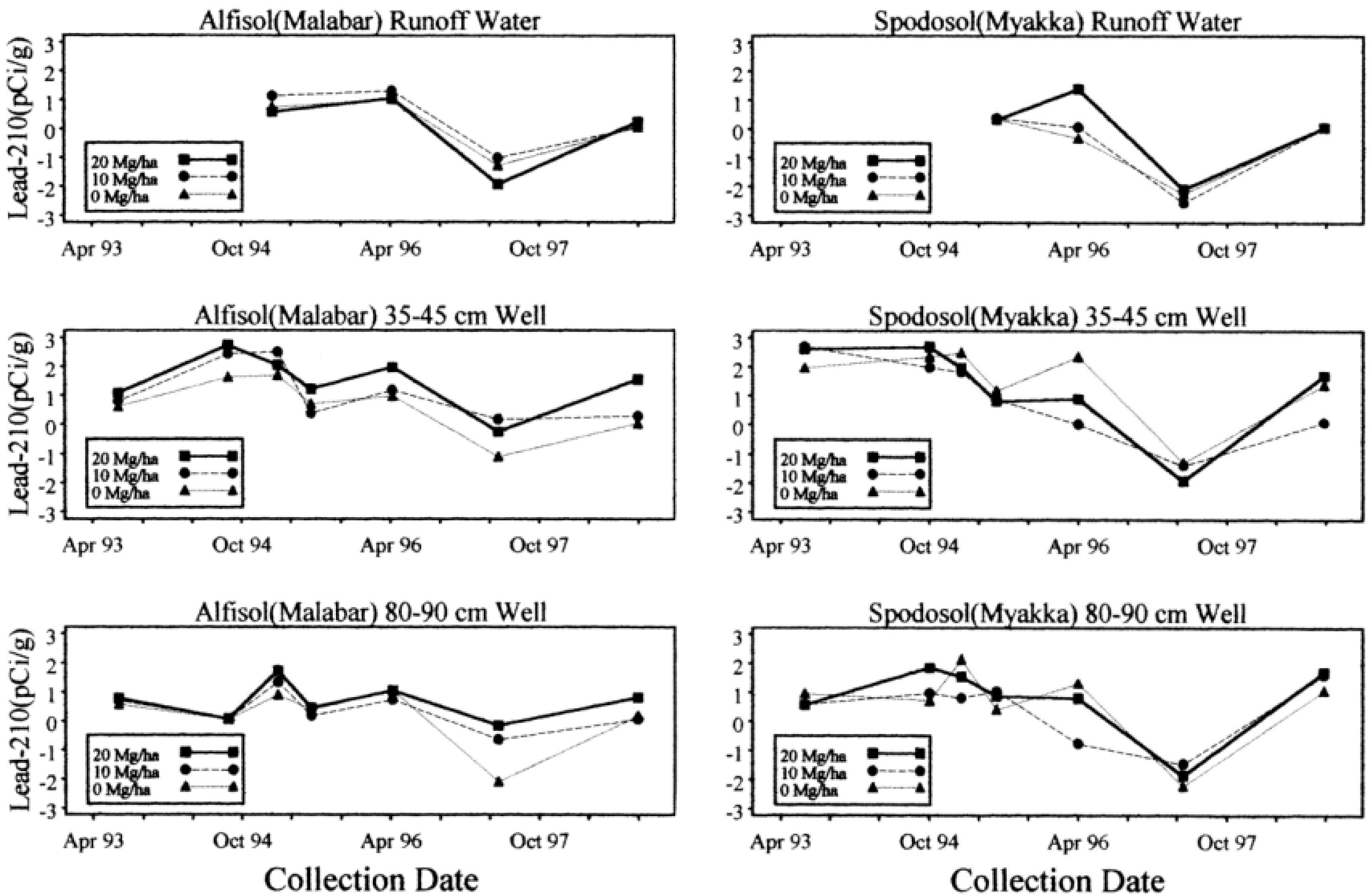

Figure 14. Lead-210 in Groundwater of PG-treated Florida Land Cropped to Bahiagrass.

Table 7. Summary of ^{210}Pb in Groundwater from PG-Treated Florida Land Cropped to Bahiagrass (Page 1 of 2).

	Malabar Site		Myakka Site	
A. Runoff*	Years 2-3 (#3a & 5)	Years 4-5 (#6 & #7)	Years 2-3 (#4 & 5)	Years 4-5 (#6 & #7)
Concentration, pCi L^{-1}:				
At 0 Mg ha^{-1}	0.80 a	negative	0.02 a	negative
10	1.19 a	negative	0.22 a	negative
20	0.72 a	negative	0.85 a	negative
LSD, pCi L^{-1}	0.81	1.73	0.88	1.46
ANOVA P Values:				
Treatment Effect	NS	NS	NS	NS
Treatment Trends:				
Linear	NS	NS	0.06	NS
Nonlinear	NS	NS	NS	NS
Linear Equation:				
Intercept	0.941	-0.932	-0.064	-1.652
Slope	-0.0046	-0.0059	0.0416	-0.0120
Slope Std Error	0.0199	0.0239	0.0239	0.0467

B. 35-45 cm Well	Overall (Years 1-5, Collections #1-# 7)	
	Malabar Site	Myakka Site
Concentration, pCi L^{-1}:		
At 0 Mg ha^{-1}	0.77 b	1.48 a
10	1.34 ab	0.92 a
20	1.57 a	1.27 a
LSD, pCi L^{-1}	0.64	0.92
ANOVA P Values:		
Treatment Effect	0.05	NS
Treatment Trends:		
Linear	0.02	NS
Nonlinear	NS	NS
Linear Equation:		
Intercept	0.775	1.326
Slope	0.0430	-0.0104
Slope Std Error	0.0163	0.0227

Continued...

Table 7. Summary of ^{210}Pb in Groundwater from PG-Treated Florida Land Cropped to Bahiagrass (Page 2 of 2).

	Malabar Site	Myakka Site
C. 80-90 cm Well	Overall (Years 1-5; Collections #1-#7)	
Concentration, pCi L^{-1}:		
At 0 Mg ha^{-1}	0.43 a	0.56 a
10	0.48 a	0.36 a
20	0.74 a	0.93 a
LSD, pCi L^{-1}	0.54	0.80
ANOVA P Values:		
Treatment Effect	NS	NS
Treatment Trends:		
Linear	NS	NS
Nonlinear	NS	NS
Linear Equation:		
Intercept	0.456	0.447
Slope	0.0149	0.0175
Slope Std Error	0.0133	0.0203

Notes:

* No Runoff samples obtained during Year 1.

- Negative: Mean of reported concentrations was negative.
- PG Application: Malabar, 5/25/93; Myakka, 6/01/93.
- Experimental design called for sampling six replicate plots per treatment for collections #1-#3 and four replicates for collections #4-#7. Not all designated plots yielded a sample for each collection. See Appendix Tables A-17 and A-18 for exact numbers of samples for each.
- Means with the same letter code (a, b, or c) are not significantly different at the $P \leq 0.05$ level.
- NS = Not statistically significant at the $P \leq 0.10$ level.
- Linear equation: $C_R = a + bT$; where concentration, C_R, and intercept, a, are pCi L^{-1}, and T = treatment level, Mg ha^{-1}.
- Coefficients for regression equations are generally presented with one more decimal place than the reported data and with two significant digits.

Polonium-210

Results are plotted by collection in Figure 15, data analyses are presented in Appendix Tables A-23 and A-24, and results are summarized in Table 8.

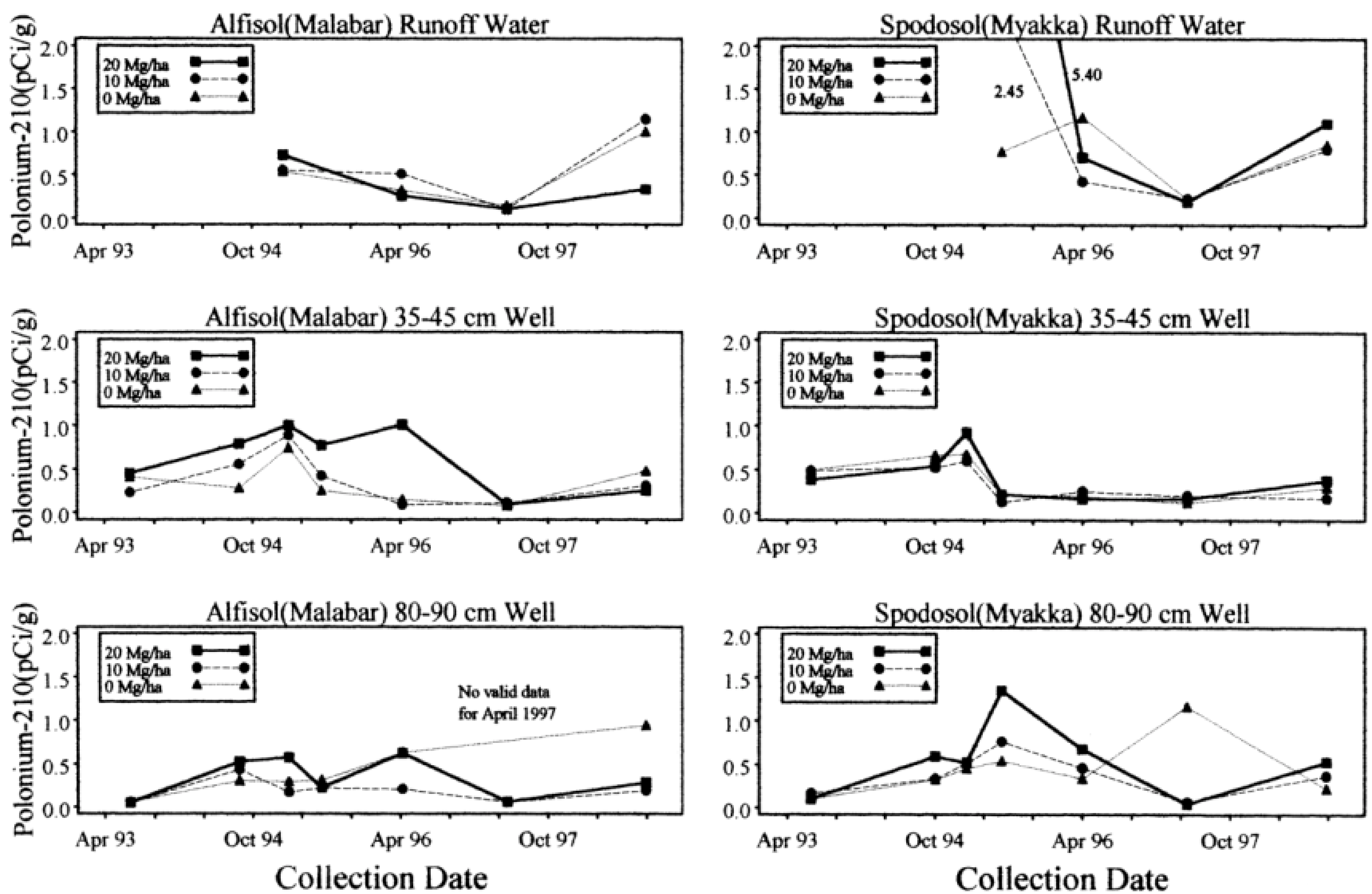

Figure 15. Polonium-210 in Groundwater of PG-treated Florida Land Cropped to Bahiagrass.

Table 8. Summary of ^{210}Po in Groundwater from PG-Treated Florida Land Cropped to Bahiagrass (Page 1 of 2).

	Malabar Site		Myakka Site	
A. Runoff*	Year 2 (#3a)	Years 3-5 (#5 - #7)	Year 2 (#4)	Yr 3-5 (#5 - #7)
Concentration, pCi L^{-1}:				
At 0 Mg ha^{-1}	0.52 a	0.32 a	0.77 c	0.68 a
10	0.55 a	0.52 a	2.45 b	0.38 a
20	0.72 a	0.20 a	5.40 a	0.48 a
LSD, pCi L^{-1}	0.70	0.41	1.19	0.52
ANOVA P Values:				
Treatment Effect	NS	NS	<0.01	NS
Treatment Trends:				
Linear	NS	NS	<0.01	NS
Nonlinear	NS	NS	0.07	NS
Linear Equation:				
Intercept	0.501	0.406	0.500	0.625
Slope	0.0096	-0.0067	0.2350	-0.0102
Slope Std Error	0.0145	0.0094	0.0544	0.0129
B. 35-45 cm Well	Years 1-3 (#1 - # 5)	Years 4-5 (#6 - #7)	Years 1-3 (#1 - # 5)	Years 4-5 (#6 - #7)
Concentration, pCi L^{-1}:				
At 0 Mg ha^{-1}	0.39 b	0.28 a	0.49 a	0.19 a
10	0.49 ab	0.23 a	0.43 a	0.19 a
20	0.78 a	0.17 a	0.48 a	0.25 a
LSD, pCi L^{-1}	0.35	0.33	0.23	0.15
ANOVA P Values:				
Treatment Effect	0.09	NS	NS	NS
Treatment Trends:				
Linear	0.04	NS	NS	NS
Nonlinear	NS	NS	NS	NS
Linear Equation:				
Intercept	0.362	0.278	0.467	0.183
Slope	0.0194	-0.0054	-0.0001	0.0027
Slope Std Error	0.0087	0.0075	0.0058	0.0035

Continued...

Table 8. Summary of ^{210}Po in Groundwater from PG-Treated Florida Land Cropped to Bahiagrass (Page 2 of 2).

	Malabar Site		Myakka Site	
C. 80-90 cm Well	Years 1-3 (#1 - # 5)	Years 4-5 (#6 - #7)	Years 1-3 (#1 - # 5)	Years 4-5 (#6 - #7)
Concentration, pCi L^{-1}:				
At 0 Mg ha^{-1}	0.28 a	0.95 b	0.34 a	0.15 a
10	0.22 a	0.14 a	0.40 a	0.18 a
20	0.38 a	0.19 a	0.59 a	0.34 a
LSD, pCi L^{-1}	0.22	0.61	0.28	0.21
ANOVA P Values:				
Treatment Effect	NS	0.09	NS	NS
Treatment Trends:				
Linear	NS	0.11	0.08	0.05
Nonlinear	NS	0.10	NS	NS
Linear Equation:				
Intercept	0.243	0.637	0.317	0.130
Slope	0.0049	-0.0285	0.0126	0.0095
Slope Std Error	0.0056	0.0164	0.0070	0.0048

Notes:

* No Runoff samples obtained during Year 1.

- PG Application: Malabar, 5/25/93; Myakka, 6/01/93.
- Experimental design called for sampling six replicate plots per treatment for collections #1-#3 and four replicates for collections #4-#7. Not all designated plots yielded a sample for each collection. See Appendix Tables A-17 and A-18 for exact numbers of samples for each.
- Means with the same letter code (a, b, or c) are not significantly different at the $P \leq 0.05$ level.
- NS = Not statistically significant at the $P \leq 0.10$ level.
- Linear equation: $C_R = a + bT$; where concentration, C_R, and intercept, a, are pCi L^{-1}, and T = treatment level, Mg ha^{-1}.
- Coefficients for regression equations are generally presented with one more decimal place than the reported data and with two significant digits.

Runoff. The data suggest an effect in the first runoff collection (1995), stronger at the Myakka site than at the Malabar site, but no effect for subsequent collections. For this radionuclide, the runoff data were grouped for analysis into slightly different groups than for the other two radionuclides--Year 2 and Years 3-5. For the Year 2 collection at the Malabar site, average concentrations increased with treatment level but differences and trends were not significant. For the Year 2 collection at the Myakka site, the treatment effect was significant and there was a significant linear trend and positive slope for concentration vs. treatment. The test for a nonlinear treatment trend had a P value of 0.07, but this single indication of a nonlinear trend of radionuclide concentration in water vs. PG treatment level was probably a spurious occurrence. There was no evidence of an effect for the overall data from the remaining collections at either site.

Wells. The ^{210}Po concentrations for both well depths at both sites were quite variable; inspection of the figure suggests that overall, across the two sites and two depths, there was a stronger indication of a treatment effect initially than in the last two years. Therefore, the data were combined for analysis into two time periods, Years 1-3 and Years 4-5.

For this radionuclide, the data suggest that the two sites have different time-depth patterns. At the Malabar site, during the initial time period, there was a significant treatment effect and a significant linear trend with a positive concentration vs. treatment level slope for the 35-45 cm wells; while for the 80-90 cm wells, although the average concentrations were higher for the 20 Mg ha^{-1} treatment level than for the control plots, there were no statistically-significant effects or trends. There were no significant effects or trends for the subsequent time period at this site. At the Myakka site, there were no effects observed for 35-45 cm wells for either time period; for the deeper wells, effects for both time periods were suggested (but not statistically significant) with a significant linear trend and positive slope for concentration vs. treatment level.

RADIONUCLIDES IN BAHIAGRASS FORAGES

Radionuclide analyses were performed for regrowth forage collected during the growing season and for end-of-season (November or December) mature forage from each site for five of the six growing seasons following the May 1993 application of PG. Samples were analyzed for 1993, 1994, 1996, 1997, and 1998--seasons 1-2 and 4-6. For the first two post-treatment seasons, individual regrowth samples from several harvests (three or four) were analyzed for radionuclides and annual means were calculated. Thereafter, samples from multiple regrowth harvests were composited and analyses were performed on a single 3-harvest, weighted composite annual sample for each site. For 1993-1996, radionuclide analyses were performed on samples from six replicate plots for each treatment, for 1997 and 1998, the number of replicate plots was reduced to four (five for 1997 mature forage). This results in some reduction in the power to detect treatment effects.

As with the other types of measurements in this study, the data were fitted to linear regression equations to describe the response vs. treatment level. For forages, the ANOVA suggested significant nonlinear trends for several cases. A nonlinear (saturation) effect has been observed in other studies of uptake of U-series radionuclides by plants. Therefore, it is possible that some form of nonlinear function that describes an approach to saturation would provide a better predictive model than a linear one. However, defining the form of response model was beyond the scope of this study.

Annual values for regrowth and mature forage are plotted in Figures 16, 17, and 18 for ^{226}Ra, ^{210}Pb, and ^{210}Po, respectively. All results are tabulated in Appendix Tables A-25 and A-26 for the Malabar and Myakka sites, respectively.

Several preliminary observations provide insight for the approach to evaluation of the forage data:

1. Radionuclide concentrations in the first post-treatment regrowth harvest at the Myakka site represent a special effect (probably leaf surface contamination) not seen at the Malabar site or in subsequent harvests (explained in the next section).
2. If the special Myakka first-harvest effect is excluded, PG-attributable radionuclide concentrations in regrowth forage are generally low and challenge the detection capability of the measurement methods.
3. If the Myakka first-harvest effect is excluded, the mature forage is generally characterized by higher concentrations (control and treated plots), larger concentration vs. treatment level slopes, and higher tissue/soil concentration ratios than for regrowth forage. The contrast is especially pronounced for ^{210}Pb and ^{210}Pb.

It was concluded that the mature forage data are more robust than the regrowth data in describing the behavior of PG-attributable radionuclides. Consequently, the form of the forage data analyses was patterned to the mature forage data; then the mature forage data analyses served as a template for grouping the regrowth forage data for analyses.

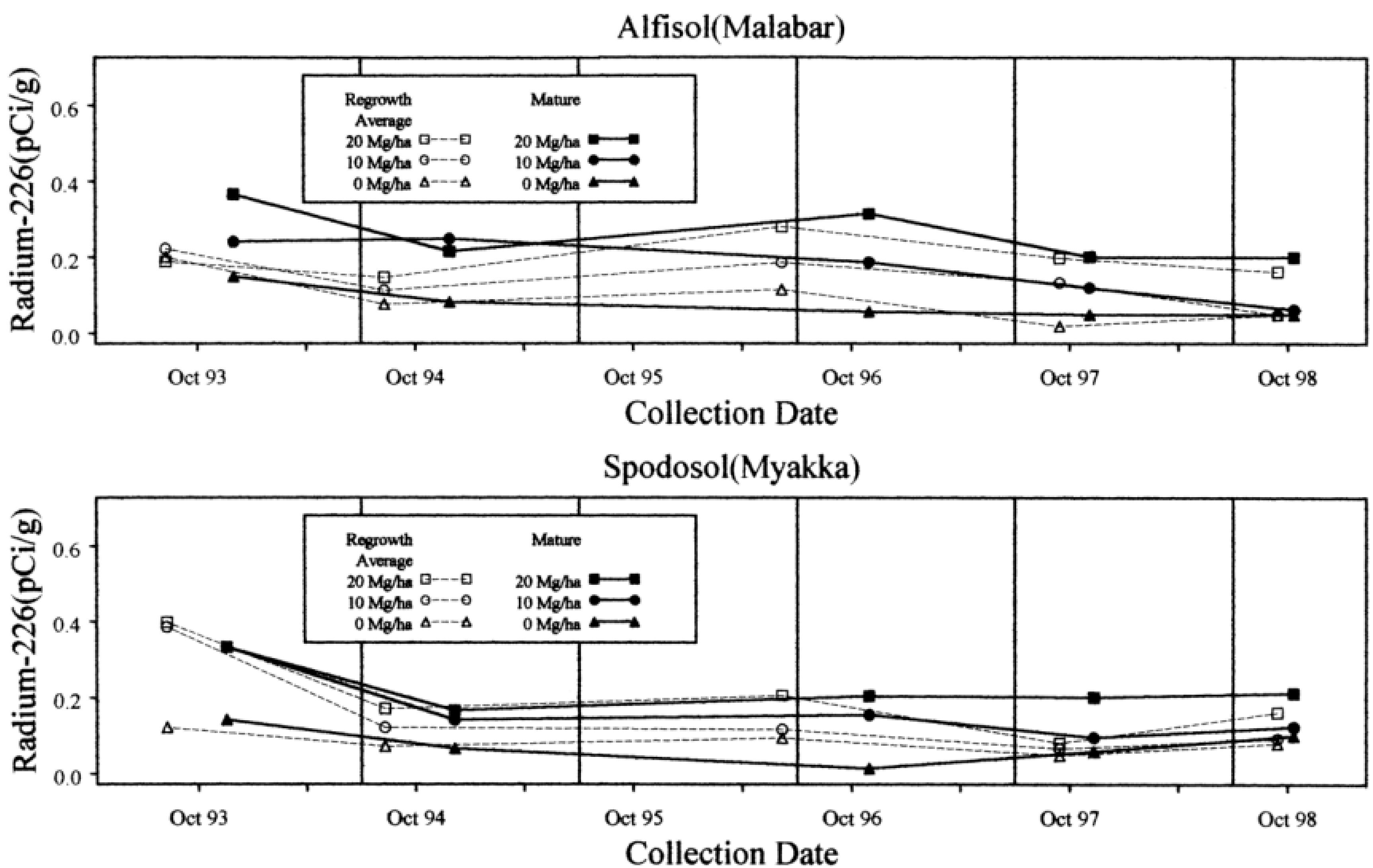

Figure 16. Radium-226 in Bahiagrass Forage Grown on PG-treated Florida Land--Annual Values, 1993-1998.

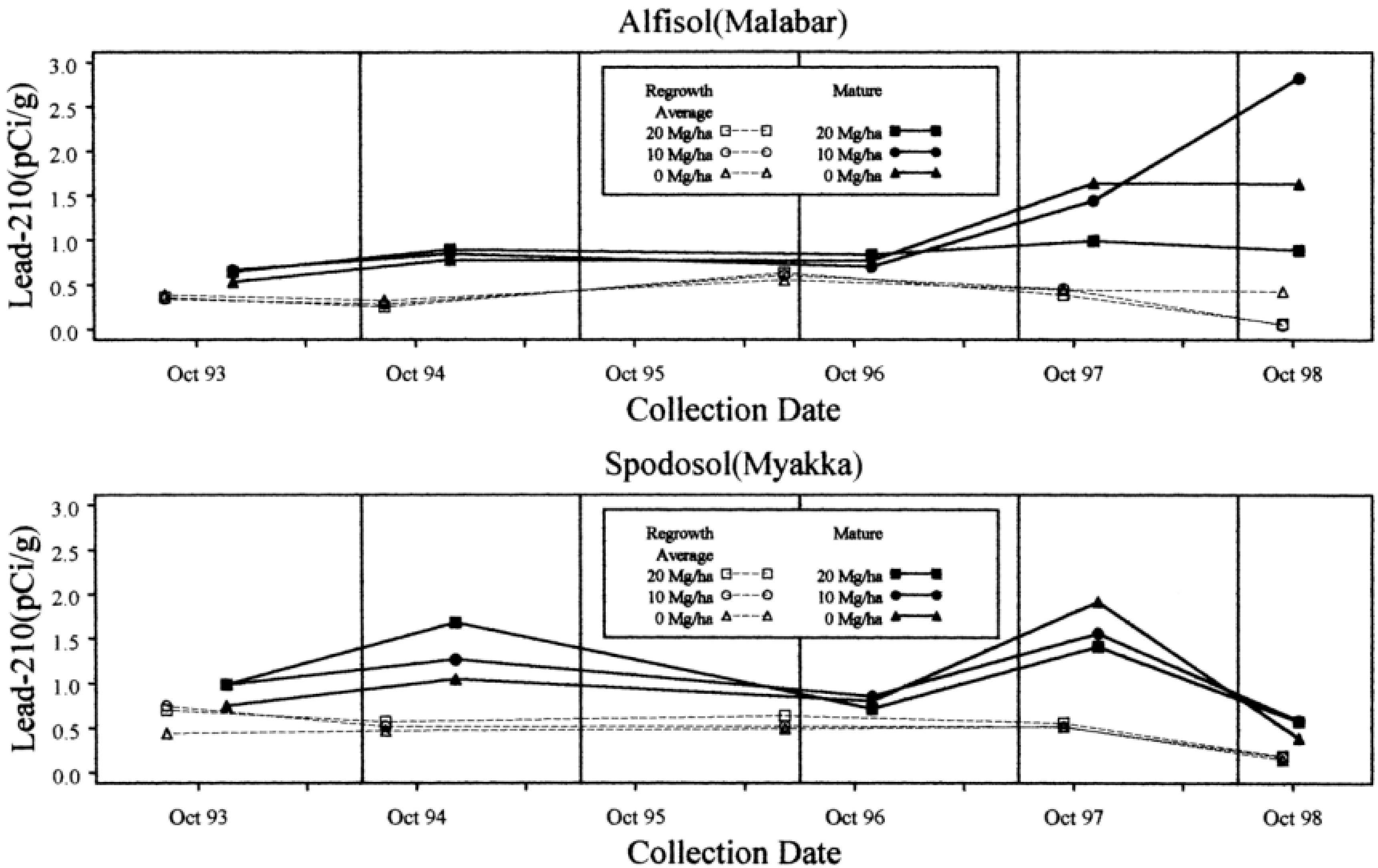

Figure 17. Lead-210 in Bahiagrass Forage Grown on PG-treated Florida Land--Annual Values, 1993-1998.

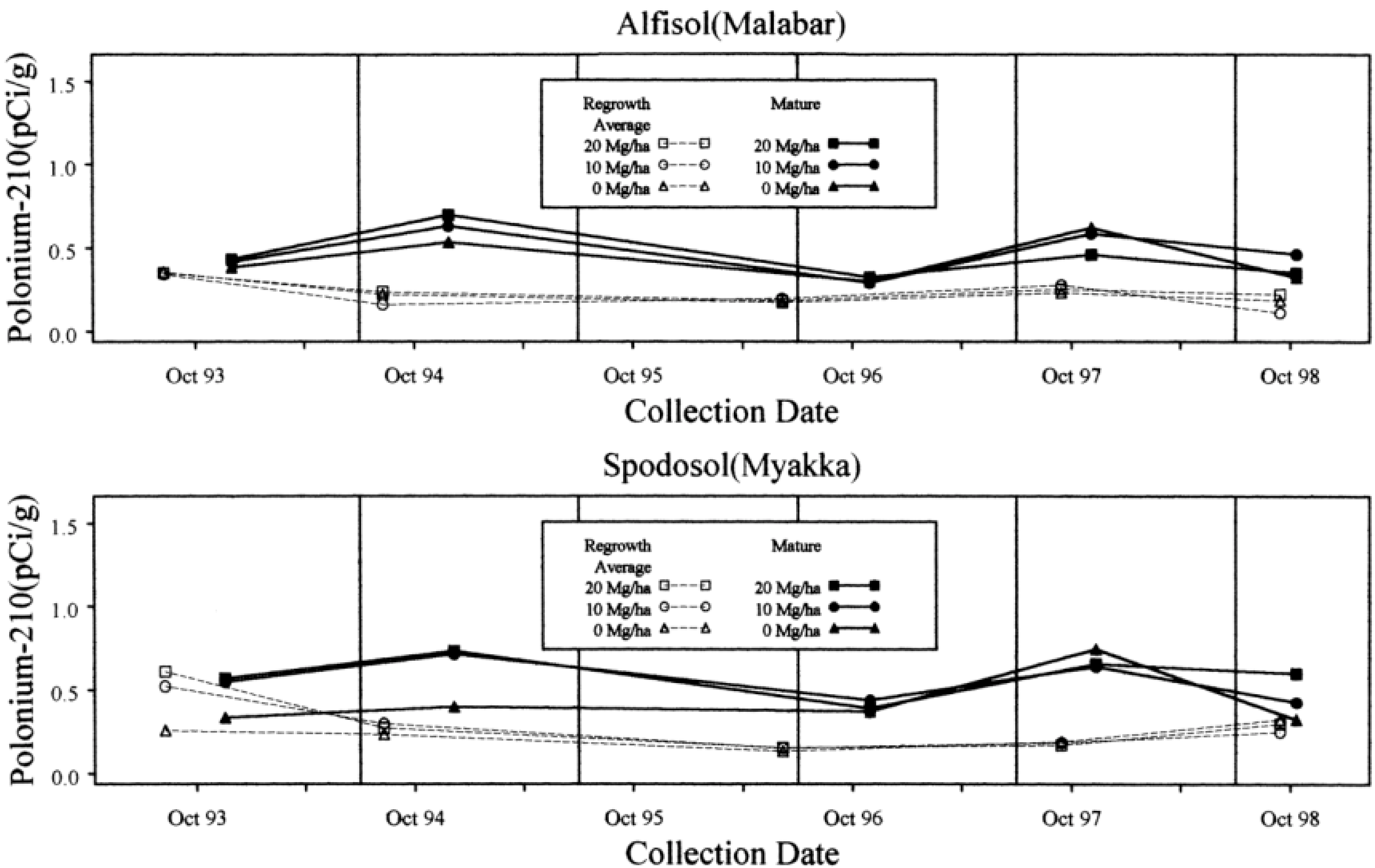

Figure 18. Polonium-210 in Bahiagrass Forage Grown on PG-treated Florida Land--Annual Values, 1993-1998.

Early Post-Treatment Effects in Regrowth Forage

One of the most striking features of the regrowth data is the difference between the two sites in the first season. Results for individual harvests for the 1993 and 1994 seasons are presented in Figures 19, 20, and 21 for ^{226}Ra, ^{210}Pb, and ^{210}Po, respectively. At the Myakka site, significantly-elevated concentrations of all three radionuclides were seen for the treated plots at the first post-treatment harvest (July 1993) with a sharp decrease to subsequent collections (August and September); this was not observed for the Malabar site (sampled in June, August, and September).

The rainfall data for the Research Center suggest a likely explanation for the difference in first-harvest effect between the two sites. After the treatment at the Malabar site (5/25/93), the first significant station rainfall (greater than a few mm) occurred within four days. However, after the treatment at the Myakka site (6/01/93), the first significant station rainfall did not occur until 20 days later. It is hypothesized that radionuclides contained in PG deposited on the surface of the grass during land treatment would be washed off by a prompt rainfall (4 days in the Malabar case) but can gradually undergo foliar absorption or become fixed if the interval to the first significant rainfall is sufficiently long and that the 20 days in the Myakka case was long enough. It should be noted, however, that rain events can be localized, that the weather station is located some distance from the test sites, and that no record was made of actual rainfall at the specific individual experimental sites.

It is further hypothesized that following surface application of PG to established grassland, PG-attributable radionuclide concentrations in regrowth forages can potentially have two components: (a) the "basic" component due to uptake via the roots, and (b) a potential additional component related to retained surface contamination that may or may not be present in the first post-treatment harvest, depending upon the timing of the first post-treatment rainfall. The first component may be influenced by soil type; the second component should be independent of the soil itself, but may be influenced by the ratio of leaf surface area to soil surface area (i.e., the "stand" of the crop).

The potential leaf-surface retention effect as exemplified by the first harvest at the Myakka site should be separated from the "normal" effect for regrowth forage and should be considered as a potential effect under the appropriate conditions for other sites as well.

Radium-226

Figure 16 presents the annual average concentrations in regrowth forage (plotted at the midpoint of the growing season) and the concentrations in end-of-season mature hay for the five sampled years and Table 9 presents summaries. Detailed statistical analyses are presented in Appendix Tables A-27 and A-28 for the Malabar and Myakka sites, respectively.

For the mature hay, persistent treatment effects were observed. While there was variation between years, there were no systematic trends with time, and thus analyses of the combined overall data are presented in the summary tables.

For the regrowth forage from the Malabar site, treatment effects are observed and there is a significant linear trend and positive slope for concentration vs. treatment level. At the Myakka site, concentrations for the first year are influenced by the “first harvest” effect and are significant. If the first harvest is excluded, treatment effects still are observed, there is a significant linear trend for concentration vs. treatment level, and the slope is comparable to that observed for the Malabar site.

Lead-210

Figure 17 presents the annual average concentrations in regrowth forage and the concentrations in end-of-season mature hay for the five sampled years, and Table 10 presents summaries. Detailed statistical analyses are presented in Appendix Tables A-29 and A-30 for the Malabar and Myakka sites, respectively.

For the mature hay, treatment effects were observed in years 1 and 2 but decreased in subsequent years. Therefore, the data were aggregated into two time periods for analysis. The overall data from the first two years represent the initial effect and the overall data from years 4-6 represent the subsequent behavior of ^{210}Pb in mature forages following the application of PG. In the initial period, treatment effects were significant at the Myakka site and suggested at the Malabar site. In the subsequent time period, the effects of PG application could not be detected.

For the regrowth forage from the Malabar site, no effect could be detected for either the initial two-year period or subsequently. At the Myakka site, concentrations for the first year were influenced by the “first harvest” effect, and treatment effects were significant. If the first harvest is excluded, during the initial two-year period the average concentrations for the treated plots were greater than for the control plots but there were no significant effects or trends. In subsequent years, no treatment effect was detected.

Polonium-210

Figure 18 presents the annual average concentrations in regrowth forage and the concentrations in season-end mature hay for the five sampled years and Table 11 presents summaries. Detailed statistical analyses are presented in Appendix Tables A-31 and A-32.

For the mature hay, treatment effects were observed in Years 1 and 2 but by the fourth year there was little evidence of an effect. Therefore, the data were aggregated into two time periods for analysis. The overall data from the first two years represent the initial behavior of ^{210}Pb in mature forages following the application of PG and the overall data from Years 4-6 represent the subsequent behavior. In the initial period, treatment effects were significant at the Myakka site and suggested at the Malabar site. In the subsequent time period the effects of PG application could not be detected.

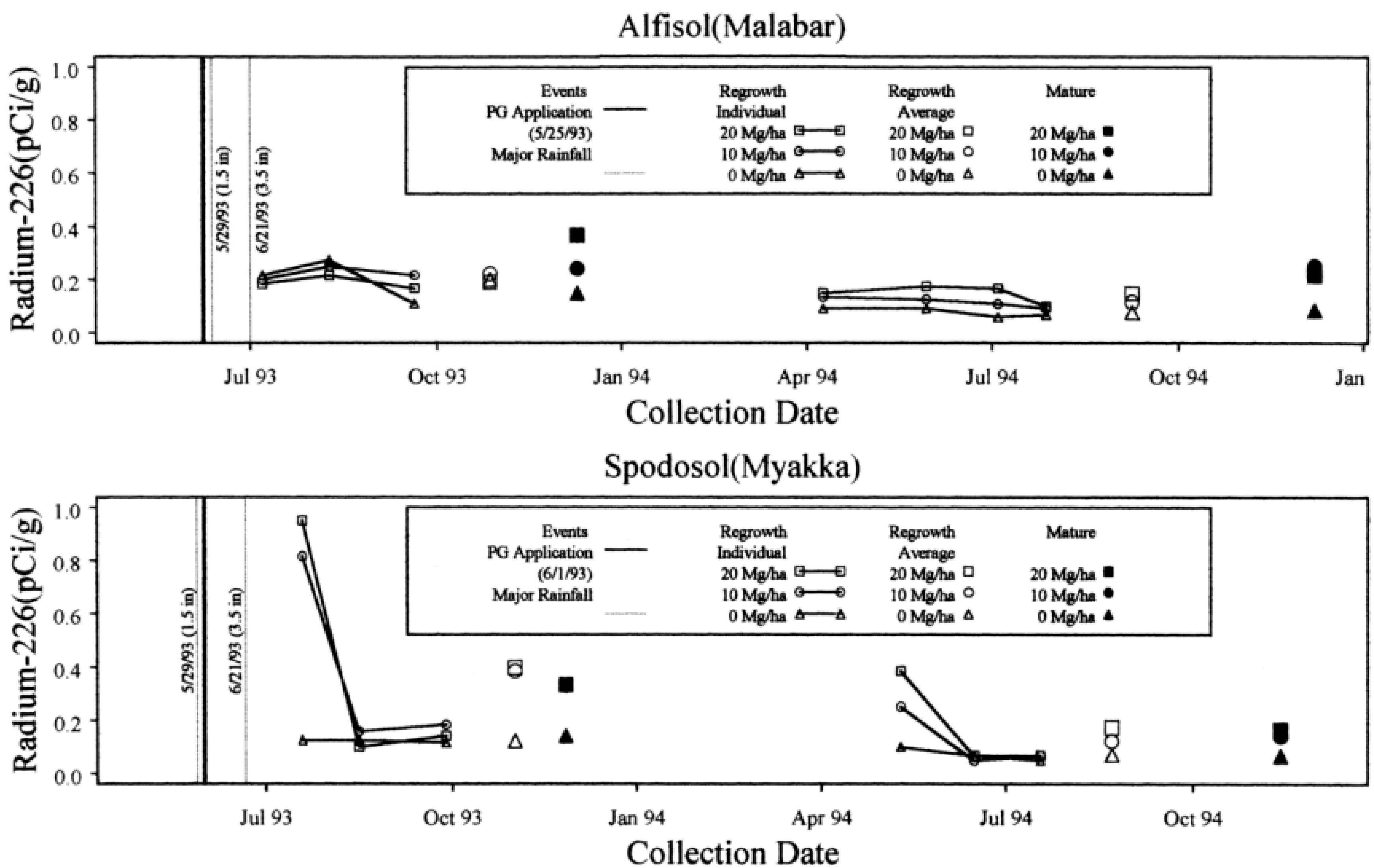

Figure 19. Radium-226 in Bahiagrass Forage Grown on PG-treated Florida Land--Individual Collections, 1993 and 1994.

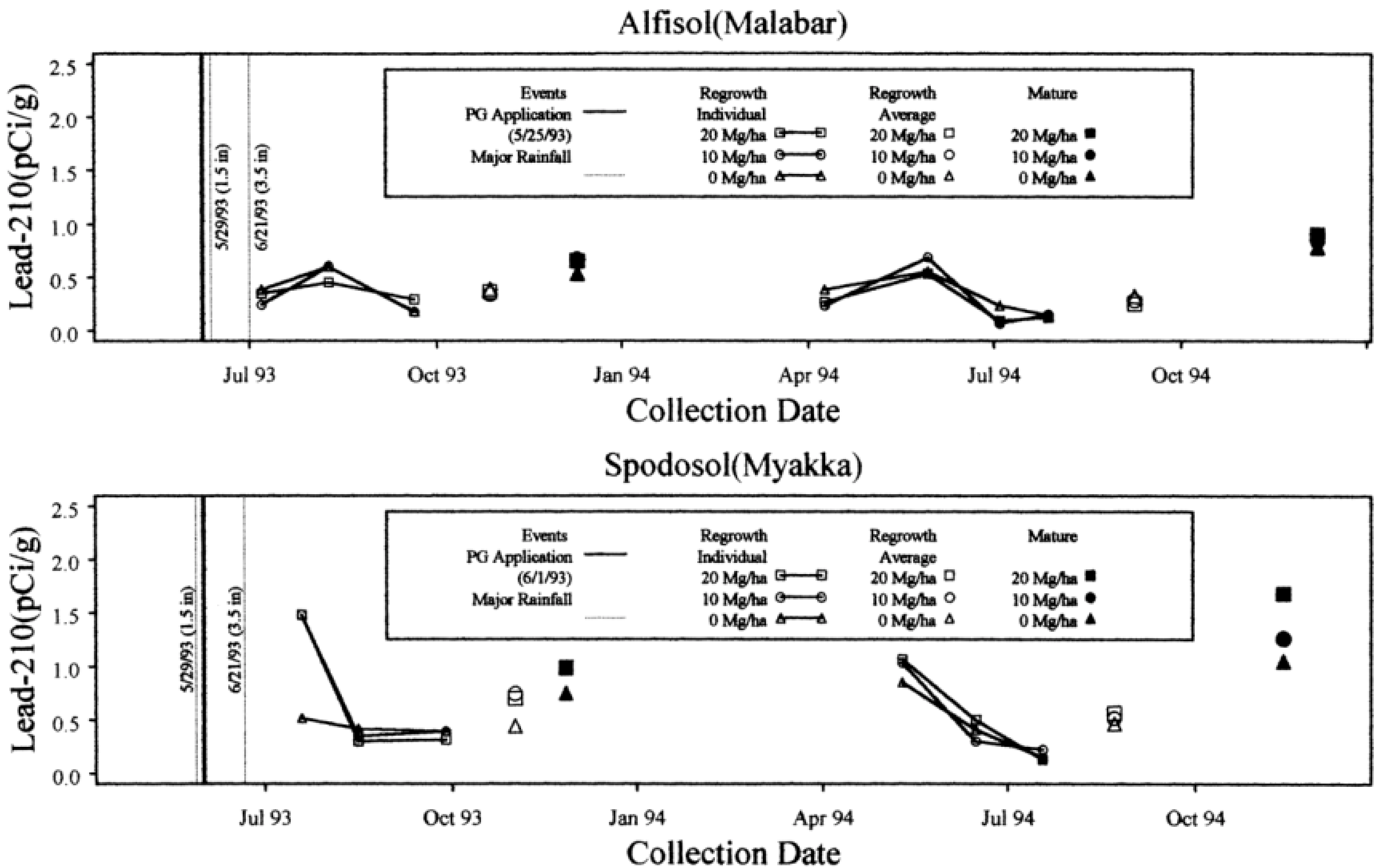

Figure 20. Lead-210 in Bahiagrass Forage Grown on PG-treated Florida Land--Individual Collections, 1993 and 1994.

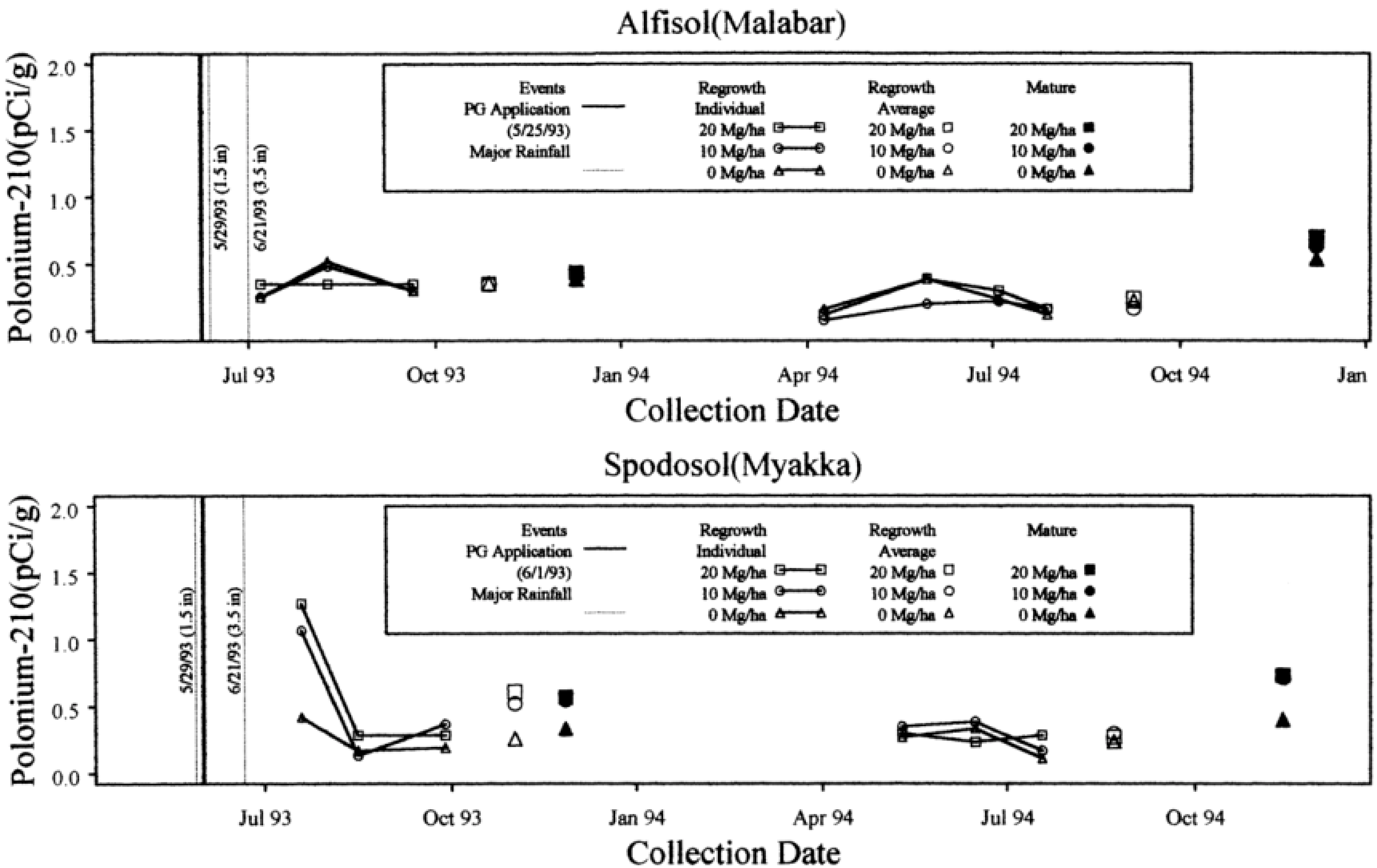

Figure 21. Polonium-210 in Bahiagrass Forage Grown on PG-treated Florida Land--Individual Collections, 1993 and 1994.

For the regrowth forage from the Malabar site, no effect could be detected for either the initial or the subsequent period. At the Myakka site, concentrations for the first year were influenced by the "first harvest" effect, and treatment effects were significant. If the first harvest is excluded, treatment effects during the first two years are suggested and the concentration vs. treatment level regression slope is positive, but differences are not statistically significant. For subsequent years, no effect was detected and the concentration vs. treatment level regression slope was not significantly different from zero.

Overall Pattern of PG-Attributable Radionuclides in Bahiagrass Forages

Overall, forage data suggest the following patterns:

- Concentrations and concentration vs. treatment level slopes are higher for mature forage than for regrowth forage, particularly for ^{210}Pb and ^{210}Po – this suggests that the equilibration time to reach a maximum or "saturation" concentration levels is longer than the time between regrowth harvests, particularly for ^{210}Pb and ^{210}Po.
- Concentrations and concentration vs. treatment level slopes are higher for the Myakka soil than for the Malabar soil. This suggests that the radionuclides are less available from the Malabar soil than from the Myakka soil, perhaps due to the higher content of organic matter in the surface layer of the Malabar soil.
- Effects are more pronounced for ^{226}Ra than for ^{210}Pb and ^{210}Po.
- There is a general decrease in forage radioactivity with time (at least for ^{210}Pb and ^{210}Po) that is more rapid than the loss of radioactivity from the root zone (top 15 cm) of the soil. This suggests that there is a small, more available component of the PG-associated radioactivity that disappears, either due to transport, removal, and/or transformation, or that the PG-associated radionuclides become fixed in the soil with time.
- These above characteristics interact to produce the overall behavior of radionuclides applied to the soil surface as PG.

Table 9. Summary of ^{226}Ra in Forage from PG-Treated Florida Land Cropped to Bahiagrass.

	Malabar Site		Myakka Site
MATURE HAY	Overall		Overall
Concentration, pCi g^{-1}:			
At 0 Mg ha^{-1}	0.08 c		0.08 b
10	0.18 b		0.18 a
20	0.27 a		0.22 a
LSD, pCi g^{-1}	0.07		0.06
ANOVA P Values:			
Treatment Effect	<0.01		<0.01
Treatment Trends:			
Linear	<0.01		<0.01
Nonlinear	NS		NS
Linear Equation:			
Intercept	0.084		0.084
Slope	0.0093		0.0075
Slope Std Error	0.0017		0.0016
REGROWTH	Overall	Year 1	Overall, Harvest #1 Excluded
Concentration, pCi g^{-1}:			
At 0 Mg ha^{-1}	0.12 b	0.12 b	0.09 b
10	0.15 ab	0.39 a	0.13 ab
20	0.18 a	0.40 a	0.15 a
LSD, pCi g^{-1}	0.04	0.22	0.04
ANOVA P Values:			
Treatment Effect	0.01	0.03	0.01
Treatment Trends:			
Linear	<0.01	0.02	<0.01
Nonlinear	NS	NS	NS
Linear Equation:			
Intercept	0.117	0.164	0.089
Slope	0.0033	0.0138	0.0033
Slope Std Error	0.0011	0.0054	0.0011

See notes following Table 11.

Table 10. Summary of ^{210}Pb in Forage from PG-Treated Florida Land Cropped to Bahiagrass.

	Malabar Site		Myakka Site	
MATURE HAY	Years 1-2	Years 4-6	Years 1-2	Years 4-6
Conc., pCi g^{-1}:				
At 0 Mg ha^{-1}	0.66 a	1.29 ab	0.90 b	1.06 a
10	0.76 a	1.52 a	1.12 ab	1.02 a
20	0.78 a	0.90 b	1.33 a	0.91 a
LSD, pCi g^{-1}	0.17	0.60	0.31	0.45
ANOVA P Values:				
Treatment Effect	NS	0.12	0.03	NS
Treatment Trends:				
Linear	NS	0.19	<0.01	NS
Nonlinear	NS	0.11	NS	NS
Linear Equation:				
Intercept	0.672	1.169	0.903	1.074
Slope	0.0058	-0.0129	0.0217	-0.0077
Slope Std Error	0.0040	0.0103	0.0077	0.0106

REGROWTH	Years 1-2	Years 4-6	Year 1	Years 1-2 (Harvest #1 Excluded)	Years 4-6
Conc., pCi g^{-1}:					
At 0 Mg ha^{-1}	0.35 a	0.49 a	0.44 a	0.44 a	0.40 a
10	0.31 a	0.40 a	0.74 a	0.46 a	0.42 a
20	0.30 a	0.40 a	0.70 a	0.46 a	0.49 a
LSD, pCi g^{-1}	0.10	0.22	0.36	0.19	0.21
ANOVA P:					
Treatment Effect	NS	NS	NS	NS	NS
Treatment Trends:					
Linear	NS	NS	NS	NS	NS
Nonlinear	NS	NS	NS	NS	NS
Linear Equation:					
Intercept	0.347	0.482	0. 499	0.446	0.395
Slope	-0.0026	-0.0047	0.0129	0.0017	0.0041
Slope Std Err	0.0025	0.0055	0.0085	0.0047	0.0052

See notes following Table 11.

Table 11. Summary of ^{210}Po in Forage from PG-Treated Florida Land Cropped to Bahiagrass.

	Malabar Site		Myakka Site	
MATURE HAY	Years 1-2	Years 4-6	Years 1-2	Years 4-6
Conc., pCi g^{-1}:				
At 0 Mg ha^{-1}	0.46 a	0.41 a	0.37 b	0.48 a
10	0.52 a	0.44 a	0.63 a	0.50 a
20	0.57 a	0.38 a	0.65 a	0.54 a
LSD, pCi g^{-1}	0.24	0.15	0.20	0.14
ANOVA P Values:				
Treatment Effect	NS	NS	0.01	NS
Treatment Trends:				
Linear	NS	NS	<0.01	NS
Nonlinear	NS	NS	NS	NS
Linear Equation:				
Intercept	0.463	0.428	0.408	0.481
Slope	0.0054	-0.0019	0.0142	0.0026
Slope Std Error	0.0054	0.0036	0.0055	0.0034

REGROWTH	Years 1-2	Years 4-6	Year 1	Year 1-2 (Harvest #1 Excluded)	Years 4-6
Conc., pCi g^{-1}:					
At 0 Mg ha^{-1}	0.28 a	0.19 a	0.26 b	0.21 a	0.21 a
10	0.24 a	0.20 a	0.52 a	0.28 a	0.19 a
20	0.29 a	0.22 a	0.61 a	0.28 a	0.20 a
LSD, pCi g^{-1}	0.08	0.05	0.28	0.08	0.08
ANOVA P:					
Treatment Effect	NS	NS	0.04	NS	NS
Treatment Trends:					
Linear	NS	NS	0.02	NS	NS
Nonlinear	NS	NS	NS	NS	NS
Linear Equation:					
Intercept	0.265	0.189	0.288	0.225	0.201
Slope	0.0004	0.0012	0.0176	0.0032	-0.0002
Slope Std Err	0.0020	0.0013	0.0067	0.0021	0.0018

See notes on following page.

Notes for Tables 9, 10, & 11:

- PG Application: Malabar, 5/25/93; Myakka, 6/01/93.
- Results for each site are based on six replicate plots per treatment in Years 1, 2, & 4, four (regrowth) or five (mature hay) replicates in Year 5, and four replicates in Year 6.
- Means with the same letter code (a, b, or c) are not significantly different at the $P \leq 0.05$ level.
- NS = Not statistically significant at the $P \leq 0.10$ level.
- Linear equation: $C_R = a + bT$; where concentration, C_R, and intercept, a, are pCi g^{-1}, and T = treatment level, Mg ha^{-1}.
- Coefficients for regression equations are generally presented with one more decimal place than the reported data and with two significant digits.

ATMOSPHERIC RADON

Atmospheric Rn measurements were performed inside chimneys over the control plots for an approximately 30-day period beginning about seven weeks prior to application of the PG. After the PG application, measurements were conducted for roughly 60-day periods in the chimneys over all the contiguous plots and both inside ($C_{ext,i}$) and outside ($C_{ext,o}$) chimneys over external control stations. After August 1997, atmospheric Rn measurements were discontinued. During the 4+ post-application years, measurements were performed 17 times at the Malabar site and 16 times at the Myakka site. The data are presented in Figure 22 and tabulated in Appendix Tables A-33 and A-34. Data points represent the average airborne Rn concentration over the measurement period based on replicate plots or stations, each with one or more EICs. The experimental design through 2/95 (through Collection #8 at the Malabar site and Collection # 7 at the Myakka site) called for 12 replicate plots, each with three EICs for each treatment level; six stations, each with three EICs for the $C_{ext,i}$; and six stations, each with one EIC for $C_{ext,o.}$ For the remainder of the study, the experimental design called for six replicate plots for each treatment level, four $C_{ext,i}$ stations, and four $C_{ext,o}$ stations, all with two EICs each. However, not all collections were successful; the actual complements of measurements are indicated in Appendix Tables A-33 and A-34.

Data recovery (number of useable data points vs. number of detectors deployed) for the 21 site-collection combinations through 5/96 (Collections #1-#11 for the Malabar site and #1-#10 for the Myakka site) was ≥60% for 95% of the cases and ≥70% for 81% of the cases. However, for the subsequent 12 site-collection combinations (#12-#17 for the Malabar site and #11-#16 for the Myakka site), data recovery was much poorer; recovery values ranged from 25% to 72%, were ≥60% only 25% of the time and were <50% half of the time. The shaded area on Figure 22 indicates the time period where the data have a high degree of uncertainty as a result of reduced replication and low data retrieval due to discharged electrets. At least some of the data loss was due to severe weather (wind and rain) during this time period; the EICs were subjected to high humidity and on several occasions were even found on the ground.

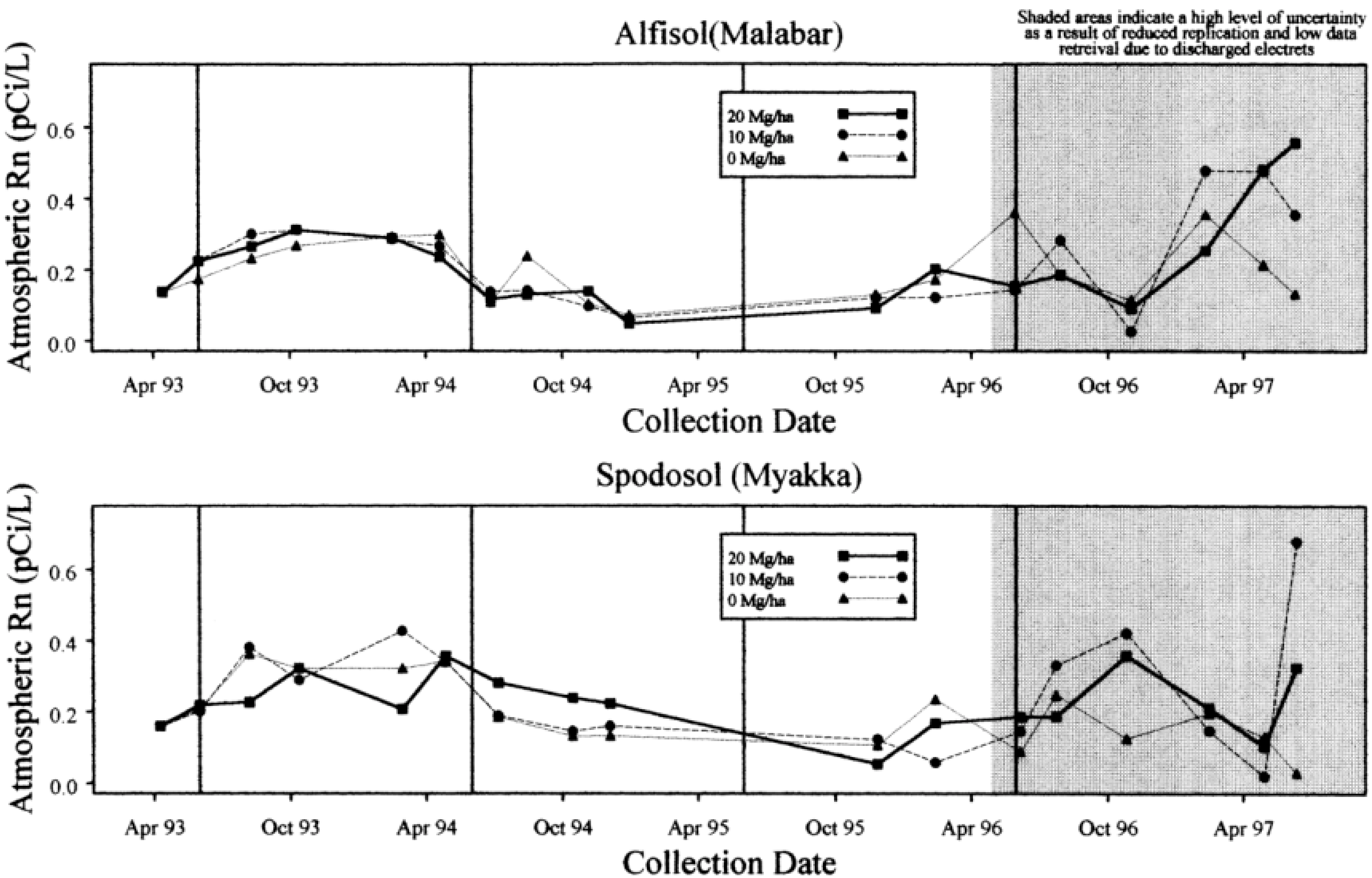

Figure 22. Atmospheric Rn over PG-treated Florida Land Cropped to Bahiagrass.

The data were grouped by years to test for treatment effects (Appendix Tables A-35 and A-36). There was no consistent evidence of treatment effects or trends. A significant treatment effect and a significant linear concentration vs. treatment level trend with positive slope was observed for Year 2 (1994-95) at the Myakka site; otherwise there were no significant treatment effects or meaningful trends (in fact, five of the eight cases had negative concentration vs. treatment level slopes). For the final analysis, the overall data for the entire study period were grouped within sites. As indicated in Table 12, overall there were no significant effects or trends.

It is of interest to note whether the chimneys, intended to isolate air columns from the effect of adjacent plots and lateral air movements, might actually result in enhanced airborne Rn concentrations. Comparison of the pairs of inside and outside measurements at the external control stations as presented in Appendix Tables A-33 and A-34 indicates that overall the concentrations measured inside the chimneys were no higher than those measured outside.

TRANSFER FACTORS (TFs)

Assessment of the radiological impact of future PG-use scenarios requires a tool for predicting the radiations levels and radionuclide concentrations for the proposed PG application rate. A simple linear model, where the radiological parameter of interest is predicted by multiplying the quantity of PG or radioactivity applied by a factor, the "transfer factor" (TF), is a reasonable representation for all the radiological parameters considered here with the possible exception of forages.

While certain parameters may behave similarly for different soil types, there were soil-type differences for the initial values and/or changes with time for some of the parameters studied here. Therefore, separate TFs are reported for the Malabar site and the Myakka site.

A gradual relocation of the PG-attributable radioactivity from the surface layer of the soil by weathering, removal by cropping, and/or leaching is to be expected. Consequently there should be a gradual change with time of the various TFs following a single application of PG to the soil surface. One practice in use is to define both an initial value of the factor and also the function that describes the change with time. For some parameters in this study, such as Rn flux, any overall unidirectional change with time was too small to be observed over the 5+ years of observation and only an initial value could be determined. For other parameters, there was an observable change with time during the observation period. In some cases there appeared to be an initial mobilization of a small fraction of the radioactivity, following which the radioactivity was less mobile. This might be the result of the added radioactivity containing a small more highly mobile fraction and/or becoming fixed in the soil with time. In a number of cases, after the initially-observed effect, the subsequent effect was too small to be measured. Thus it was difficult to describe a continuous time-dependent function from these data. Therefore, a simplified, step-function time dependence model was used and TFs were calculated for a) an initial time period and b) subsequent years. The length of the initial time interval was not necessarily the same for all media or for all radionuclides but was considered to be the same for the two sites.

Table 12. Airborne Rn at 1 m over PG-Treated Florida Land Cropped to Bahiagrass.

	Malabar Site	Myakka Site
PRE-PG TREATMENT		
Concentration, pCi g^{-1}:		
0 Mg ha^{-1} plots (C_{int})	0.14	0.16
POST-PG TREATMENT		
External Control Stations		
Concentration, pCi L^{-1}:		
$C_{ext,o}$ (Outside Chimney)	0.31	0.29
$C_{ext,i}$ (Inside Chimney)	0.23	0.26
Treatment Plots		
Concentration, pCi L^{-1}:		
At 0 Mg ha^{-1} (C_{int})	0.20 a	0.22 a
10	0.21 a	0.24 a
20	0.21 a	0.24 a
LSD, pCi g^{-1}	0.03	0.04
ANOVA P Values:		
Treatment Effect	NS	NS
Treatment Trends:		
Linear	NS	NS
Nonlinear	NS	NS

Notes:

- PG Application: Malabar 5/25/93; Myakka 6/01/93.
- C_{int} = Internal Control = Untreated plot within the treatment array.
- C_{ext} =External Control = Stations over untreated land outside the treatment array. $C_{ext,i}$ and $C_{ext,o}$ are from detectors inside and outside the chimney, respectively.
- Measurement design called for the following complements of multiple detectors at replicate plots or stations:

	5/93 - 2/95 (Malabar #1 - #9) (Myakka #1 - #8)	11/95 - 8/97 (Malabar #10 - #17) (Myakka #9 - #16)
Contiguous Plots	12 plots x 3 EICs = 36	6 plots x 2 EICs = 12
$C_{ext,i}$	6 stations x 3 EICs = 18	4 stations x 2 EICs = 8
$C_{ext,o}$	6 stations x 1 EIC = 6	4 stations x 2 EICs = 8

Not all collections were successful. See Appendix Tables A-33 and A-34 for exact complements of measurements.

In some cases (parameter and time interval combinations), the data were characterized by significant treatment effects, a significant linear trend, and a significant positive slope for the regression of measured parameter vs. treatment level; in these cases, TFs could be calculated with a high degree of confidence. In other cases, significant treatment effects and trends were not observed. In the extreme case, calculated slopes were even negative. While the cases where there were no significant environmental effects for single PG applications up to 20 Mg ha^{-1} (about 50 times the agronomically optimum annual treatment rate) were reassuring, it is still important to have tools for predicting the potential effect of long-term continuous practices resulting in cumulative applications of 10's of Mg ha^{-1}. For this reason, central values were reported wherever possible and, in addition, a one-tailed 95% upper confidence limit was estimated for all cases. The reported TFs fall in three quality categories:

1. Significant--Based on significant effects and significant positive slopes (Slope relative standard error or RSE ≤ 61%).
2. Best estimate--Based on data that suggested an effect and slopes were positive but not significant at the P = 0.05 level (slope RSE > 61%). These values are presented in parentheses in the tables.
3. Upper limit only--Cases where no effect could be discerned and slopes had a very large uncertainty (slope RSE > 100%) or were even negative. In these cases, "N" is entered for the central value, and only the upper confidence limit is presented for use in the absence of other data.

Two forms of TF were calculated: (a) on a "treatment" or per unit applied PG basis (TF_T), and (b) on a per unit applied activity basis (TF_A) . TF_T is numerically equal to slope for the linear regression of the measured parameter vs. PG treatment level and has units of parameter units per Mg PG ha^{-1}. Values of TF_T are presented in Table 13. Projections for proposed PG use are calculated from the formula:

$$\text{Parameter} = TF_T \times T, \text{ where } T = \text{the PG treatment level in Mg ha}^{-1}.$$

This form is applicable for PG with radionuclide concentrations similar to those in the test PG. (These TFs can be used for other PGs by appropriate scaling for radionuclide concentration).

Values of TF_A are presented in Table 14. This form is referenced to a specific relevant radionuclide, is derived from the slope and the radionuclide concentration in the test PG, and has units of parameter units per pCi m^{-2}. Projections for proposed PG use are calculated from the formula:

$$\text{Parameter} = TF_A \times A, \text{ where } A = \text{the activity applied per unit area in pCi m}^{-2}.$$

The applied activity is calculated from the formula:

$$A = 10^2\, T \times C_{PG},$$

where T is the treatment level in Mg ha^{-1}, C_{PG} is the concentration of the relevant radionuclide in pCi g^{-1} and 10^2 reconciles units.

Table 13. Transfer Factors per Unit PG Applied (TF_T) (Page 1 of 2).

Medium, Radiological Parameter, and Units	TF_T, Parameter Units per Mg PG ha^{-1}			
	Malabar Site		Myakka Site	
	Central Value	Upper Limit*	Central Value	Upper Limit*
Rn Flux, pCi m^{-2} s^{-1}	0.0017	0.0020	0.0019	0.0021
Gamma Radiation, μR h^{-1}				
Initial year	0.013	0.021	0.012	0.024
Subsequent years	0.009	0.021	(0 .007)	0.020
Groundwater, pCi L^{-1}				
^{226}Ra:				
Runoff, Years 1-3**	(0.0169)	0.0444	0.0704	0.1143
Subsequent years	0.0183	0.0288	(0.0060)	0.0137
45-cm well (overall)	(0.0066)	0.0177	(0.0047)	0.0179
90-cm well (overall)	N	0.0123	(0.0064)	0.0191
^{210}Pb:				
Runoff, Years 1-3**	N	0.0281	0.0416	0.0809
Subsequent years	N	0.0034	N	0.0648
45-cm well (overall)	0.0430	0.0698	N	0.0269
90-cm well (overall)	(0.0149)	0.0368	(0.0175)	0.0509
^{210}Po:				
Runoff, Years 1-2**	(0.0096)	0.0836	0.2350	0.3245
Subsequent years	N	0.0088	N	0.0110
45-cm well, Years 1-3	0.0194	0.0337	N	0.0094
Subsequent years	N	0.0069	(0.0027)	0.0085
90-cm well, Years 1-3	(0.0049)	0.0141	0.0126	0.0241
Subsequent years	N	Neg	0.0095	0.0174

Continued ...

Table 13. Transfer Factors per Unit PG Applied (TF_T) (Page 2 of 2).

Forage, pCi g^{-1}				
^{226}Ra:				
Mature Hay:	0.0093	0.0121	0.0075	0.0101
Regrowth, basic	0.0033	0.0051	0.0033	0.0051
Year 1 "added"***	[0.0105]	[0.0176]	0.0105	0.0176
^{210}Pb:				
Mature Hay, Years 1-2	(0.0058)	0.0124	0.0217	0.0344
Subsequent years	N	0.0040	N	0.0097
Regrowth, Years 1-2	N	0.0015	(0.0017)	0.0094
Subsequent years	N	0.0043	(0.0041)	0.0127
Year 1 "added"***	[0.0112]	[0.0174]	0.0112	0.0174
^{210}Po:				
Mature Hay, Years 1-2	(0.0054)	0.0143	0.0142	0.032
Subsequent years	N	0.0040	(0.0026)	0.0082
Regrowth, Years 1-2	(0.0004)	0.0036	(0.0032)	0.0067
Subsequent years	(0.0012)	0.0033	N	0.0028
Year 1 "added"***	[0.0144]	[0.0220]	0.0144	0.0220

Notes:

Applicable for PG with ^{226}Ra, ^{210}Pb, and ^{210}Po at 21.4, 22.6, and 20.1 pCi g^{-1}, respectively.

TFs in parentheses represent "best estimates" when the slope was not statistically significant.

N = Slope not determined because calculated value was negative or had an extremely large relative standard error.

*Upper Limit represents the 95% one-tailed upper confidence limit calculated as the slope + 1.645 slope std. error.

**No runoff collections obtained during the first year following PG application, therefore values for the initial period for runoff are based on collections in Years 2 and 3 for ^{226}Ra and ^{210}Pb and collections in Year 2 for ^{210}Po.

***The regrowth forage Year 1 "added" component represents the potential additional radioactivity (surface deposition) in the first post-treatment year regrowth average if there is a long time lag between treatment and the first significant rainfall. Values for the Malabar site, in [ ], are inferred from the observations for the Myakka site.

Table 14. Transfer Factors per Unit of Radioactivity Applied (TF_A) (Page 1 of 2).

Medium, Radiological Parameter, and Units	TF_A, Parameter Units per pCi m^{-2} (multiply all by 10^{-6})			
	Malabar Site		Myakka Site	
	Central Value	Upper Limit*	Central Value	Upper Limit*
Rn Flux, pCi m^{-2} s^{-1}	0.800	0.935	0.888	0.981
Gamma Radiation, μR h^{-1}				
Initial year	6.17	9.80	5.65	11.34
Subsequent years	4.30	9.83	(3.22)	9.30
Groundwater, pCi L^{-1}				
^{226}Ra:				
Runoff, Years 1-3**	(7.90)	20.75	32.90	53.41
Subsequent years	8.55	13.46	(2.80)	6.40
45 cm well (overall)	(3.08)	7.94	(2.20)	8.36
90-cm well (overall)	N	5.75	(2.99)	8.92
^{210}Pb:				
Runoff, Years 1-3**	N	11.91	17.63	34.28
Subsequent years	N	1.44	N	27.46
45 cm well (overall)	18.22	29.58	N	11.40
90-cm well (overall)	(6.31)	15.59	(7.42)	21.57
^{210}Po:				
Runoff, Years 1-2**	(4.80)	41.59	116.92	161.44
Subsequent years	N	4.38	N	5.47
45 cm well, Years 1-3	9.65	16.77	N	4.68
Subsequent years	N	3.43	(1.34)	4.23
90-cm well, Years 1-3	(2.44)	7.01	6.27	11.99
Subsequent years	N	Neg	4.73	8.66

Continued ...

Table 14. Transfer Factors per Unit of Radioactivity Applied (TF_A) (Page 2 of 2).

Forage, pCi g^{-1}				
^{226}Ra:				
Mature Hay:	4.34	5.65	3.50	4.72
Regrowth, basic	1.54	2.38	1.54	2.38
Year 1 "added"***	[4.91]	[8.22]	4.91	8.22
^{210}Pb:				
Mature Hay, Years 1-2	(2.46)	5.25	9.19	14.58
Subsequent years	N	1.69	N	4.11
Regrowth, Years 1-2	N	0.64	(0.72)	3.98
Subsequent years	N	1.82	(1.74)	5.38
Year 1 "added"***	[4.74]	[7.37]	4.74	7.37
^{210}Po:				
Mature Hay, Years 1-2	(2.70)	7.11	7.06	15.92
Subsequent years	N	1.99	(1.29)	4.08
Regrowth, Years 1-2	(0.20)	1.79	(1.59)	3.33
Subsequent years	(0.60)	1.64	N	1.39
Year 1 "added"***	[7.16]	[10.94]	7.16	10.94

Notes:

Rn flux and gamma radiation are referenced to unit ^{226}Ra application.

TFs in parentheses represent "best estimates" when the slope was not statistically significant.

N = Slope not determined because calculated value was negative or had an extremely large relative standard error.

*Upper Limit represents the 95% one-tailed upper confidence limit calculated as the slope + 1.645 slope std. error.

**No runoff collections obtained during the first year following PG application, therefore values for the initial period for runoff are based on collections in Years 2 and 3 for ^{226}Ra and ^{210}Pb and collections in Year 2 for ^{210}Po.

***The regrowth forage Year 1 "added" component represents the potential additional radioactivity (surface deposition) in the first post-treatment year regrowth average if there is a long time lag between treatment and the first significant rainfall. Values for the Malabar site, in [ ], are inferred from the observations for the Myakka site.

ASSESSMENT OF RADIOLOGICAL IMPACT FOR A SCENARIO OF PG USE

Assessment of the potential radiological impact of a proposed PG use involves: (1) defining the PG use scenario of interest, (2) projecting the resulting future environmental radiation and radioactivity levels, and (3) evaluating these levels and the associated resulting human radionuclide intakes, radiation doses, and risks.

THE PG-USE SCENARIO

The purpose of this study was to evaluate the radiological consequences of the application of PG to forage lands in Florida. The recommended agronomically optimum program for long-term use is application at the annual rate of 0.4 Mg ha^{-1} (Alcordo and Rechcigl 1993). Therefore, for this assessment, it was assumed that Central Florida PG would be applied annually to bahiagrass pastures at the rate of 0.4 Mg ha^{-1} for 100 years. It was then assumed that the land may be used for a number of purposes, including residential construction.

PROJECTED FUTURE RADIATION AND RADIOACTIVITY LEVELS

Calculated Radioactivity Levels in Soil

Table 15 presents projected radionuclides levels in several upper layers of soil after 100 years of applying PG with radionuclide concentrations of the reference PG. Values are presented for concentrations averaged over three different layers – 1) 0-5 cm (2-in), the minimum sampling depth in this study, 2) 0-15 cm (6 in), intended to represent a tilling depth for agricultural purposes, and 3) 0-61 cm (2 ft), the upper layer depth used in the RAETRAD-F program for calculating site-specific Rn potential in Florida (Nielson and others 1996). The concentration projected for the 5-cm layer is likely an overestimate since no downward movement was assumed whereas there was some evidence of beginning downward movement in the 5-year observation period of this study. The concentration as averaged over the first 15 cm may possibly be a slight overestimate because movement out of this layer was not considered.

Projecting for Other Media

As indicated earlier in the Transfer Factors section, a simple linear model relating radiation levels and radioactivity concentrations to the amount of PG applied was felt to be a reasonable approach for the radiological parameters considered here. With this model, the value of the radiological parameter, y, at any point in time is:

Table 15. Calculated Effect on Soil Radionuclide Content of Surface Application of Central Florida PG Annually at 0.4 Mg ha^{-1} for 100 Years.

	PG	^{226}Ra	^{210}Pb	^{210}Po
PG-attributable contributions per Mg ha^{-1} PG Treatment (100 g PG m^{-2})				
Surface addition, pCi m^{-2}	- -	2,140	2,260	2,010
Concentration in soil:	-- g g^{-1} --	--------------	pCi g^{-1}	-------------
Upper 5 cm (2 in), ρ = 750 kg m^{-3}	0.00267	0.0571	0.0603	0.0536
Upper 15 cm (6 in), ρ = 1500 kg m^{-3}	0.00044	0.0095	0.0100	0.0089
Upper 61 cm (24 in), ρ = 1500 kg m^{-3}	0.00011	0.0023	0.0025	0.0022
For PG treatment of 40 Mg ha^{-1} (0.4 Mg ha^{-1} y^{-1} x 100 y)				
Surface addition, pCi m^{-2}	- -	85,600	90,400	80,400
Concentration in soil:	-- g g^{-1} --	---------------	pCi g^{-1}	------------
Averaged over 5 cm (2 in):	0.1067			
Addition		2.28	2.41	2.14
Baseline		0.44	0.80	0.59
Total		2.72	3.21	2.73
(% of baseline)		*(618)*	*(401%)*	*(463%)*
Averaged over 15 cm (6 in):	0.0178			
Addition		0.38	0.40	0.36
Baseline		0.39	0.62	0.46
Total		0.77	1.02	0.82
(% of baseline)		*(197%)*	*(165%)*	*(178%)*
Averaged over 61 cm (24 in):	0.00437			
Addition		0.094	0.099	0.088
Baseline		0.48	0.48	0.36
Total		0.57	0.58	0.45
(% of baseline)		*(120%)*	*(120%)*	*(124%)*

Notes:

- For PG with ^{226}Ra, ^{210}Pb, and ^{210}Po at 21.4, 22.6, and 20.1 pCi g^{-1}, respectively.
- Averaging Layers:
  - 5-cm (2-in) layer = Minimum sampling layer in this study. *PG-attributable concentration is an upper limit assuming no downward movement; likely an overestimate.*
  - 15-cm (6-in) layer = Tilling depth.. *PG-attributable concentration is an upper limit assuming no downward movement; possibly an overestimate.*
  - 61-cm (24-in) layer = Rn modeling layer.
- Soil density: 5-cm layer uses measured value for Malabar site; other layers use default value of 1500 kg m^{-3}.
- Baseline data from Appendix B, Worksheet B-1.

$$y = a + bT;$$

where y and a are in consistent units and T = treatment level, Mg ha^{-1}.

The intercept, a, is also the site-specific baseline value, y_{BL} The slope, b, the value of the radiological quantity at that particular point in time per unit initial PG application, is also the relevant TF as defined earlier, and the term bT is the projected PG-attributable value of the radiological characteristic. Thus, the equations for the PG-attributable value and the site-specific total value, respectively, can also be written:

$$y_{PG} = bT, \text{ and}$$
$$y = y_{BL} + y_{PG} = y_{BL} + bT.$$

For this assessment, TFs are expressed in terms of PG with the radionuclide composition used in this study: ^{226}Ra at 21.4 pCi g^{-1}, ^{210}Pb at 22.6 pCi g^{-1}, and ^{210}Po at 20.1 pCi g^{-1}. For PG with radionuclides at other concentrations, the linear transfer factors can be scaled linearly or the TF_A factors can be used.

As indicated in the earlier section, the various transfer factors would be expected to decrease with time as a result of PG-attributable radioactivity undergoing initial mobilization of a small, more mobile, fraction and/or undergoing a more gradual general relocation from the surface layer of the soil by weathering, cropping, and/or leaching. The field study did not provide enough information to derive a continuous environmental loss function. For some of the parameters, no overall trend with time following a single PG application was observed and thus only a single average value of TF is available. For others, the trend with time following the single PG application was approximated by a step function with a higher value for an initial period (1 to 3 years for the various cases) and a lower value for subsequent years. For these cases the results of the long-term practice can be simulated by applying the lower values for the cumulative results of the longer period of early years and the initial value for the results of the last 1, 2, or 3 years of PG treatment.

Projected Radiation and Radioactivity Levels

Projections for values of Rn flux and gamma radiation and of ^{226}Ra, ^{210}Pb, and ^{210}Po concentrations in groundwater and forages after 100 years of the PG-treatment practice are developed in Table 16. These values were projected using TFs selected from those determined in this study (from Table 13). While Table 13 presents values for both the Malabar and Myakka sites, a single value was selected for this assessment exercise. Where the Malabar and Myakka TF values were appreciably different, the higher of the two was used to provide a conservative (on the high side) estimate; where the values were similar, the average of the two was used as the best overall estimate. The sources of the respective TFs are indicated as annotations in the TF column of the table. As noted earlier in the Transfer Factor section of this report, the reported TFs fell in three quality categories and the quality categories of the TFs are also indicated in the TF column annotations. Factors based on statistically-significant effects, effect vs. treatment trends, and effect vs. treatment slopes (coded “SS”) are used where possible. In some cases more definitive data were not available and it was necessary to use “best estimate” (“BE”) TFs which were based on data where effects were suggested and slopes were positive but not significant at the P=0.10 level. In selected cases, where no effects could be discerned in the field study for treatments up to 20 Mg ha^{-1}, “upper limit” (“UL”) TFs were used.

The Rn flux projection was based on a single average TF with linear increase for the entire 100 years – the field data did not provide information on a change with time.

Gamma radiation levels were based on the observations at the Malabar site. In this case, two values of TF were used for the long-term projection, one for effects of each of the first 99 years and another for the first year following the 100^{th} application.

Radionuclide concentrations in runoff water were calculated using the two-step model. Because of the limited detection of ^{210}Pb and ^{210}Po shortly after PG application, it was necessary to use upper limit values for the effects of the initial 97 or 98 years of PG application for these radionuclides. Thus the projected concentrations are quite likely to be overestimates. For the groundwater, “high-side” conservatism resulted in projections based on data from a mixture of sites, collection depths; and one- or two-step time functions. For ^{226}Ra, the projection was based on a “best estimate” TF.

For the mature hay projections, the various TFs were based on either Myakka site data or average data and are a mixture of “significant”, “best estimate”, and “upper limit” values. The ^{226}Ra projection is based on a single average value, while the ^{210}Pb and ^{210}Po projections are based on two-step time functions. Regrowth forage projections were performed for the “basic” case (no retained surface deposition). An additional projection was made for the potential case of retained surface deposition in the last year of PG treatment. The potential retained surface deposition has a significant effect on the concentration for the first year following PG treatment; however, since the effect is only expressed for a single year, the potential increased concentrations for a 100-year long-term treatment practice are in the range of only 2.5 - 5%.

Table 16. PG-Attributable Radiological Values Related to Bahiagrass Pastures Treated with Central Florida PG Annually at 0.4 Mg ha^{-1} for 100 Years (Page 1 of 2).

Medium	Years of Treatment	Transfer Factor, TF per Mg ha^{-1} (Source* and Category†)	Level or Concentration	
			Annual Contribution	Cumulative for Period
Rn flux, pCi m^{-2} s^{-1}	100	0.0018 (Avg, SS)	0.00072	0.072
Gamma, μR h^{-1}	99	0.009 (Mal, SS)	0.0036	0.36
	1	0.013 (Mal, SS)	0.0052	<0.01
	100			0.36
Runoff Water, pCi L^{-1}				
^{226}Ra	97	0.0183 (Mal, SS)	0.00732	0.710
	3	0.0704 (My, SS)	0.02816	0.084
	100			0.794
^{210}Pb	97	0.0341 (Avg, UL)	0.01364	1.323
	3	0.0416 (My, SS)	0.01664	0.050
	100			1.373
^{210}Po	98	0.0099 (Avg, UL)	0.00396	0.388
	2	0.2350‡ (My, SS)	0.09400	0.188
	100			0.576
Groundwater, pCi L^{-1}				
^{226}Ra	100	0.0057 (Avg 45-cm, BE)	0.00228	0.228
^{210}Pb	100	0.0430 (Mal 45-cm, SS)	0.01720	1.720
^{210}Po	97	0.0095 (My 90-cm, SS)	0.0038	0.369
	3	0.0160 (Avg Mal 45-cm & My 90-cm, SS)	0.0064	0.019
	100			0.388
Mature Hay, pCi g^{-1}				
^{226}Ra	100	0.0084 (Avg; SS)	0.00336	0.336
^{210}Pb	98	0.0097 (My, UL)	0.00388	0.380
	2	0.0127 (My, SS)	0.00868	0.017
	100			0.398
^{210}Po	98	0.0026 (My, BE)	0.00104	0.102
	2	0.0142 (My, SS)	0.00568	0.011
	100			0.113

Continued on next page ...

Table 16. PG-Attributable Radiological Values Related to Bahiagrass Pastures Treated with Central Florida PG Annually at 0.4 Mg ha^{-1} for 100 Years (Page 2 of 2).

Medium	Years of Treatment	Transfer Factor, TF per Mg ha^{-1} (Source* and category†)	Level or Concentration	
			Annual Contribution	Cumulative for Period
Regrowth, pCi g^{-1}				
^{226}Ra				
"Basic"	100	0.0033 (Avg, SS)	0.00132	0.132
Potential "Added"	1	0.0105 (My, SS)	0.00420	+0.004
Total w/Surf. Dep.				0.136
^{210}Pb	98	0.0041 (My, BE)	0.00164	0.161
	2	0.0017 (My, BE)	0.00068	0.001
"Basic"	100			0.162
Potential "Added"	1	0.0112 (My, SS)	0.00448	+0.004
Total w/Surf. Dep.				0.166
^{210}Po	98	0.0031 (Avg, UL)	0.00124	0.121
"Basic"	2	0.0032 (My, BE)	0.00128	0.003
	100			0.124
Potential "Added"	1	0.0144 (My, SS)	0.00576	+0.006
Total w/Surf. Dep.				0.130

*TF Data Sources: Avg = Average of Malabar & Myakka; Mal = Malabar; My = Myakka.

†TF Quality Categories:

SS = "Statistically significant". From data having significant effects and effect vs. treatment level trends and regression slopes.

BE = "Best estimate". Based on data where effects were suggested and slopes were positive but not significant at the P = 0.10 level.

UL = "Upper Limit" (95% one-tailed upper confidence limit). From cases where no effect could be discerned and slopes had a large uncertainty or were negative.

‡Likely an overestimate. The initial ^{210}Po runoff value is based on a single collection at the Myakka site; the concentration vs. treatment level slope for this time period at the Malabar site value was 24 times lower and not statistically significant.

EVALUATION OF THE PROJECTED EFFECTS OF THE LONG-TERM APPLICATION OF PG TO BAHIAGRASS PASTURES

Several approaches can be used for evaluating the projection of future PG-use and human exposure scenarios; these include:

1. Comparison to background values Projected values of radiation levels, radionuclide concentrations, and radiation doses can be compared to preexisting baseline or background values and their local spatial variations. *A practice for which the attributable contribution to radiation levels, radioactivity concentrations, or radiation doses is no greater than the variation in relevant background for the particular vicinity is not of great consequence.*

2. Comparison to environmental radiation and radioactivity standards. In some cases there are existing standards against which projected environmental radiation or radioactivity levels can be compared. Examples include comparison of radioactivity concentrations in water to drinking water standards and comparison of indoor Rn concentrations to indoor Rn action levels.

3. Comparison to radiation dose limits. By applying exposure models (occupancy factors, dietary models, etc.) and dosimetry models (such as intake-to-dose conversions), projected environmental radiation and/or radioactivity levels can be converted to predicted radiation dose to humans. These projected radiation doses then can be compared to established radiation dose limits. The dose limit for members of the general public is 100 mrem y^{-1} above background for all exposure pathways combined. It is recommended that doses from a single practice or pathway not exceed some fraction of the dose limit.

4. Estimation of risk. Risk coefficients can be applied to projected radiation doses and/or radionuclide intakes to make prospective assessments of long-term exposure to radiation and radionuclides in the environment. Various projected exposure situations then can be compared on the basis of the calculated hypothetical risk.

Radionuclides in Soil

Table 15 compares PG-attributable radionuclide concentrations in surface soil layers to baseline values. The radioactivity contributed by a single treatment at agronomic rates cannot be detected for sampling layers of 5 cm or more--an application of 1 Mg ha^{-1} would result in radionuclide concentration increases on the order of only 0.05-0.06 pCi g^{-1} averaged over 5 cm. For a long-term practice involving 100 annual applications of 0.4 Mg ha^{-1} each to soil with the Research Center baseline values on the order of 0.5 to 1.0 pCi g^{-1}, concentration increases would be 300 to 500% in the upper 5 cm if all the cumulative added radioactivity were retained in that layer. Concentrations averaged over a 15 cm (6-in, root zone) top layer would be increased by 65 to 100%. Concentrations of ^{226}Ra averaged over a 61 cm (24-in, Rn modeling layer) would be increased by about 20%, a value that is considerable less than the typical variations in soil ^{226}Ra concentrations in nonenhanced Florida soils.

The real significance of radioactivity added to the soil is in the effect on radiation exposures via various potential pathways: indoor exposure to Rn originating from ^{226}Ra added to the soil, exposure to gamma radiation from radionuclides added to the soil, ingestion of radioactivity transferred from the soil to water, and ingestion of radionuclides transferred to forage (and subsequently to animals and human food products).

Rn Flux and Indoor Rn

Potential Rn production is evaluated in Table 17. The projected PG-attributable Rn flux contribution of 0.072 pCi m^{-2} s^{-1} represents an addition of about 288% to the baseline value (an increase to 388%) for the low-background Ona Research Center. Compared to a broader base, this increment is about 35% of the statewide average for undisturbed nonmineralized lands in Florida and well within the range of variations seen in the state.

In this assessment, Rn flux is used as an indicator of the potential source term for indoor Rn. Using empirical models of the relationship of indoor Rn to Rn flux (Appendix B and Worksheet B-5), the projected PG-attributable additions to the indoor Rn concentrations in structures built directly over the treated land without any special Rn-resistant features were in the range of 0.02 to 0.5 pCi L^{-1} with a geometric mean value of 0.11 pCi L^{-1}. The total concentration on the order of 1.1 to 2.1 pCi L^{-1} is about 110% of the average Florida indoor Rn value of 1-2 pCi L^{-1} This resulting concentration would be on the order of 28 to 53% of the EPA Action Level of 4 pCi L^{-1} (total indoor Rn). This increment is small relative to the variations in levels normally seen among Florida houses.

The calculated PG-attributable contribution represents an increased effective dose of 7.2 mrem y^{-1}. This value is in keeping with recommendations that doses to the general public not exceed some fraction of 100 mrem y^{-1} above background. Calculated risks from the PG-attributable Rn, using the stated risk factor, are estimated to be on the order of 5.4×10^{-6} from one year of exposure and on the order of 4.0×10^{-4} for a lifetime (75.2 years) exposure.

External Gamma Radiation

The evaluation of projected external gamma radiation is summarized also in Table 17. The projected PG-attributable gamma radiation contribution of 0.4 µR h^{-1} represents an addition of about 6% to the baseline value for the research site. The added increment represents <2 % of the Florida Department of Health 20 µR h^{-1} standard for indoor radiation; and when added to the typical background of 5.7 µR h^{-1}, gives a total external radiation exposure rate (6.1 µR h^{-1}) that is about 30% of that standard.

Assuming a 100% occupancy over the treated lands (either indoors or outdoors), assuming no attenuation of the indoor radiation field by the building floor (i.e., assuming a wood floor rather than a concrete slab), and using the exposure to dose conversion stated in the table, the calculated PG-attributable contribution represents an increased effective dose of 3.2 mrem y^{-1}. This value is in keeping with recommendations that doses to the general public should not exceed some fraction of 100 mrem y^{-1} above background.

Table 17. Radiological Impact of 100 Years of PG Application at 0.4 Mg ha^{-1} to Florida Land–Rn Flux, Indoor Rn, and Gamma Radiation.

	Rn Flux	Indoor Rn	Gamma
ENVIRONMENTAL LEVELS	---- pCi m^{-2} s^{-1} ---	---- pCi L^{-1} ----	---- µR h^{-1} ----
Predicted PG-attributable	0.072	0.11	0.36
Research Center baseline	0.025 (0.007)	- -	5.7 (0.5)
Predicted local total	0.097	- -	6.1
(Ratio to local baseline)	*(3.88)*	- -	*(1.06)*
Standard (for total Rn or gamma)	NA	4	20
(Predicted local total/standard)	NA	- -	*(0.30)*
Predicted PG-attributable	0.072	0.11	- -
Florida Avg baseline	0.2 (<0.1 to 1.7)*	1-2	- -
Predicted FL avg. total	0.27	1.1- 2.1	- -
(Ratio to FL Avg baseline)	*(1.35)*	*(1.1)*	- -
(Ratio to standard)	NA	*(0.28-0.53)*	- -
DOSE & RISK (PG-ATTRIBUTABLE)			
Dose factor, mrem y^{-1} per unit	NA	*65*	*8.77*
Effective dose, mrem y^{-1}	NA	7.2	3.2
Risk factor	NA	*4.9×10^{-5}*	*5.75×10^{-7}*
(Risk factor units)	NA	*(per pCi-y L^{-1})*	*(per mrem)*
Risk from 1-year exposure	NA	5.4×10^{-6}	1.8×10^{-6}
Risk from lifetime exposure#	NA	4.0×10^{-4}	1.4×10^{-4}

Notes:

Predicted values: Rn flux and gamma from Table 16; Indoor Rn from Worksheet B-5.

Baseline values: Rn flux and gamma local values from Worksheet B-2.

*FL Rn flux baseline values for undisturbed nonmineralized lands (Roessler and others 1980).

NA = Not Applicable.

Standards: Indoor Rn: EPA Guideline, 4 pCi L^{-1} (total); Gamma Radiation: Florida Dept. of Health, Radiation Standards for Buildings, 64E-5.1001(2), FAC, 20 µR h^{-1}, including bkg.

Dose factors:

- Rn assumes 0.4 Progeny/Rn equilibrium factor and 7000 h y^{-1} occupancy; dose factor derived from ICRP Publication 65 (1993) .
- Gamma assumes 100% occupancy (8766 h y^{-1}) over PG-treated land (indoor and/or outdoor); no attenuation by building floors; 1 R exposure results in 1 rem effective dose.

Risk factors: Mortality factors, age-averaged, combined genders.

- Factor for Rn derived from ICRP Publication 65 (1993).
- Factor for gamma from Federal Guidance Report 13 (Interim) (EPA 1998).
- #Lifetime exposure taken as 75.2 years (From FGR #13, EPA 1998).

Calculated risks from the PG-attributable gamma radiation, using the stated risk factor, are estimated to be on the order of 1.8×10^{-6} from one year of exposure and on the order of 1.4×10^{-4} for a lifetime exposure.

Surface Water and Groundwater

The evaluation of the projected effect on surface water and groundwater is presented in Table 18. Concentrations were taken from Table 16, but assessment was done for a single nonspecified water type. Following the practice of high-side conservatism, values for run-off were used for ^{226}Ra and ^{210}Po while the groundwater value was used for ^{210}Pb.

PG-attributable contributions to radionuclide concentrations were projected to be 0.79, 1.72, and 0.58 pCi L^{-1} for ^{226}Ra, ^{210}Pb, and ^{210}Po, respectively. These concentration increments represent additions of about 2.6, 2.9, and 1.1 times the baseline for the research site; added to the typical baseline concentrations this would result in total concentrations that are about 3.6, 3.9, and 2.1 times the baseline.

The concentrations can be compared to the Maximum Contaminant Levels (MCLs) for drinking water (Federal Register 1976). The ^{226}Ra concentration was compared to the 5 pCi L^{-1} limit for ^{226}Ra and ^{228}Ra combined. Currently there is no drinking water standard for ^{210}Pb (a naturally-occurring beta emitter); however, consideration is being given to applying 4 mrem y^{-1} as a dose criterion for any beta-emitting radionuclide in water. For a reference adult person consuming 1.11 L d^{-1}, this dose limit corresponds to a ^{210}Pb concentration in drinking water of about 4 pCi L^{-1} and that value was used as an "inferred" standard for comparison. There is presently no explicit standard for ^{210}Po in drinking water but the limit for gross alpha activity (excluding U, ^{226}Ra ^{222}Rn) is 15 pCi L^{-1} and that value was used for comparison.

The projected PG-attributable additions to water are 16%, 43 and 4 of the explicit or inferred drinking water standards for the respective radionuclides and when added to the baseline values would result in concentrations that are about 22%, 58%, and 7% of the respective explicit or inferred standards.

The assessment of ingestion intake and radiation dose was limited to drinking water for humans. The pathways to humans involving ingestion of crops irrigated with the water in question or involving consumption of animal products from animals drinking the water in question or being fed crops from irrigated lands were not considered to be of sufficient importance to be included in this assessment.

If this water is used as the exclusive drinking water source for humans, the three radionuclides in combination represent a PG-attributable increased effective dose of 3.1 mrem y^{-1}. This value is in keeping with recommendations that doses to the general public should not exceed some fraction of 100 mrem y^{-1} above background. Under the same usage assumptions, the PG-attributable risks were calculated to be 8.1×10^{-7} for one year of consumption and on the order of 6.2×10^{-5} from a lifetime (75.2 years) usage. The dose and the risk calculated for the water pathway are dominated by ^{210}Pb.

Table 18. Radiological Impact of 100 Years of PG Application at 0.4 Mg ha^{-1} to Florida Land Cropped to Bahiagrass – Radionuclides in Water.

	^{226}Ra	^{210}Pb	^{210}Po	Combined
ENVIRONMENTAL LEVELS, pCi L^{-1}				
Predicted PG-attributable	0.79 RO	1.72 GW	0.58 RO	NA
Research Center baseline	0.30 RO	0.59 GW	0.53 RO	NA
Predicted total	1.09	2.31	1.10	NA
(Ratio to baseline)	*(3.6)*	*(3.9)*	*(2.1)*	NA
Standard	5	(4 inf)	(15 GA)	NA
(Predicted total/standard)	*(0.22)*	*(0.58)*	*(0.07)*	NA
INTAKE, DOSE, RISK (PG-ATTRIBUTABLE)				
Ingested, pCi y^{-1}	320	697	195	NA
Dose factor, mrem pCi^{-1}	*1.04 x 10^{-3}*	*2.55 x 10^{-3}*	*4.44 x 10^{-3}*	NA
Effective dose, mrem y^{-1}	0.33	1.78	1.03	3.1
Risk factor, per pCi inges.	*1.97 x 10^{-10}*	*6.48 x 10^{-10}*	*13.1 x 10^{-10}*	*NA*
Risk: From 1-year expos.	6.3 x 10^{-8}	4.5 x 10-7	3.0 x 10^{-7}	8.1 x 10^{-7}
Risk from lifetime expos.*	4.7 x 10^{-6}	3.4 x 10^{-5}	2.3 x 10^{-5}	6.2 x 10^{-5}

Notes:

- Predicted values from Table 16; baseline values from Appendix B, Worksheet B-3.
- Coding for data source for baseline and predicted values:
  RO = runoff data; GW = shallow groundwater data (wells).
- Standards = Drinking Water Standards (Federal Register 1976):
  ^{226}Ra: Standard for ^{226}Ra + ^{228}Ra in combination is 5 pCi L^{-1}.
  ^{210}Pb: Inf = Inferred; no explicit standard for ^{210}Pb; 4 pCi L^{-1} derived from 4 mrem y^{-1} dose limit for beta emitters and ^{210}Pb ingestion dose factor.
  ^{210}Po: GA = Gross Alpha; no explicit limit for ^{210}Po; limit for gross alpha emitters (excluding U, ^{226}Ra, and ^{222}Rn) is 15 pCi L^{-1}.
- Intake based on 1.11 L d^{-1} (405 L y^{-1}).
- Dose factors are for adult member of the public; derived from ICRP Publication 72 (1996). Effective dose is committed effective dose from 1 y intake.
- Risk factors are age-averaged, combined gender mortality factors for ingestion of water; from Federal Guidance Report 13 (Interim) (EPA 1998).
- NA = Not Applicable.
- *Lifetime exposure taken as 75.2 years (From FGR #13, EPA 1998).

Forage and the Forage-Beef-Human Pathway

The evaluation of the projected effect on forage and on the forage-beef-human pathway is summarized in Table 19. Projections of radionuclide concentrations in forage were made using factors for the type of forage giving the larger concentration value--mature hay for ^{226}Ra and ^{210}Pb, and regrowth with surface deposition for ^{210}Po.

PG-attributable contributions to radionuclide concentrations in forage following the 100 years of PG treatment were projected to be 0.34, 0.40, and 0.13 pCi g^{-1} for ^{226}Ra, ^{210}Pb, and ^{210}Po, respectively. These concentration increments represent 5.7, 0.4, and 0.5 times the respective baseline values for the research site; total concentrations (PG-attributable plus baseline) would be expected to be 670%, 140%, and 150% of those for untreated lands.

The principal significance of the forage is how the radionuclide content might be reflected in beef tissue, intake by humans, and resulting radiation dose and risk to humans. See Appendix B and Worksheets B-6 and B-7 for further explanation of the model and factors and Transfer Coefficients used to project PG-attributable radionuclide levels in beef tissue. Assuming forages from the PG-treated lands are the exclusive feed source, PG-attributable contributions to radionuclide concentrations in beef tissue were projected to be 3.4, 3.2, and 6.5 pCi kg^{-1} for ^{226}Ra, ^{210}Pb, and ^{210}Po, respectively.

Assuming individuals consume 50 kg y^{-1} of this beef, the projected annual radionuclide intakes from this source are about 170, 160, and 320 pCi y^{-1} for the three radionuclides, respectively (see Appendix B and Worksheet B-8 for further development of the intake by humans.) The annual effective doses from this intake are 0.2, 0.4, and 1.4 mrem y^{-1}, respectively, or a combined dose of 2.0 mrem y^{-1}. This value is a small fraction of 100 mrem y^{-1} above background.

Under the same assumptions of intake, the PG-attributable risks from the three radionuclides in combination were calculated to be 7.1×10^{-7} for one year of beef consumption and on the order of 5.4×10^{-5} for lifetime exposure (75.2 years).

While ^{226}Ra was the major player in radioactivity uptake by forages, ^{210}Pb and ^{210}Po made greater contributions to projected dose and calculated risk under the assumptions used.

Summary of Doses and Risks

Projected radiation doses and calculated risks are summarized in Table 20 for four pathways: inhalation exposure to indoor Rn originating in the treated soil, external irradiation by gamma radiation from radionuclides in the treated soil, ingestion of drinking water containing radionuclides attributable to the soil treatment, and ingestion of beef fed with forages grown on the treated land. The major contributor in this analysis is indoor Rn.

Table 19. Radiological Impact of 100 Years of PG Application at 0.4 Mg ha^{-1} to Florida Land Cropped to Bahiagrass – Forages and Beef.

	^{226}Ra	^{210}Pb	^{210}Po	Combined
FORAGES, pCi g^{-1}				
Predicted PG-Attributable	0.34 M	0.40 M	0.13 R,SD	NA
Research Center baseline	0.06 M	1.12 M	0.26 R	NA
Predicted total	0.40	1.52	0.39	NA
(Ratio to baseline)	*(6.7)*	*(1.4)*	*(1.5)*	NA
BEEF (PG-ATTRIBUT.)				
Radionuc. Intake, pCi d^{-1}	3,360	3,980	1,300	NA
Transfer Coefficient, d kg^{-1}	*1×10^{-3}*	*8×10^{-4}*	*5×10^{-3}*	NA
Conc. In tissue, pCi kg^{-1}	3.4	3.2	6.5	NA
INTAKE, DOSE, RISK (PG-ATTRIBUTABLE)				
Ingested, pCi y^{-1}	168	159	325	NA
Dose factor, mrem pCi^{-1}	*1.03×10^{-3}*	*2.55×10^{-3}*	*4.44* $\times 10^{-3}$	NA
Effective dose, mrem y^{-1}	0.17	0.41	1.44	2.0
Risk factor, per pCi ingested	*2.64×10^{-10}*	*8.55×10^{-10}*	*16.4×10^{-10}*	NA
Risk: From 1-year exposure	4.4×10^{-8}	1.4×10^{-7}	5.3×10^{-7}	7.1×10^{-7}
From lifetime exposure*	3.3×10^{-6}	1.0×10^{-5}	4.0×10^{-5}	5.4×10^{-5}

Notes:

- Predicted values in forage from Table 16.
- Baseline values from Appendix B, Worksheet B-3.
- Coding for forage baseline and predicted values:
  M = Mature hay; R,SD = Regrowth forage with surface deposition in latest year.
- Radionuclide intake by beef animals based on forage consumption of 10 kg d^{-1} dry matter (see Appendix B, Worksheet B-6).
- Feed to beef tissue Transfer Coefficient from Appendix B, Worksheet B-7.
- Radionuclide intake by humans based on beef consumption of 50 kg y^{-1} (see Appendix B and Worksheet B-8).
- Dose factors are for adult member of the public; derived from ICRP Publication 72 (1996).
- Risk factors are age-averaged, combined gender mortality factors for ingestion of food; from Federal Guidance Report 13 (Interim) (EPA 1998).
- NA = Not Applicable.
- *Lifetime exposure taken as 75.2 years; from FGR #13 (EPA 1998).

Table 20. Radiological Impact of 100 Years of PG Application at 0.4 Mg ha^{-1} to Florida Land Cropped to Bahiagrass – Summary for All Pathways.

Pathway	PG-Attributable Effective Dose mrem y^{-1} (%)	PG-Attributable Risk		
		1-year Exposure	Lifetime Exposure	(%)
Soil - Indoor Rn (Inhalation)	7.2 (46.5%)	5.4×10^{-6}	4.0×10^{-4}	(61.0%)
Gamma (External)	3.2 (20.6%)	1.8×10^{-6}	1.4×10^{-4}	(21.3%)
Water (Ingestion)	3.1 (20.0%)	0.81×10^{-6}	0.62×10^{-4}	(9.5%)
Forage-Beef (Ingestion)	2.0 (12.9%)	0.71×10^{-6}	0.54×10^{-4}	(8.2%)
Total	15.5 (100.0%)	8.7×10^{-6}	6.6×10^{-4}	(100.0%)

Note: See Tables 17, 18, and 19 for development of the doses and risks.

The doses and risks calculated here for the PG to grass to beef to human pathway are low; the treatment of grassland with PG and the consumption of beef grazing or consuming hay from these lands does not present a radiological health concern for humans. Thus the effect on radionuclides in forage is not a major concern in the application of PG to forage land. Furthermore, this method overestimated intakes, doses, and risks because of the several assumptions, i.e., that all feed was derived from the PG-treated grasslands, that grass-fed animals would go directly to slaughter without being fed out on grain and concentrate, and that beef from this type of animal would constitute a high percentage of the consumers' diets.

The maximum exposed individual would be one who lives in a house built over land formerly treated with PG, who works at home or nearby over the PG-treated land, whose principal drinking water supply is a pond or shallow well impacted by the treated land and whose major source of meat is beef fed exclusively from the treated land. For this individual, the combined PG-attributable annual effective dose from all the listed pathways is estimated to be about 16 mrem y^{-1}. This value is in keeping with recommendations that doses to the general public should not exceed some fraction of 100 mrem y^{-1} above background. The risks to this individual from the combined PG-attributable radiation exposure pathways are estimated to be on the order of 8.7×10^{-6} from one year of exposure and on the order of 6.6×10^{-4} for a lifetime exposure (75.2 years).

UNCERTAINTIES IN THE ASSESSMENT

A complete quantitative uncertainty analysis will not be attempted for this report; the presentation here will be largely qualitative. Uncertainties in the dose and risk assessment may be grouped in three categories according to the source of the information:

1. Arising from the field measurements and their interpretation, including those related to input data, measured transfer factors, and model parameters;
2. Associated with values taken from the literature and thus beyond the control of the investigators, including those related to non-measured transfer coefficients, dose factors, and risk factors; and
3. Related to the assumptions chosen for the assessment scenario.

Four human exposure pathways were considered in the assessment: indoor Rn, gamma radiation, water, and forage-beef. This section will address each in turn.

An uncertainty common to all the pathways is introduced by the treatment of the time trend over 100 years. It is expected that the radioactivity applied to the surface will gradually be relocated through weathering, cropping, and/or leaching and that the various radiological parameters related to near-surface radioactivity concentrations will undergo a change with time. Environmental behavior is often described with a continuous function, typically one or more exponentials with a characteristic environmental half life (or half lives). However, this field study did not provide enough information to derive a continuous environmental loss function. For some parameters (Rn flux, ^{226}Ra and ^{210}Pb in groundwater, and ^{226}Ra in forage), no discernible overall loss was observed during the course of the study; and these were described with a constant relationship (single TF for the entire 100 years). For the other parameters (gamma radiation and the other water and forage radionuclides), the trend with time following a single PG application was approximated by a two-step function with a higher value for Step 1 (an initial period of 1, 2, or 3 years) and a lower value for Step 2 (subsequent years). For these cases, the results of the 100-year practice was simulated by applying the higher, Step 1 TF value to calculate the contribution from the last 1, 2, or 3 years of PG treatment and the lower, Step 2 TF value for calculating the contribution of PG treatment during each of the earlier years. The use of the single, initial TF for the entire 100 years is likely to overestimate the effect. Where the two-step function is applied, the use of the Step 2 TF (derived during the 5-year study) to project values expected up to 90 years after PG application is also likely to overestimate the effect due to early years of PG application. For the cases in this assessment, the long-term Step 2 typically contributes 90% or more of the concentration in the 100th year. This overestimation effect is further exaggerated if the Step 2 TF is an "upper limit" value.

Another source of uncertainty relates to the strength of the experimentally-determined TFs used to project the future radiation or radioactivity levels in the assessment (refer to earlier section on TFs). TFs were considered to be significant if they were based on data showing significant effects and significant positive slopes for effect vs. treatment level. This condition was not always satisfied. In cases where the data suggested an effect and slopes were positive but not statistically significant, "best estimate" TFs were calculated (and coded BE). In still other cases, no effect could be discerned and effect vs. treatment level slopes had a large uncertainty, or even were negative. In these cases, an upper confidence limit (coded UL) was presented for use in the absence of other data. Radiation and radioactivity levels projected with BE TFs, and associated derived doses, will have a higher degree of uncertainty. Those calculated with UL TFs will also have a higher uncertainty and are likely to be biased high.

Dose and risk factors were taken from the literature. These have uncertainties that are beyond the control of the investigators. It is interesting to note that the effective dose and the risk calculations in Table 20 are generally consistent except for the relative contribution of water ingestion which contributed 27% of the calculated effective dose and only 10% of the calculated risk. Both sets of calculations were based on the same projected radionuclide intakes. Both the effective dose factors, derived from ICRP Publication 72 (1996), and the risk factors, taken from Federal Guidance Report 13 (FGR #13) as prepared by EPA (1998), are based on ICRP methodology for calculating doses to various individual tissues. The ICRP effective dose factors employ the ICRP risk-based tissue weighting factors to generate an overall risk-weighted dose (the effective dose). The EPA risk factors involve conversion of individual tissue doses to cancer risk by an EPA methodology. The Table 20 differences in the relative contribution of a pathway to effective dose vs. relative contribution to overall risk are presumably due to differences in the way the two literature sources relate risk to tissue dose.

The Indoor Rn Inhalation Pathway

Evaluating the potential indoor Rn exposure pathway involved 1) using the measured Rn flux TF to project future Rn flux as an indication of the increased soil Rn source and then 2) estimating indoor Rn increase from the projected Rn flux increase.

Rn Flux. Since at the present time there are no standardized Rn flux sources, no on-going Rn flux measurement intercomparison programs, and no validated reference method for Rn flux measurement, the absolute value for the Rn flux and the resulting TF have an undetermined uncertainty. The number of replicate plots used for the Rn flux measurements was adequate to provide confidence in the relative comparison of different treatment levels and the use of four measurement campaigns per year served to average out the annual seasonal cyclic effect. The intercomparison experiment, described in Appendix C, indicates an uncertainty in the absolute value reported for any measurement campaign; this was tentatively attributed to batch-to-batch variations in charcoal efficiency. This suggests an uncertainty in the initial Rn flux transfer factor of no more than a factor of two.

The calculated initial TFs were quite similar for the two sites: 0.0017 and 0.0019 pCi m^{-2} s^{-1} per Mg ha^{-1} for the Malabar site and the Myakka site, respectively. Thus, the use of the average value of 0.0018 pCi m^{-2} s^{-1} per Mg ha^{-1} for the assessment did not introduce much uncertainty. Because the field data did not provide information on an overall time trend for Rn flux, the future Rn flux projection was based on a single average TF with linear increase for the entire 100 years. This probably resulted in an overestimate of the Rn flux after 100 years of PG treatment practice.

Indoor Rn. Future indoor Rn concentrations were predicted using simple empirical models. Prediction of indoor Rn is characterized by considerable uncertainty, even when highly-developed models are used. Predictions represent the best estimates of the average of a number of similar cases; individual cases may vary several-fold from the projected average case. Several empirical models were used to predict indoor Rn concentration; these produced estimates ranging from 0.02 to 0.5 pCi L^{-1} (Appendix B, Worksheet B-5). This suggests that the geometric mean value of 0.11 pCi L^{-1} used for the assessment had an uncertainty of less than an order of magnitude.

It is estimated that the overall uncertainty in the estimate of radiation dose and risk from the indoor Rn inhalation pathway is less than an order of magnitude.

The Gamma Radiation External Irradiation Pathway

For the first year after PG treatment, the gamma exposure rate TFs were based on statistically significant treatment effects and the two sites had comparable values. Thus the contribution to future gamma exposure rate from PG applied in the 100th year had a low uncertainty. The contributions from the increments of PG applied during the first 99 years were calculated from a single constant TF based on the pooled Year-2 through Year-4 observations for the Malabar site (the treatment effects for the Myakka site were not statistically significant). This selective use of the factor from the Malabar site observations without any time trend effect over 99 years most likely results in an overestimate for this time period. Since this represents virtually 100% of the effect at 100 years, the total gamma exposure rate contribution at 100 years is likely to be overestimated.

Annual gamma radiation dose was calculated assuming no attenuation of the indoor radiation field by the building floor. This is realistic for houses with wood floors but provides an overestimate for persons occupying houses with concrete slab floors.

Because of the likely overestimate of the exposure rate, the radiation dose and risk from the external gamma radiation exposure pathway are likely to be overestimated.

The Drinking Water Ingestion Pathway

"High-side" conservatism was used liberally for projecting future radionuclide concentrations in drinking water and thus concentrations are likely to be overestimates.

The concentration for ^{226}Ra in drinking water was based on the projected value for runoff, which was a factor of 3 to 4 times the projected value for shallow groundwater. Runoff was modeled by a two-step (3-year, 97-year) function. The contribution for the three proximate years was calculated using the Myakka site TF which was about four times the Malabar site TF (BE). The contribution for the earlier 97 years was based on the Malabar site TF which was about three times the Myakka site TF (BE).

Uncertainty is introduced by the fact that the runoff TFs are based on a limited number of samplings – no runoff was collected the first year at the Myakka site, and the TFs for the two time steps were based on only two collections each. The selective choice of TFs probably introduced a high-side bias. The portion attributable to the 97-year time step (about 90% of the total projected concentrations) is likely to be an overestimate since it was calculated using a single TF for this entire time step.

The concentration for ^{210}Pb in drinking water was based on the projected value for groundwater, which was calculated from a single-step TF derived from the Malabar site 45-cm well data. This TF was a factor of 2 to 3 times the TFs for the 90-cm well and the two Myakka site wells (all BE or UL values). The use of a single factor for the entire 100-year period and the selective choice of TFs are likely to produce an overestimate.

The projected concentration of ^{210}Po in drinking water has a high degree of uncertainty, but is likely to be an overestimate. It was based on the projected value for runoff, which was about 1.5 times the shallow groundwater value. Runoff was modeled by a two-step (2-y, 98-y) function. The contribution for the two proximate years was calculated using the Myakka-site TF which was based on a single collection and was about 24 times the Malabar site TF (BE). The contribution for the earlier 98 years (about 67% of the calculated total concentration) was calculated from a TF based on the average of fairly comparable (11% differences from the mean) UL values for the two sites.

A variety of different usage rates for drinking water appear in the literature. The value of 1.11 L d^{-1} used in this assessment is the combined-gender, lifetime-average value presented in Table 3.1 of Federal Guidance Report No. 13 (EPA 1998) and thus has the uncertainties associated with gender differences and age differences.

Due to the limitations of the field study database supporting the TFs, there is a great deal of uncertainty in the projected radionuclide concentrations in drinking water. However, because of the selection of factors that tend to overestimate concentrations, it is not likely that the dose and risk were underestimated.

The Forage-Beef-Human Diet Ingestion Pathway

Evaluating the potential consequences of radionuclide uptake by forages involved (1) using the measured forage TFs to project future radionuclides in forages, (2) using factors to project radionuclide levels in beef tissue, and (3) using an assumed usage factor for this type of beef to estimate radionuclide intake from this source by humans.

Radionuclides in Forage. The concentration of ^{226}Ra in future forage was projected from a single TF for mature hay. This factor should be relatively precise as the TF was taken as the average of the two sites whose individual values varied about ± 11% from the mean value. Since the mature hay TF was about 2.5 times that for regrowth forage; this should be an overestimate if the animals obtained the forage exclusively by grazing.

The concentration of ^{210}Pb was modeled for the assessment using mature hay TFs and a two-step (2-year, 98-year) function. The two-year component was based on the Myakka site TF and the 98-year component was based on the Myakka site TF (UL). The 98-year component represented 96% of the calculated activity. Projections should be on the high side – the projection for mature hay is about 2.5 times that for regrowth forage, the selected Myakka site Step 1 TF (applied to two years) was about 3.7 times the Malabar site value, and the selected Myakka site Step 2 TF (UL) (applied to 98 years) was 2.8 times the comparable Malabar site TF and, of necessity, a UL rather than a mean value.

The concentration of ^{210}Po was modeled for the assessment using regrowth forage TFs and a two-step (2-year, 98-year) function. There is considerable uncertainty in the estimated concentration and the values are likely to be on the high side. Only BE TFs were available for the two-year component; the two-year projection was based on the Myakka site TF which was about eight times the Malabar site TF; and the 98-year component (representing 90+% of the calculated radioactivity) was based on the two-site average UL TF.

Whether or not the surface retention can be expected for regrowth forage in first year is another uncertainty. This is probably not significant for ^{226}Ra because of the persistent influence of other years on the concentration after the long-term practice. For the other radionuclides, it only had an effect of a few percent for the modeling performed here. It would represent a greater proportion of the total activity if lower concentrations are attributed to the long-term components.

Linear response models were used to relate the radionuclide concentrations in forage to PG addition to the soil. Other studies indicate that the response of plants to the concentrations of uranium-series radionuclides in the soil may actually be sublinear. If such is the case, the approach used here underestimated the radionuclide content in forages due to a single year's application and overestimated the content due to the long-term cumulative application. However, the use of linear equations based on single applications of 0 to 20 Mg PG ha^{-1} probably does not greatly overestimate the concentrations resulting from a cumulative total of 40 Mg PG ha^{-1} applied in annual increments over a period of 100 years.

Radionuclides in Beef Tissue. Concentrations of radionuclides in beef tissue were predicted from the projected concentrations in forage using radionuclide transfer coefficients from the literature and making assumptions about the beef feeding practice and the animals' feed intake. Feed to tissue transfer coefficients were taken from the most recent literature source available (NCRP 1999). However, values from various literature sources can vary by approximately a factor of two (See Appendix B, Worksheet B-4). The assessment assumed a feed intake of 10 kg d^{-1}. Based on conversations with a University of Florida animal scientist (Appendix B, Worksheet B-3), this should be a reasonable mean value for this type of animal. However, feed intake will vary with breed, size of animal, and individual animal differences. Values reported in the literature range from about 0.5 to 1.5 times this value. It was assumed that the sole feed source up to the time of slaughter was forage from PG-treated lands. This probably results in an overestimate of radionuclide levels in beef. A more likely scenario is for the animals to be taken off the range and shipped to a feed lot for finishing on grain and concentrate, If the radionuclide concentrations in the feed are lower than in the forage from the PG-treated lands, it is likely that the radionuclide concentrations in the beef tissue would be lower at the time of slaughter than when taken off the pasture. Even in the special case of the “backyard animal”, it is still likely that the animal would be fed some grain and concentrate to improve the quality of the meat.

Beef Consumption by Humans. Usage values presented in the literature vary in the total meat intake, how the meat is categorized, and the assignments to the various categories (See Appendix B, worksheet B-8). For this assessment it was assumed that an individual consumes 50 kg y^{-1} of beef from this source. This is 50% of the 100 kg y^{-1} generic meat value (type not specified) suggested by NCRP for screening purposes, 79% of the EPA Office of Radiation Programs total meat value of 63 kg y^{-1}, and 156% of the EPA beef value (Appendix B, worksheet B-8). The 50 kg y^{-1} represents the critical individuals who get most of their meat from the “back yard” beef animal. It is an overestimate for the individuals who use the “back yard” animal but have a more varied meat diet, and an extreme overestimate for most members of the public who consume a variety of meats all obtained from markets stocking meats from a variety of sources.

Uncertainties Related to the PG Application Scenario

Radionuclide Concentrations. This assessment was based on radionuclide concentrations for the PG used in the field study: 21.4, 22.6, and 20.1 pCi g^{-1} for ^{226}Ra, ^{210}Pb and ^{210}Po, respectively. However, radionuclide concentrations vary with PG source. For example, the mean ^{226}Ra concentrations for five Central Florida phosphogypsum stacks were reported to range from 25 to 34 pCi g^{-1} with a five-stack average of 31 pCi g^{-1} (EPA 1992). Most projected radiological values should scale linearly with radionuclide concentrations in the PG used. For example, Rn flux values for 31 pCi g^{-1} PG should be 45% higher than projected here for 21.4 pCi g^{-1} PG.

PG Use Practice. This assessment assumed that PG would be applied to the surface of pasture lands at the annual rate of 0.4 Mg ha^{-1} for 100 years following which the land would be converted to alternative uses. Since there is no history of PG treatment of forage lands, it is unknown what combinations of rates and frequencies might evolve as preferred practice over the years. Furthermore, the question of whether it is likely that the same parcel of land would continue to be treated with PG for as long as 100 years has not been addressed – the impacts would be less if the land were treated for a shorter period of time or if the application rate were reduced in response to the buildup of applied PG.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS FROM THE FIELD STUDY

These conclusions are based on the cumulative observations for 5+ years (1993-1998) following the May-June 1993 surface application of PG to established bahiagrass pastures at a non-spodic soil (Malabar) site and a spodic soil (Myakka) site. Observations were conducted throughout the 5+ years except that gamma radiation and airborne Rn measurements were terminated after the fourth post-treatment year (during 1997) and forage samples were collected for the first and second (1993 and 1994) and fourth through sixth (1996-1998) post-treatment growing seasons.

Radionuclides in Soil

- The natural radioactivity of this soil is low. Average baseline ^{226}Ra concentrations are ≤0.5 pCi g^{-1} from the surface down to a 1-m depth; average baseline ^{210}Pb and ^{210}Po concentrations are on the order of 1 pCi g^{-1} for the surface (0-5 cm) layer and generally ≤0.5 between 5 and 100 cm from the surface.
- The effect of PG application was seen in the surface (0-5 cm) layer for all three radionuclides throughout the study at both sites.
- No overall time trends for concentrations in the surface layer could be seen for these soils in the first 5 years after PG application.
- Although the analyses were not sensitive enough to directly detect losses from the surface layer or estimate a rate of loss, there was developing evidence for the appearance of these radionuclides in the second (5-10 cm) layer.
- There were no indications of significant transport of these radionuclides to layers deeper than 10 cm over the five years of study.

Soil Surface Rn Flux

- PG application was clearly reflected in elevated soil surface Rn flux values at both sites.
- Rn flux values from these sites followed a general cyclic pattern with peaks in the winter (October - February time window) and valleys in the spring and summer (March - September time window).

  Comment: A mid-summer peak was superimposed on this pattern in June 1997, but not repeated in June 1998.
- Variations in addition to the annual cyclic pattern may occur, but it is not known whether the mid-summer 1997 observation was a more frequent occurrence missed in previous years because of the spacing of sampling schedules (*not likely*), a random event, or representation of variations of a longer-than-annual period.

- The environmental loss rate for PG-attributable Rn flux following application of PG to Florida lands cropped to bahiagrass is slow relative to the approximately five years of observations and cannot be estimated from the data collected to date. *(Time-trend analysis did not indicate any unidirectional trend with time.)*

Gamma Radiation

- Following the application of PG to the ground surface at rates up to 20 Mg ha^{-1}, barely-detectable increases in gamma radiation levels at 1 m above the surface were observed during the first post-treatment year.
- In the subsequent three years *(measurements were terminated after the fourth year)*, the effects were less--the overall average values for treated plots were higher than for control plots but the differences were significant for only some of the various measurement campaigns.
- The differences between the first and subsequent years are probably due to weathering of the PG with time, removal of the applied radionuclides with forage harvests, and/or penetration of the radionuclides into the upper layer of the soil.

Radionuclides in Groundwater

Comment. It is difficult to draw conclusions about the effect of the application of PG to the ground surface on radionuclides in groundwater because application at levels up to 20 Mg ha^{-1} did not have a consistent measurable effect over the five post-treatment years – results were highly variable for the various depths, radionuclides, and sites; there were only occasional significant effects or trends, and there were few consistent patterns with time.

Runoff. Several conclusions are specific to runoff:

Comment: Evaluation for runoff in the early post-treatment period is compromised because during the first two years the rainfall seldom exceeded the soil infiltration capacity and only one runoff sample was collected.

- While the radionuclide was not observed consistently or in a systematic pattern, these data do indicate that there is some probability of PG-attributable ^{226}Ra occurring in runoff water following PG treatment at levels up to 20 Mg ha^{-1}. *(There was suggestive and limited statistical evidence of an effect at various times during the Year 2 - Year 5 period .)*
- There was very limited evidence of PG-attributable ^{210}Pb in runoff samples collected during years for which samples were obtained, and assessments have to be based on estimated upper limit values.

- PG-attributable concentrations of ^{210}Po were observed in runoff from the second year following treatment (***effects were suggested for the Malabar site** and significant for the Myakka site)*; but could not be detected for subsequent years.
- The above conclusion leads to the corollary conclusion that PG-related ^{210}Po is more mobile in the early years following treatment and less mobile in subsequent years.

Shallow Wells. Several conclusions are specific to shallow wells:

<u>*Comment*</u> *: The data from the wells was equivocal for all three radionuclides. Following surface application of PG at levels up to 20 Mg ha^{-1}, PG-attributable radionuclides were neither consistently detected nor totally absent.*

- Although overall average PG-attributable ^{226}Ra concentrations were generally greater for treated plots than for controls, there were no significant differences or trends; radiological assessment will have to be based on "best estimate" and "upper limit" factors.
- PG-attributable ^{210}Pb was observed in the 45-cm well at the Malabar site, but not at the other depth-site combinations. Radiological assessments have to be based on a combination of significant, "best estimate" and "upper limit" transfer factors.
- While PG-attributable ^{210}Po was not observed consistently, these data do indicate that there is some probability of this radionuclide occurring in shallow well water following PG treatment at levels up to 20 Mg ha^{-1}. Radiological assessments have to be based on a combination of significant, "best estimate" and "upper limit" transfer factors.

Groundwater in General. The data suggest several general conclusions:

- A single PG application has a very limited radiological impact on surface and groundwater quality. *(Suggested by the fact that PG-attributable radionuclides were detected in groundwater only on a very limited basis.)*
- These data do not provide a strong basis for projecting the effects of future PG-application practices on surface and groundwater and it is necessary to make liberal use of estimated upper bounds in environmental assessments.
- These data provided only limited information on the time-dependent function for PG-attributable radionuclides in surface and shallow groundwater following surface application of PG.

Radionuclides in Bahiagrass Forages

<u>*Comments*</u>*. Concentrations of ^{226}Ra, ^{210}Pb, and ^{210}Po in the first post-treatment regrowth harvest at the Myakka site were strikingly in excess of those in subsequent*

Myakka-site and all Malabar-site regrowth harvests. This observation and the associated observations on rainfall occurrence at the Ona Research Center leads to a set of hypotheses about effects of deposition of PG on plant surfaces:

1. *PG deposited on the surface of the grass during land treatment would be washed off by a prompt rainfall (4 days in the Malabar case), but, if the interval to the first significant rainfall is sufficiently long, the radionuclides can gradually undergo foliar absorption or become fixed (the 20-day interval in the Myakka case was long enough).*
2. *Following surface application of PG to established grassland, PG-attributable radionuclide concentrations in regrowth forages can potentially have two components: a) the "basic" component due to uptake via the roots and b) a potential additional component that is related to retained surface contamination. This surface contamination component may or may not be present in the first post-treatment harvest, depending upon the timing of the first post-treatment rainfall. The first component may be influenced by soil type; the second component should be independent of the soil itself, but may be influenced by the ratio of leaf surface area to soil surface area (i.e., the "stand" of the crop).*

The First Harvest Effect. The above observations led to the following conclusions:

- The radionuclide concentrations in the first post-treatment regrowth harvest at the Myakka site represent a special effect (probably leaf surface contamination) not seen at the Malabar site or in subsequent harvests.
- In describing uptake of PG-attributable radionuclides in forage, the potential surface-retention effect as exemplified by the first harvest at the Myakka site should be separated from the "basic" effect for regrowth forage.
- The first harvest, surface-retention effect observed at the Myakka site should be considered as a potential effect under the appropriate conditions for other sites as well.

General Conclusions. If the special Myakka first-harvest effect is excluded, the following conclusions are drawn:

- The mature forage is generally characterized by higher concentrations (for both control and treated plots), larger concentration vs. treatment level slopes, and higher tissue/soil concentration ratios than for regrowth forage. This difference is especially pronounced for ^{210}Pb and ^{210}Po.

  Comments: PG-attributable radionuclide concentrations in regrowth forage were generally low and challenged the detection capability of the measurement methods. The mature forage data are more robust in describing the behavior of PG-attributable radionuclides and provide a template for organizing the regrowth data for analysis.

- The mature hay vs. regrowth harvest concentration differences suggest that the equilibration time to reach maximum or "saturation" concentration levels in bahiagrass tissue is longer than the time between regrowth harvests, particularly for ^{210}Pb and ^{210}Po.
- With regard to ^{226}Ra:
    - The effects of PG treatment at levels up to 20 Mg ha^{-1} were reflected as measurable concentrations in both mature hay and regrowth (even with the exclusion of the Myakka first-harvest effect) at both sites.
    - There was no measurable overall decrease in ^{226}Ra uptake through the 6th growing season following the PG application.
    - The PG-attributable concentrations in mature hay were two to three times as high as those in regrowth forages.
- With regard to ^{210}Pb and ^{210}Po:
    - PG-attributable concentrations of these radionuclides were observed in mature hay during the first two post-treatment seasons; but not in subsequent seasons.
    - The effects were more pronounced for the Myakka site than for the Malabar site *(effects were suggested for Malabar and significant for Myakka; the regression slope was greater for Myakka than for Malabar).*
    - The above conclusion suggests that these radionuclides are less available from the Malabar soil than from the Myakka soil, perhaps due to the higher content of organic matter in the surface layer of the Malabar soil.
    - The short persistence of detectable PG-attributable ^{210}Pb and ^{210}Po in the mature hay, with a decrease more rapid than the rate of radioactivity loss from the root zone (top 15 cm) of the soil, suggests that either initially there is a small, more readily available fraction of the PG-associated radioactivity that disappears through transport and/or removal, or the PG-associated radionuclides become fixed in the soil with time.
    - If the first-harvest effect is excluded, any effects on ^{210}Pb and ^{210}Po in regrowth forage could not be detected for either radionuclide at either site.

Atmospheric Radon

- The results of the atmospheric Rn measurements were inconclusive.

CONCLUSIONS FROM THE RADIOLOGICAL ASSESSMENT

These conclusions are based on the assessment of potential radiological impact for a scenario of Central Florida PG applied annually to bahiagrass pastures at the rate of 0.4 Mg ha^{-1} for 100 years and the land then becoming available for a variety of purposes, including residential construction. The conclusions were drawn from evaluations at several levels:

1. Comparison of projected PG-attributable environmental radiation and radioactivity levels to baseline values,
2. Comparison of these levels to environmental radiation standards (where available),
3. Comparison of projected human radiation doses to radiation dose limits for members of the general public, and
4. Review of projected risks from the radionuclide intakes and radiation doses.

Radionuclides in Soil

- Following a long-term practice involving 100 annual applications of 0.4 Mg ha^{-1} each to soil having the Research Center baseline values (on the order of 0.5 to 1.0 pCi g^{-1}), increased radionuclide concentrations will be detectable in the surface soil layer:
  - Concentration increases would be 300 to 500% in the upper 5 cm (the minimum sampling depth in this study) if all the cumulative added radioactivity is retained in that layer. The values projected for the 5-cm layer are likely to be over-estimates since no downward movement was assumed, whereas there was some evidence of beginning downward movement in the 5-year observation period of this study.
  - Concentrations averaged over a 15-cm (6-in., root zone) top layer would be increased by 65 to 100%. This may be a slight overestimate; movement out of this layer was not considered.
- From a soil radioactivity standpoint, the practice is not likely to have a serious impact on the Rn source term.. Concentrations of ^{226}Ra averaged over a 61-cm (24-in, Rn modeling layer) would be increased by about 20%, a value that is considerably less than the typical variations in soil ^{226}Ra concentrations in nonenhanced Florida soils.

  Comment: *The radioactivity contributed by a single treatment at agronomic rates cannot be detected for sampling layers of 5 cm or more; an application of 1 Mg ha^{-1} would result in radionuclide concentration increases on the order of only 0.05-0.06 pCi g^{-1} averaged over 5 cm.*

Rn Flux and Indoor Rn

- The long-term practice was projected to result in Rn flux contributions that are detectable for low background areas (such as the Ona Research Center), but well within the range of variations seen in the state. *The projected PG-attributable Rn flux contribution of 0.072 pCi m^{-2} s^{-1} represents an addition of about 288% to the baseline value (an increase to 388%) for the Ona Research Center; compared to a broader base, this increment is about 35% of the statewide average for undisturbed non-mineralized lands in Florida.*
- It was projected that this would result in an approximately 10% increase in indoor Rn. *PG-attributable additions to the indoor Rn concentrations in structures built directly over the treated land without any special Rn-resistant features were projected to be in the range of 0.02 to 0.5 pCi L^{-1} with a geometric mean value of 0.11 pCi L^{-1}, whereas general indoor Rn concentrations are on the order of 1 to 2 pCi L^{-1}.*

- The projected total concentrations, on the order of 1.1 to 2.1 pCi L-1, are on the order of 28 to 53% of the EPA Action Level of 4 pCi L-1 (total indoor Rn), an increment that is small relative to the variations in levels normally seen among Florida houses.
- The calculated PG-attributable contribution represents an increased effective dose of 7.2 mrem y^{-1}. *This value is in keeping with recommendations that doses to the general public not exceed some fraction of 100 mrem y^{-1} above background.*
- Calculated risks from the PG-attributable Rn, using the stated risk factor, are estimated to be on the order of 5.4×10^{-6} from one year of exposure and on the order of 4.0×10^{-4} for a lifetime exposure (75.2 years).

External Gamma Radiation

- The projected PG-attributable gamma radiation contribution of 0.4 μR h^{-1} represents an addition of about 6% to the baseline value for the research site and is small relative to existing variations and background radiation levels.
- The added increment represents <2 % of the Florida Department of Health 20 μR h^{-1} standard for indoor radiation; and when added to the typical background of 5.7 μR h^{-1}, gives a total external radiation exposure rate (6.1 μR h^{-1}) that is about 30% of that standard.
- The calculated PG-attributable contribution to effective dose of 3.2 mrem y^{-1} is in keeping with recommendations that doses to the general public should not exceed some fraction of 100 mrem y^{-1} above background. This calculation was conservative on the high side in that it assumed 100% occupancy over the treated lands (either indoors or outdoors) and no attenuation of the indoor radiation field by the building floor (i.e., assuming a wood floor rather than a concrete slab).
- Calculated risks from the PG-attributable gamma radiation, using the stated risk factor, are estimated to be on the order of 1.8×10^{-6} from one year of exposure and on the order of 1.4×10^{-4} for a lifetime exposure.

Surface Water and Groundwater, and the Water-to-Human Pathway

The assessment for water was based on ingestion intake of drinking water by humans and the associated radiation dose. Other potential exposure pathways, such as ingestion of crops irrigated with the water in question or consumption of animal products from animals drinking the water in question or being fed crops from irrigated lands, were not considered to be of sufficient importance to be included in this assessment.

- The projected PG-attributable ^{226}Ra concentration of 0.79 pCi L^{-1} would be measurable (2.6 times the 0.30 pCi L^{-1} baseline) but the resulting total concentration of 1.09 pCi L^{-1} would be only a fraction (22%) of the drinking water standard of 5 pCi L^{-1}.
- The projected PG-attributable ^{210}Pb concentration of 1.72 pCi L^{-1} would be measurable (2.9 times the 0.59 pCi L^{-1} baseline); the resulting total concentration of 2.31 pCi L^{-1} would be about 60% the inferred drinking water standard of 4 pCi L^{-1}. *(In the absence*

of an explicit standard for ^{210}Pb, the value of 4 was calculated from a proposed 4 mrem y^{-1} dose criterion for beta emitters in water.)

- The projected PG-attributable ^{210}Po concentration of 0.58 pCi L^{-1} would be measurable (1.1 times the 0.53 pCi L^{-1} baseline) but the resulting total concentration of 1.10 pCi L^{-1} would be only a small fraction (7%) of the gross alpha standard of 15 pCi L^{-1}. *(In the absence of an explicit standard for ^{210}Po, the gross alpha standard was used for this comparison.*
- The three radionuclides in combination represent a PG-attributable increased effective dose of 3.1 mrem y^{-1}, a value in keeping with recommendations that doses to the general public should not exceed some fraction of 100 mrem y^{-1} above background.
- The PG-attributable risks were calculated to be 8.1 x 10^{-7} for one year of consumption and on the order of 6.2 x 10^{-5} from a lifetime (75.2-year) usage.
- The dose and the risk calculated for the water (drinking water) pathway are dominated by ^{210}Pb.

Note: The dose and risk estimates are based on the assumption that this water is used as the exclusive drinking water source for humans. The various projections for radionuclides in water are probably overestimates as "high-side" conservatism was used in assigning TFs for projecting concentrations.

Forage and the Forage-Beef-Human Pathway

- Of the three radionuclides, ^{226}Ra was predicted to have the greatest uptake by forages--the projected PG-attributable concentration of 0.34 pCi g^{-1} in forage would be 5.7 times the 0.06 pCi g^{-1} baseline.
- Lower uptake was projected for ^{210}Pb and ^{210}Po with respective PG-attributable concentrations of 0.40 pCi g^{-1} (0.4 times the 1.12 baseline) and 0.13 pCi g^{-1} (0.5 times the 0.26 baseline).

Note: There are no standards for environmental levels of radionuclides in vegetation.

- The projected combined three-nuclide annual radiation dose from consumption of beef fed grass from PG-treated lands of 2.0 mrem y^{-1} is low and in keeping with recommendations that doses to the general public should not exceed some fraction of 100 mrem y^{-1} above background. for a single exposure pathway.
- The PG-attributable risks from the three radionuclides in combination were calculated to be 7.1 x 10^{-7} for one year of beef consumption and on the order of 5.4 x 10^{-5} for lifetime (75.2-year) exposure.

Note: Estimates of human radiation dose and risk from the forage-beef-human pathway were based on the assumptions that forages from the PG-treated lands are the exclusive feed source for the animals (10 kg dry matter d^{-1}) and that humans consume 50 kg y^{-1} of this beef. Intakes, doses, and risks are likely to be overestimated in this analysis. Concentrations in forages were based on mature hay data, it was assumed that all feed was derived from the PG-treated grasslands, that grass-fed animals would go directly to slaughter without being fed out on grain and concentrate, and that beef from this type of animal would constitute a high percentage of the consumers' diets.

- Although ^{226}Ra demonstrated the greatest enhancement of radioactivity in forages, ^{210}Pb and ^{210}Po were major contributors to projected dose and calculated risk under the assumptions and factors used.

Overall Doses and Risks

Four pathways were considered: indoor inhalation exposure to Rn originating in the treated soil, external irradiation by gamma radiation from radionuclides in the treated soil, ingestion of drinking water containing radionuclides attributable to the soil treatment, and ingestion of beef fed with forages grown on the treated land. The various pathways might apply separately to different individuals or apply in combination to a maximum exposed individual. Considering the four pathways:

- The major contributor in this analysis is indoor Rn exposure.
- Next in ranking are external gamma radiation and drinking water.
- Projected doses and calculated risks from the grass to beef to human pathway are lower than from the other individual pathways. The treatment of grassland with PG and the consumption of beef grazing or consuming hay from these lands does not present a radiological health concern for humans; and thus the effect on radionuclides in forage is not a major concern in the application of PG to forage land.
- For the maximum exposed individual, the 16 mrem y^{-1} estimated PG-attributable annual effective dose from all the listed pathways combined is in keeping with recommendations that doses to the general public should not exceed some fraction of 100 mrem y^{-1} above background.
- The risks to this individual from the combined PG-attributable radiation exposure pathways are estimated to be on the order of 8.7×10^{-6} from one year of exposure and on the order of 6.6×10^{-4} for a lifetime (75.2-year) exposure. These are screening level estimates using factors that were generally conservative on the high side.

RECOMMENDATIONS

1. **Continued Soil Sampling.** It is recommended that soil sampling and analysis be continued to better document the slow movement of the radionuclides added via the applied PG. The upper three layers should be sampled every several years; the fourth layer should be added when or if PG-attributable radioactivity is detected in the third layer.

2. **Continued Rn Flux Measurement.** It is recommended that the flux levels at these PG-treated sites be tracked for a longer time period in order to gain additional information about any overall long-term change with time and to gain further insight into possible variations in addition to the annual cycle. Sampling should occur at least every several years.

3. **Additional Forage Sampling.** It is recommended that sampling of forage at these plots be continued with analysis for ^{226}Ra in order to follow the

radioactivity concentrations and determine the persistence of this radionuclide and the rate at which concentrations decrease. Sampling should be performed every several years as long as levels can be detected. Sampling should definitely include mature hay and preferably also include regrowth forage as long as levels can be detected.

4. **Rn Flux Measurements in General.** It is recommended that any program of sampling Rn flux to establish average values for land areas involve at least quarterly measurements for at least a year because of the annual cyclic pattern.

5. **Further Dose and Risk Assessment.** It is recommended that, as a part of further exploration of the feasibility of PG application to agricultural lands, additional effort be directed to refining the various factors identified as likely overestimates; and that this screening-level, deterministic assessment be followed up with a probabilistic risk assessment.

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APPENDIX A

CUMULATIVE RADIOLOGICAL DATA (1993-1998)

Table A-1. Radionuclides in Soil from PG-treated Florida Land Cropped to Bahiagrass -- Non-Spodic Soil (Malabar).

Collection No. and Sampling Date	Concentration, pCi g^{-1}, for Indicated Radionuclide and Mg ha^{-1} Treatment Level																	
	^{226}Ra						^{210}Pb						^{210}Po					
	0		10		20		0		10		20		0		10		20	
SURFACE LAYER (0-5 cm)																		
0. 05/18/93 #	0.70		0.58		0.40		1.52		1.28		1.28		0.60		0.90	(5)	0.95	
1. 09/02/93	0.67		1.02		1.72		0.93		1.63		1.87		0.65		1.22		1.70	
2. 02/07/94	0.53		1.23		1.62		1.65		2.98		3.42		0.72		1.10	(5)	1.07	
3. 12/01/94	0.62		1.72		1.70		1.42		2.47		2.38		1.20		2.08		2.08	
4. 03/01/95	0.42		0.95		0.87		0.62		1.30		1.17		0.67		1.67		1.08	
5. 06/20/96	0.15	(4)	0.90	(4)	1.00	(4)	1.09	(4)	1.43	(4)	1.81	(4)	1.37	(4)	1.62	(4)	2.28	(4)
6. 02/20/97	0.11		0.52		1.07		0.31		0.69		1.48		0.71		1.15		2.12	
7. 08/24/98	0.40	(4)	0.78	(4)	1.60	(4)	0.56	(4)	1.00	(4)	2.60	(4)	0.70	(4)	1.58	(4)	1.73	(4)
INTERMEDIATE LAYER A (5-10 cm)																		
4. 03/01/95	0.32		0.38		0.35		0.43		0.33		0.41		0.18		0.26		0.31	
5. 06/20/96	0.08	(4)	0.25	(4)	0.20	(4)	0.32	(4)	0.46	(4)	0.21	(4)	0.43	(4)	0.85	(4)	0.59	(4)
6. 02/20/97	0.24		0.12		0.38		0.16		0.14		0.17		0.37		0.42		0.45	
7. 08/24/98	0.55	(4)	0.53	(4)	0.6667	(3)	0.05	(4)	0.80	(4)	1.56	(4)	0.44	(4)	0.73	(4)	0.73	(4)
INTERMEDIATE LAYER B (10-15 cm)																		
4. 03/01/95	0.37		0.52		0.32		0.33		0.36		0.29		0.16		0.44		0.37	
5. 06/20/96	0.18	(4)	0.14	(4)	0.14	(4)	-0.36	(4)	-0.29	(4)	0.05	(4)	0.24	(4)	0.30	(4)	0.34	(4)
6. 02/20/97	0.08		0.20		0.11		-0.10		0.17		0.15		0.30		0.33		0.30	
7. 08/24/98	0.28	(4)	0.28	(4)	0.33	(4)	0.39	(4)	0.43	(4)	0.05	(4)	0.39	(4)	0.14	(4)	0.26	(4)
INTERMEDIATE LAYER C (15-30 cm)																		
4. 03/01/95	0.28		0.33		0.27		0.20		0.14		0.24		0.28		0.22		0.12	

Continued ...

Table A-1. Radionuclides in Soil ... (Malabar), Continued.

Collection No. and Sampling Date	Concentration, pCi g^{-1}, for Indicated Radionuclide and Mg ha^{-1} Treatment Level																	
	^{226}Ra						^{210}Pb						^{210}Po					
	0		10		20		0		10		20		0		10		20	
INTERMEDIATE LAYER D (30-60 cm)																		
0. 05/18/93 #	0.45		0.45		0.60		0.53		0.38		0.57		0.17		0.34		0.17	
1. 09/02/93	0.60		0.58		0.62	(5)	0.43		0.35		0.34	(5)	0.20		0.20		0.11	(5)
2. 02/07/94	0.53		0.72		0.67		0.68		0.83		0.76	(5)	0.26		0.35		0.16	
3. 12/01/94	0.20		0.23		0.28	(5)	0.37		0.27		0.45		0.17		0.14		0.19	
LOWER LAYER (CLAYEY)																		
0. 05/18/93 #	0.47	(3)	0.87	(3)	0.90	(2)	0.60	(3)	0.70	(3)	0.50	(2)	0.30	(3)	0.30	(3)	0.50	(2)
1. 09/02/93	NC		NC		NC		NC		NC		NC		NC		NC		NC	
2. 02/07/94	0.53	(4)	0.60	(3)	0.50	(3)	0.78	(4)	1.23	(3)	1.03	(3)	0.14	(4)	0.22	(3)	0.17	(3)
3. 12/01/94	0.38		0.47		0.28		0.48		0.32		0.41		0.16		0.18		0.20	
4. 03/01/95	NA		NA		NA		NA		NA		NA		NA		NA		NA	
5. 06/20/96	0.15	(4)	0.06	(4)	0.04	(4)	0.10	(4)	0.16	(4)	0.07	(3)	0.16	(4)	0.08	(4)	0.09	(4)
6. 02/20/97	0.15		0.29		0.07		-0.28		-0.23		-0.15		0.09		0.09		0.11	(5)

Notes:

\# Collection 0 is prior to PG treatment.

- PG Application 5/25/93
- Reported concentrations are the means of six replicates unless indicated otherwise by number in ( )
- NC = Not collected. Stony materials in the profile at the Malabar site prevented collection of samples from the lower layer on 9/02/93.
- NA = Not Analyzed

Table A-2. Radionuclides in Soil from PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

Collection No. and Sampling Date	Concentration, pCi g^{-1}, for Indicated Radionuclide and Mg ha^{-1} Treatment Level																	
	^{226}Ra						^{210}Pb						^{210}Po					
	0		10		20		0		10		20		0		10		20	
SURFACE LAYER (0-5 cm)																		
0. 05/20/93 #	0.24	(5)	0.27		0.28		0.61		0.62		0.38		0.62		0.55		0.52	
1. 09/09/93	0.48		0.98		1.25		0.33		0.78		1.38		0.55		0.93		1.10	
2. 02/15/94	0.35		0.87		1.15		0.68		0.82		1.60		0.42		0.73		0.68	
3. 12/12/94	0.47		0.88	(5)	1.12	(5)	1.15		1.63		1.85		0.58		1.18		1.10	
4. 03/01/95	0.25		0.63		0.95		0.80		1.17		1.60		0.98		0.83		1.08	
5. 06/20/96	0.09	(4)	0.60	(4)	0.95	(4)	0.72	(4)	1.15	(4)	1.34	(4)	0.87	(4)	1.36	(4)	1.66	(4)
6. 02/17/97	0.14		0.31		0.63		0.62		0.49		1.39		0.79		0.99		1.53	
7. 08/24/98	0.40	(4)	0.83	(4)	1.38	(4)	1.73	(4)	1.95	(4)	3.95	(4)	0.85	(4)	1.25	(4)	2.48	(4)
INTERMEDIATE LAYER A (5-10 cm)																		
4. 03/01/95	0.17		0.28		0.38		0.38		0.40		0.40		0.29		0.26		0.39	
5. 06/20/96	0.01	(4)	0.17	(4)	0.17	(4)	0.51	(4)	0.37	(4)	0.48	(4)	0.43	(4)	0.50	(4)	0.46	(4)
6. 02/17/97	0.24		0.19		0.31		0.18		0.13		0.15	(5)	0.34		0.38		0.49	
7. 08/24/98	0.33	(4)	0.675	(4)	0.70	(4)	1.93	(4)	2.54	(4)	2.90	(4)	0.80	(4)	0.75	(4)	0.875	(4)
INTERMEDIATE LAYER B (10-15 cm)																		
4. 03/01/95	0.34		0.21		0.37		0.26		0.14		0.39		0.09		0.09		0.19	
5. 06/20/96	0.21	(4)	0.09	(4)	0.03	(4)	0.51	(4)	0.21	(4)	0.33	(4)	0.29	(4)	0.24	(4)	0.27	(4)
6. 02/17/97	0.03		0.13		0.37		-0.16		0.19		0.25		0.26		0.24		0.17	(5)
7. 08/24/98	0.28	(4)	0.38	(4)	0.30	(4)	2.09	(4)	2.08	(4)	2.20	(4)	0.28	(4)	0.35	(4)	0.35	(4)
INTERMEDIATE LAYER C (15-30 cm)																		
4. 03/01/95	0.28		0.25		0.26		0.20		0.25		0.27		0.08		0.06		0.10	

Continued ...

Table A-2. Radionuclides in Soil ... (Myakka), Continued.

Collection No. and Sampling Date	Concentration, pCi g^{-1}, for Indicated Radionuclide and Mg ha^{-1} Treatment Level								
	^{226}Ra			^{210}Pb			^{210}Po		
	0	10	20	0	10	20	0	10	20
INTERMEDIATE LAYER D (5 cm to spodic)									
0. 05/20/93 #	0.37	0.30	0.30	0.13	0.10	0.14	0.29	0.17	0.28
1. 09/09/93	0.42	0.68	0.55	0.31	0.12	0.30	0.20	0.12	0.13
2. 02/15/94	0.37	0.47	0.40	0.27	0.34	0.43	0.24 (5)	0.13	0.23 (5)
3. 12/12/94	0.32	0.43	0.44 (5)	0.51	0.39	0.41	0.18	0.14	0.19
LOWER LAYER (First 10cm of spodic horizon)									
0. 05/20/93 #	0.27	0.35	0.38	0.12	0.13	0.08	0.24	0.27	0.16
1. 09/09/93	0.92 (5)	0.97 (3)	0.90 (4)	0.30 (5)	0.15 (3)	0.09 (4)	0.21 (5)	0.15 (3)	0.14 (4)
2. 02/15/94	0.53 (4)	0.74 (5)	0.58 (5)	0.39 (4)	0.39 (5)	0.38 (5)	0.24 (4)	0.16 (5)	0.33 (5)
3. 12/12/94	0.62	0.75	0.72	0.58	0.59	0.46	0.24	0.23	0.27
4. 03/01/95	NA	NA	NA	NA	NA	NA	NA	NA	NA
5. 06/20/96	0.07 (4)	0.04 (4)	0.08 (4)	-0.02 (4)	-0.54 (4)	0.11 (4)	0.11 (4)	0.11 (4)	0.10 (4)
6. 02/17/97	0.27	0.30	0.25	-0.09 (4)	0.07	0.30	0.23 (5)	0.30	0.28 (5)

Notes:

\# Collection 0 is prior to PG treatment.

- PG Application 6/01/93
- Reported concentrations are the means of six replicates unless indicated otherwise by number in ( )
- NA = Not Analyzed

Table A-3. Data Analysis for Radium-226 in Soil from PG-Treated Florida Land Cropped to Bahiagrass--Non-Spodic Soil (Malabar).

	Pre-PG	Post-Application							
		Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Overall
	5/18/93	9/2/93	2/7/94	12/1/94	3/1/95	6/20/96	2/20/97	8/24/98	1993-1998
SURFACE LAYER (0-5 cm)									
Means For:									
0 Mg/ha	A 0.700	B 0.667	B 0.533	B 0.617	B 0.417	B 0.150	B 0.106	C 0.400	C 0.427
10	BA 0.583	B 1.017	A 1.233	A 1.717	A 0.950	A 0.895	B 0.517	B 0.775	B 1.034
20	B 0.400	A 1.717	A 1.617	A 1.700	A 0.867	A 1.000	A 1.072	A 1.600	A 1.375
LSD	0.235	0.461	0.479	0.734	0.384	0.330	0.543	0.320	0.221
ANOVA									
P(Treatment)	0.049	0.002	0.002	0.011	0.024	0.001	0.009	< 0.001	< 0.001
P(Trends):									
Linear	0.017	< 0.001	0.001	0.008	0.026	0.001	0.003	< 0.001	< 0.001
Nonlinear	0.722	0.352	0.415	0.079	0.066	0.034	0.739	0.094	0.171
Linear Equation:									
Intercept	0.709	0.608	0.635	0.803	0.519	0.257	0.082	0.325	0.477
Slope	-0.0150	0.0525	0.0542	0.0542	0.0225	0.0425	0.0483	0.0600	0.0474
Slope Std Error	0.0062	0.0123	0.0106	0.0171	0.0092	0.0090	0.0109	0.0095	0.0055
INTERMEDIATE LAYER A (5-10 cm)									
Means For:									
0 Mg/ha					A 0.317	A 0.078	A 0.235	A 0.550	A 0.291
10					A 0.383	A 0.250	A 0.122	A 0.525	A 0.307
20					A 0.350	A 0.195	A 0.378	A 0.667	A 0.376
LSD	No Sample	No Sample	No Sample	No Sample	0.194	0.201	0.508	0.388	0.177
ANOVA									
P(Treatment)					0.751	0.181	0.550	0.837	0.586
P(Trends):									
Linear					0.709	0.202	0.543	0.714	0.334
Nonlinear					0.522	0.161	0.373	0.659	0.717
Linear Equation:									
Intercept					0.333	0.115	0.173	0.198	0.282
Slope					0.0017	0.0059	0.0072	0.0040	0.0042
Slope Std Error					0.0038	0.0041	0.0111	0.0027	0.0044

Continued ...

Table A-3. Data Analysis for Radium-226 in Soil...(Malabar), Continued.

	Pre-PG	Post-Application							
		Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Overall
	5/18/93	9/2/93	2/7/94	12/1/94	3/1/95	6/20/96	2/20/97	8/24/98	1993-1998
INTERMEDIATE LAYER B (10-15 cm)									
Means For:									
0 Mg/ha					A 0.367	A 0.180	A 0.084	A 0.275	A 0.226
10					A 0.517	A 0.140	A 0.204	A 0.275	A 0.299
20					A 0.317	A 0.143	A 0.114	A 0.325	A 0.223
LSD	No	No	No	No	0.201	0.181	0.191	0.173	0.116
ANOVA	Sample	Sample	Sample	Sample					
P(Treatment)					0.118	0.836	0.379	0.729	0.334
P(Trends):									
Linear					0.591	0.630	0.740	0.506	0.949
Nonlinear					0.049	0.751	0.185	0.697	0.141
Linear Equation:									
Intercept					0.425	0.173	0.119	0.267	0.251
Slope					-0.0025	-0.0019	0.0015	0.0025	-0.0002
Slope Std Error					0.0053	0.0033	0.0043	0.0032	0.0028
INTERMEDIATE LAYER C (15-30 cm)									
Means For:									
0 Mg/ha					A 0.283				A 0.283
10					A 0.333				A 0.333
20					A 0.267				A 0.267
LSD	No	No	No	No	0.162	No	No	No	0.162
ANOVA	Sample	Sample	Sample	Sample		Sample	Sample	Sample	
P(Treatment)					0.647				0.647
P(Trends):									
Linear					0.823				0.823
Nonlinear					0.376				0.376
Linear Equation:									
Intercept					0.303				0.303
Slope					-0.0008				-0.0008
Slope Std Error					0.0031				0.0031

Continued ...

Table A-3. Data Analysis for Radium-226 in Soil...(Malabar), Continued.

	Pre-PG	Post-Application							
		Col. 1	**Col. 2**	**Col. 3**	**Col. 4**	**Col. 5**	**Col. 6**	**Col. 7**	**Overall**
	5/18/93	**9/2/93**	**2/7/94**	**12/1/94**	**3/1/95**	**6/20/96**	**2/20/97**	**8/24/98**	**1993-1998**
INTERMEDIATE LAYER D (30-60 cm)									
Means For:									
0 Mg/ha	A 0.450	A 0.600	A 0.533	A 0.200					A 0.444
10	A 0.450	A 0.583	A 0.717	A 0.233					A 0.511
20	A 0.600	A 0.620	A 0.667	A 0.280					A 0.531
LSD	0.192	0.232	0.437	0.106	No Sample	No Sample	No Sample	No Sample	0.209
ANOVA									
P(Treatment)	0.184	0.980	0.639	0.190					0.678
P(Trends):									
Linear	0.113	0.854	0.512	0.081					0.400
Nonlinear	0.339	0.847	0.507	0.718					0.803
Linear Equation:									
Intercept	0.425	0.591	0.585	0.198					0.458
Slope	0.0075	0.0009	0.0028	0.0040					0.0026
Slope Std Error	0.0046	0.0063	0.0107	0.0027					0.0051
LOWER LAYER (CLAYEY LAYER, ~90-120 cm)									
Means For:									
0 Mg/ha	A 0.467		A 0.525	BA 0.383		A 0.153	A 0.149		A 0.295
10	A 0.867		A 0.600	A 0.467		A 0.055	A 0.288		A 0.345
20	A 0.900		A 0.500	B 0.283		A 0.038	A 0.068		A 0.198
LSD	0.560	No Sample	0.923	0.159	Not Analyzed	0.178	0.339	No Sample	0.178
ANOVA									
P(Treatment)	0.086		0.976	0.078		0.306	0.379		0.261
P(Trends):									
Linear	0.056		0.840	0.191		0.165	0.609		0.280
Nonlinear	0.259		1.000	0.056		0.549	0.202		0.216
Linear Equation:									
Intercept	0.523		0.548	0.428		0.139	0.207		0.323
Slope	0.0231		-0.0009	-0.0050		-0.0057	-0.0034		-0.0037
Slope Std Error	0.0073		0.0121	0.0056		0.0043	0.0082		0.0045

Table A-4. Data Analysis for Radium-226 in Soil from PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

	Pre-PG	Post-Application							
		Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Overall
	5/20/93	9/9/93	2/15/94	12/12/94	3/1/95	6/20/96	2/17/97	8/24/98	1993-1998
SURFACE LAYER (0-5 cm)									
Means For:									
0 Mg/ha	A 0.240	C 0.483	B 0.350	B 0.467	C 0.250	B 0.090	B 0.139	C 0.400	C 0.318
10	A 0.267	B 0.983	A 0.867	A 0.880	B 0.633	A 0.595	BA 0.305	B 0.825	B 0.725
20	A 0.283	A 1.250	A 1.150	A 1.120	A 0.950	A 0.950	A 0.628	A 1.375	A 1.048
LSD	0.158	0.264	0.324	0.328	0.221	0.458	0.342	0.328	0.142
ANOVA									
P(Treatment)	0.726	< 0.001	0.001	0.007	< 0.001	0.011	0.028	0.001	< 0.001
P(Trends):									
Linear	0.451	< 0.001	< 0.001	0.002	< 0.001	0.004	0.010	< 0.001	< 0.001
Nonlinear	0.840	0.283	0.375	0.545	0.706	0.660	0.568	0.609	0.524
Linear Equation:									
Intercept	0.242	0.522	0.389	0.491	0.261	0.115	0.113	0.379	0.3318
Slope	0.002	0.038	0.040	0.033	0.035	0.043	0.024	0.049	0.0365
Slope Std Error	0.004	0.008	0.011	0.006	0.007	0.008	0.007	0.007	0.0038
INTERMEDIATE LAYER A (5-10 cm)									
Means For:	No Sample	No Sample	No Sample	No Sample					
0 Mg/ha					B 0.167	B 0.005	A 0.238	A 0.325	B 0.187
10					BA 0.275	A 0.165	A 0.186	A 0.675	BA 0.306
20					A 0.383	A 0.173	A 0.310	A 0.700	A 0.383
LSD					0.150	0.141	0.394	0.648	0.176
ANOVA									
P(Treatment)					0.029	0.170	0.785	0.351	0.090
P(Trends):									
Linear					0.009	0.027	0.691	0.207	0.030
Nonlinear					1.000	0.178	0.580	0.505	0.778
Linear Equation:									
Intercept					0.167	0.030	0.230	0.379	0.199
Slope					0.0108	0.0084	-0.0029	0.0188	0.0083
Slope Std Error					0.0047	0.0036	0.0074	0.0118	0.0043

Continued ...

Table A-4. Data Analysis for Radium-226 in Soil ...(Myakka), Continued.

	Pre-PG	Post-Application							
	5/20/93	Col. 1 9/9/93	Col. 2 2/15/94	Col. 3 12/12/94	Col. 4 3/1/95	Col. 5 6/20/96	Col. 6 2/17/97	Col. 7 8/24/98	Overall 1993-1998
INTERMEDIATE LAYER B (10-15 cm)									
Means For:									
0 Mg/ha					A 0.342	A 0.210	A 0.032	A 0.275	A 0.209
10					A 0.208	A 0.088	A 0.126	A 0.375	A 0.193
20					A 0.367	A 0.028	A 0.373	A 0.300	A 0.287
LSD	No Sample	No Sample	No Sample	No Sample	0.272	0.367	0.455	0.229	0.170
ANOVA									
P(Treatment)					0.411	0.505	0.272	0.570	0.494
P(Trends):									
Linear					0.842	0.270	0.126	0.798	0.359
Nonlinear					0.198	0.818	0.676	0.322	0.454
Linear Equation:									
Intercept					0.293	0.200	0.006	0.304	0.191
Slope					0.0013	-0.0091	0.0171	0.0013	0.0039
Slope Std Error					0.0058	0.0085	0.0100	0.0052	0.0042
INTERMEDIATE LAYER C (15-30 cm)									
Means For:									
0 Mg/ha					A 0.283				A 0.283
10					A 0.250				A 0.250
20					A 0.258				A 0.258
LSD	No Sample	No Sample	No Sample	No Sample	0.242	No Sample	No Sample	No Sample	0.242
ANOVA									
P(Treatment)					0.950				0.950
P(Trends):									
Linear					0.822				0.822
Nonlinear					0.829				0.829
Linear Equation:									
Intercept					0.276				0.276
Slope					-0.0013				-0.0013
Slope Std Error					0.0056				0.0056

Continued ...

Table A-4. Data Analysis for Radium-226 in Soil ...(Myakka), Continued.

	Pre-PG	Post-Application							
		Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Overall
	5/20/93	9/9/93	2/15/94	12/12/94	3/1/95	6/20/96	2/17/97	8/24/98	1993-1998
INTERMEDIATE LAYER D (5 cm to Spodic)									
Means For:									
0 Mg/ha	A 0.367	B 0.417	A 0.367	A 0.317					A 0.367
10	A 0.300	A 0.683	A 0.467	A 0.433					A 0.528
20	A 0.300	BA 0.550	A 0.400	A 0.440					A 0.465
LSD	0.138	0.220	0.216	0.172	No	No	No	No	0.166
<u>ANOVA</u>					Sample	Sample	Sample	Sample	
P(Treatment)	0.489	0.065	0.593	0.179					0.152
P(Trends):									
Linear	0.308	0.207	0.738	0.084					0.240
Nonlinear	0.549	0.042	0.345	0.530					0.120
Linear Equation:									
Intercept	0.356	0.483	0.418	0.334					0.410
Slope	-0.0033	0.0067	0.0020	0.0063					0.0053
Slope Std Error	0.0032	0.0063	0.0098	0.0060					0.0043
LOWER LAYER (First 10cm of Spodic Horizon)									
Means For:									
0 Mg/ha	A 0.267	A 0.920	A 0.525	A 0.617		A 0.065	A 0.269		A 0.491
10	A 0.350	A 0.967	A 0.740	A 0.750		A 0.043	A 0.299		A 0.544
20	A 0.383	A 0.900	A 0.580	A 0.717		A 0.078	A 0.248		A 0.504
LSD	0.131	0.524	0.263	0.500	Not	0.124	0.378	No	0.234
<u>ANOVA</u>					Analyzed			Sample	
P(Treatment)	0.174	0.606	0.152	0.829		0.789	0.956		0.927
P(Trends):									
Linear	0.075	0.421	0.680	0.665		0.813	0.904		0.899
Nonlinear	0.633	0.584	0.065	0.677		0.536	0.790		0.714
Linear Equation:									
Intercept	0.275	0.933	0.600	0.644		0.055	0.283		0.504
Slope	0.0058	-0.0008	0.0020	0.0050		0.0006	-0.0011		0.0013
Slope Std Error	0.0025	0.0118	0.0071	0.0119		0.0023	0.0081		0.0060

Table A-5. Data Analysis for Lead-210 in Soil from PG-Treated Florida Land Cropped to Bahiagrass--Non-Spodic Soil (Malabar).

	Pre-PG	Post-Application							
		Col. 1	**Col. 2**	**Col. 3**	**Col. 4**	**Col. 5**	**Col. 6**	**Col. 7**	**Overall**
	5/18/93	**9/2/93**	**2/7/94**	**12/1/94**	**3/1/95**	**6/20/96**	**2/20/97**	**8/24/98**	**1993-1998**
SURFACE LAYER (0-5 cm)									
Means For:									
0 Mg/ha	A 1.517	B 0.933	B 1.650	B 1.417	B 0.617	A 1.085	B 0.314	B 0.563	B 0.952
10	A 1.283	A 1.633	BA 2.983	A 2.467	A 1.300	A 1.430	B 0.686	B 1.000	A 1.688
20	A 1.283	A 1.867	A 3.417	A 2.383	BA 1.167	A 1.810	A 1.478	A 2.600	A 2.092
LSD	0.406	0.523	1.575	0.647	0.558	1.172	0.491	1.260	0.517
ANOVA									
P(Treatment)	0.372	0.007	0.075	0.008	0.048	0.379	0.001	0.017	< 0.001
P(Trends):									
Linear	0.229	0.003	0.032	0.008	0.053	0.181	< 0.001	0.007	< 0.001
Nonlinear	0.477	0.278	0.479	0.048	0.089	0.968	0.297	0.240	0.464
Linear Equation:									
Intercept	1.487	1.011	1.899	1.606	0.753	1.079	0.244	0.369	1.012
Slope	-0.0117	0.0467	0.0883	0.0483	0.0275	0.0363	0.0582	0.1019	0.0570
Slope Std Error	0.0147	0.0149	0.0547	0.0275	0.0147	0.0226	0.0102	0.0292	0.0129
INTERMEDIATE LAYER A (5-10 cm)									
Means For:									
0 Mg/ha					A 0.433	A 0.323	A 0.159	B 0.050	A 0.252
10					A 0.333	A 0.463	A 0.135	BA 0.800	A 0.393
20					A 0.408	A 0.208	A 0.170	A 1.563	A 0.527
LSD	No Sample	No Sample	No Sample	No Sample	0.224	0.858	0.370	1.484	0.335
ANOVA									
P(Treatment)					0.602	0.776	0.978	0.118	0.265
P(Trends):									
Linear					0.809	0.754	0.951	0.047	0.105
Nonlinear					0.339	0.540	0.843	0.991	0.982
Linear Equation:									
Intercept					0.404	0.388	0.149	0.034	0.260
Slope					-0.0013	-0.0058	0.0005	0.0797	0.0117
Slope Std Error					0.0060	0.0142	0.0083	0.0288	0.0083

Continued ...

Table A-5. Data Analysis for Lead-210 in Soil... (Malabar), Continued.

	Pre-PG	Post-Application							
		Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Overall
	5/18/93	9/2/93	2/7/94	12/1/94	3/1/95	6/20/96	2/20/97	8/24/98	1993-1998
INTERMEDIATE LAYER B (10-15 cm)									
Means For:									
0 Mg/ha					A 0.325	A -0.363	A -0.104	A 0.388	A 0.071
10					A 0.358	A -0.285	A 0.168	A 0.435	A 0.186
20					A 0.292	A 0.050	A 0.149	A 0.050	A 0.152
LSD	No	No	No	No	0.341	1.164	0.314	0.745	0.272
ANOVA	Sample	Sample	Sample	Sample					
P(Treatment)					0.910	0.672	0.150	0.448	0.688
P(Trends):									
Linear					0.832	0.419	0.104	0.310	0.554
Nonlinear					0.714	0.765	0.261	0.463	0.530
Linear Equation:									
Intercept					0.342	-0.405	-0.055	0.456	0.096
Slope					-0.0017	0.0206	0.0126	-0.0169	0.0040
Slope Std Error					0.0076	0.0213	0.0074	0.0132	0.0066
INTERMEDIATE LAYER C (15-30 cm)									
Means For:									
0 Mg/ha					A 0.200				A 0.200
10					A 0.142				A 0.142
20					A 0.242				A 0.242
LSD	No	No	No	No	0.151	No	No	No	0.151
ANOVA	Sample	Sample	Sample	Sample		Sample	Sample	Sample	
P(Treatment)					0.371				0.371
P(Trends):									
Linear					0.553				0.553
Nonlinear					0.208				0.208
Linear Equation:									
Intercept					0.174				0.174
Slope					0.0021				0.0021
Slope Std Error					0.0040				0.0040

Continued ...

Table A-5. Data Analysis for Lead-210 in Soil... (Malabar), Continued.

	Pre-PG	Post-Application							
	5/18/93	Col. 1 9/2/93	Col. 2 2/7/94	Col. 3 12/1/94	Col. 4 3/1/95	Col. 5 6/20/96	Col. 6 2/20/97	Col. 7 8/24/98	Overall 1993-1998
INTERMEDIATE LAYER D (30-60 cm)									
Means For:									
0 Mg/ha	A 0.533	A 0.425	A 0.683	A 0.367					A 0.492
10	A 0.375	A 0.350	A 0.825	A 0.267					A 0.481
20	A 0.567	A 0.340	A 0.760	A 0.450					A 0.513
LSD	0.358	0.232	0.513	0.238	No Sample	No Sample	No Sample	No Sample	0.302
ANOVA									
P(Treatment)	0.470	0.734	0.798	0.274					0.980
P(Trends):									
Linear	0.840	0.862	0.610	0.453					0.905
Nonlinear	0.237	0.455	0.677	0.157					0.873
Linear Equation:									
Intercept	0.475	0.415	0.717	0.326					0.486
Slope	0.0017	-0.0044	0.0042	0.0023					0.0007
Slope Std Error	0.0077	0.0086	0.0167	0.0097					0.0075
LOWER LAYER (CLAYEY LAYER, ~90-120 cm)									
Means For:									
0 Mg/ha	A 0.600		A 0.775	A 0.475		A 0.103	A -0.276		A 0.235
10	A 0.700		A 1.233	A 0.317		A 0.163	A -0.233		A 0.256
20	A 0.500		A 1.033	A 0.408		A 0.067	A -0.150		A 0.270
LSD	2.241	No Sample	2.885	0.247	Not Analyzed	0.640	0.284	No Sample	0.392
ANOVA									
P(Treatment)	0.265		0.993	0.391		0.914	0.617		0.982
P(Trends):									
Linear	0.390		0.923	0.560		0.889	0.345		0.850
Nonlinear	0.184		0.963	0.221		0.703	0.861		0.998
Linear Equation:									
Intercept	0.646		0.861	0.433		0.127	-0.281		0.233
Slope	-0.0038		0.0143	-0.0033		-0.0014	0.0058		0.0028
Slope Std Error	0.0209		0.0314	0.0097		0.0100	0.0056		0.0096

Table A-6. Data Analysis for Lead-210 in Soil from PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

	Pre-PG	Post-Application							
		Col. 1	**Col. 2**	**Col. 3**	**Col. 4**	**Col. 5**	**Col. 6**	**Col. 7**	**Overall**
	5/20/93	**9/9/93**	**2/15/94**	**12/12/94**	**3/1/95**	**6/20/96**	**2/17/97**	**8/24/98**	**1993-1998**
SURFACE LAYER (0-5 cm)									
Means For:									
0 Mg/ha	A 0.608	B 0.325	B 0.683	A 1.150	B 0.800	A 0.723	B 0.620	B 1.725	B 0.823
10	A 0.617	B 0.783	B 0.817	A 1.633	B 1.167	A 1.150	B 0.490	BA 1.950	B 1.098
20	A 0.383	A 1.375	A 1.600	A 1.850	A 1.600	A 1.340	A 1.393	A 3.950	A 1.791
LSD	0.306	0.574	0.580	0.704	0.369	0.802	0.657	2.182	0.391
ANOVA									
P(Treatment)	0.205	0.007	0.011	0.125	0.002	0.235	0.025	0.087	< 0.001
P(Trends):									
Linear	0.132	0.002	0.006	0.051	0.001	0.108	0.025	0.047	< 0.001
Nonlinear	0.333	0.771	0.180	0.636	0.821	0.690	0.071	0.294	0.225
Linear Equation:									
Intercept	0.624	0.303	0.575	1.166	0.789	0.762	0.447	1.429	0.747
Slope	-0.0098	0.0525	0.0458	0.0457	0.0400	0.0309	0.0387	0.1113	0.0497
Slope Std Error	0.0100	0.0137	0.0118	0.0131	0.0098	0.0171	0.0148	0.0663	0.0102
INTERMEDIATE LAYER A (5-10 cm)									
Means For:									
0 Mg/ha					A 0.383	A 0.508	A 0.182	B 1.925	A 0.656
10					A 0.400	A 0.373	A 0.129	BA 2.538	A 0.741
20					A 0.400	A 0.478	A 0.149	A 2.900	A 0.877
LSD	No	No	No	No	0.196	0.525	0.401	0.708	0.764
ANOVA	Sample	Sample	Sample	Sample					
P(Treatment)					0.976	0.810	0.869	0.040	0.878
P(Trends):									
Linear					0.854	0.893	0.606	0.015	0.613
Nonlinear					0.915	0.542	0.977	0.636	0.968
Linear Equation:									
Intercept					0.335	0.435	0.171	1.967	0.648
Slope					0.0039	0.0004	-0.0018	0.0488	0.0110
Slope Std Error					0.0039	0.0119	0.0100	0.0682	0.0205

Continued ...

Table A-6. Data Analysis for Lead-210 in Soil...(Myakka), Continued.

	Pre-PG	Post-Application							
	5/20/93	Col. 1 9/9/93	Col. 2 2/15/94	Col. 3 12/12/94	Col. 4 3/1/95	Col. 5 6/20/96	Col. 6 2/17/97	Col. 7 8/24/98	Overall 1993-1998
INTERMEDIATE LAYER B (10-15 cm)									
Means For:									
0 Mg/ha					BA 0.258	A 0.505	A -0.159	A 2.088	A 0.548
10					B 0.142	A 0.205	A 0.187	A 2.075	A 0.555
20					A 0.392	A 0.328	A 0.245	A 2.200	A 0.696
LSD	No Sample	No Sample	No Sample	No Sample	0.212	0.585	0.788	0.950	0.674
ANOVA									
P(Treatment)					0.073	0.494	0.492	0.940	0.884
P(Trends):									
Linear					0.192	0.486	0.281	0.782	0.662
Nonlinear					0.050	0.347	0.648	0.845	0.817
Linear Equation:									
Intercept					0.197	0.435	-0.111	2.065	0.526
Slope					0.0067	-0.0089	0.0202	0.0056	0.0074
Slope Std Error					0.0056	0.0120	0.0147	0.0595	0.0174
INTERMEDIATE LAYER C (15-30 cm)									
Means For:									
0 Mg/ha					A 0.200				A 0.200
10					A 0.250				A 0.250
20					A 0.267				A 0.267
LSD	No Sample	No Sample	No Sample	No Sample	0.224	No Sample	No Sample	No Sample	0.224
ANOVA									
P(Treatment)					0.792				0.792
P(Trends):									
Linear					0.522				0.522
Nonlinear					0.852				0.852
Linear Equation:									
Intercept					0.206				0.206
Slope					0.0033				0.0033
Slope Std Error					0.0049				0.0049

Continued ...

Table A-6. Data Analysis for Lead-210 in Soil...(Myakka), Continued.

	Pre-PG	Post-Application							
	5/20/93	Col. 1 9/9/93	Col. 2 2/15/94	Col. 3 12/12/94	Col. 4 3/1/95	Col. 5 6/20/96	Col. 6 2/17/97	Col. 7 8/24/98	Overall 1993-1998
INTERMEDIATE LAYER D (5 cm to Spodic)									
Means For:									
0 Mg/ha	A 0.125	A 0.308	A 0.267	A 0.508					A 0.361
10	A 0.100	A 0.117	A 0.342	A 0.392					A 0.283
20	A 0.142	A 0.300	A 0.425	A 0.408					A 0.378
LSD	0.174	0.306	0.235	0.359	No Sample	No Sample	No Sample	No Sample	0.176
<u>ANOVA</u>									
P(Treatment)	0.868	0.328	0.363	0.743					0.520
P(Trends):									
Linear	0.835	0.953	0.165	0.549					0.850
Nonlinear	0.633	0.145	0.965	0.643					0.262
Linear Equation:									
Intercept	0.114	0.246	0.263	0.493					0.338
Slope	0.0008	-0.0004	0.0075	-0.0071					-0.0005
Slope Std Error	0.0040	0.0065	0.0076	0.0093					0.0046
LOWER LAYER (First 10cm of Spodic Horizon)									
Means For:									
0 Mg/ha	A 0.117	A 0.300	A 0.388	A 0.583		A -0.023	A -0.090		A 0.265
10	A 0.133	A 0.150	A 0.390	A 0.592		A -0.540	A 0.071		A 0.176
20	A 0.075	A 0.088	A 0.380	A 0.458		A 0.108	A 0.302		A 0.290
LSD	0.133	0.345	0.194	0.376	Not Analyzed	1.248	0.729	No Sample	0.281
<u>ANOVA</u>									
P(Treatment)	0.619	0.164	0.599	0.685		0.454	0.329		0.716
P(Trends):									
Linear	0.502	0.090	0.344	0.476		0.807	0.150		0.815
Nonlinear	0.486	0.384	0.808	0.638		0.235	0.878		0.435
Linear Equation:									
Intercept	0.129	0.290	0.390	0.607		-0.217	-0.118		0.228
Slope	-0.0021	-0.0107	-0.0004	-0.0063		0.0065	0.0228		0.0019
Slope Std Error	0.0033	0.0068	0.0103	0.0093		0.0253	0.0175		0.0071

Table A-7. Data Analysis for Polonium-210 in Soil from PG-Treated Florida Land Cropped to Bahiagrass--Non-Spodic Soil (Malabar).

	Pre-PG	Post-Application							
		Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Overall
	5/18/93	9/2/93	2/7/94	12/1/94	3/1/95	6/20/96	2/20/97	8/24/98	1993-1998
SURFACE LAYER (0-5 cm)									
Means For:									
0 Mg/ha	A 0.600	B 0.650	A 0.717	B 1.200	B 0.667	B 1.373	B 0.707	B 0.700	B 0.840
10	A 0.900	BA 1.217	A 1.100	A 2.083	A 1.667	B 1.623	B 1.152	A 1.575	A 1.487
20	A 0.950	A 1.700	A 1.067	A 2.083	BA 1.083	A 2.283	A 2.120	A 1.725	A 1.693
LSD	0.531	0.665	0.648	0.539	0.785	0.383	0.458	0.800	0.266
ANOVA									
P(Treatment)	0.296	0.018	0.412	0.006	0.051	0.003	< 0.000	0.040	< 0.000
P(Trends):									
Linear	0.158	0.006	0.239	0.004	0.264	0.001	< 0.000	0.020	< 0.000
Nonlinear	0.532	0.875	0.558	0.061	0.027	0.181	0.172	0.248	0.055
Linear Equation:									
Intercept	0.637	0.664	0.778	1.347	0.931	1.304	0.619	0.821	0.912
Slope	0.0175	0.0525	0.0175	0.0442	0.0208	0.0455	0.0707	0.0513	0.0427
Slope Std Error	0.0092	0.0125	0.0130	0.0152	0.0209	0.0128	0.0104	0.0246	0.0068
INTERMEDIATE LAYER A (5-10 cm)									
Means For:									
0 Mg/ha					A 0.175	B 0.433	A 0.365	A 0.438	B 0.336
10					A 0.258	A 0.848	A 0.417	A 0.725	A 0.517
20					A 0.308	BA 0.593	A 0.453	A 0.725	BA 0.492
LSD	No Sample	No Sample	No Sample	No Sample	0.240	0.408	0.103	0.645	0.164
ANOVA									
P(Treatment)					0.484	0.116	0.211	0.495	0.066
P(Trends):									
Linear					0.245	0.374	0.086	0.317	0.063
Nonlinear					0.862	0.059	0.852	0.552	0.152
Linear Equation:									
Intercept					0.181	0.544	0.368	0.471	0.370
Slope					0.0067	0.0080	0.0044	0.0187	0.0079
Slope Std Error					0.0049	0.0089	0.0023	0.0146	0.0043

Continued ...

Table A-7. Data Analysis for Polonium-210 in Soil...(Malabar), Continued.

	Pre-PG	Post-Application							
		Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Overall
	5/18/93	9/2/93	2/7/94	12/1/94	3/1/95	6/20/96	2/20/97	8/24/98	1993-1998
INTERMEDIATE LAYER B (10-15 cm)									
Means For:									
0 Mg/ha					A 0.158	A 0.243	A 0.304	A 0.388	A 0.265
10					A 0.442	A 0.303	A 0.331	A 0.138	A 0.320
20					A 0.367	A 0.343	A 0.296	A 0.263	A 0.320
LSD	No	No	No	No	0.411	0.134	0.086	0.490	0.127
<u>ANOVA</u>	Sample	Sample	Sample	Sample					
P(Treatment)					0.322	0.263	0.642	0.500	0.607
P(Trends):									
Linear					0.284	0.118	0.826	0.556	0.389
Nonlinear					0.288	0.840	0.371	0.321	0.617
Linear Equation:									
Intercept					0.218	0.246	0.315	0.325	0.274
Slope					0.0104	0.0050	-0.0004	-0.0063	0.0027
Slope Std Error					0.0080	0.0026	0.0018	0.0087	0.0030
INTERMEDIATE LAYER C (15-30 cm)									
Means For:									
0 Mg/ha					A 0.283				A 0.283
10					A 0.217				A 0.217
20					A 0.117				A 0.117
LSD	No	No	No	No	0.386	No	No	No	0.386
<u>ANOVA</u>	Sample	Sample	Sample	Sample		Sample	Sample	Sample	
P(Treatment)					0.638				0.638
P(Trends):									
Linear					0.358				0.358
Nonlinear					0.914				0.914
Linear Equation:									
Intercept					0.289				0.289
Slope					-0.0083				-0.0083
Slope Std Error					0.0075				0.0075

Continued ...

Table A-7. Data Analysis for Polonium-210 in Soil...(Malabar), Continued.

	Pre-PG	Post-Application							
	5/18/93	Col. 1 9/2/93	Col. 2 2/7/94	Col. 3 12/1/94	Col. 4 3/1/95	Col. 5 6/20/96	Col. 6 2/20/97	Col. 7 8/24/98	Overall 1993-1998
INTERMEDIATE LAYER D (30-60 cm)									
Means For:									
0 Mg/ha	A 0.167	A 0.200	A 0.258	A 0.167	No Sample	No Sample	No Sample	No Sample	A 0.208
10	A 0.342	A 0.200	A 0.350	A 0.142					A 0.231
20	A 0.167	B 0.110	A 0.158	A 0.192					A 0.156
LSD	0.212	0.086	0.285	0.130					0.113
ANOVA									
P(Treatment)	0.156	0.054	0.362	0.703					0.380
P(Trends):									
Linear	0.069	0.039	0.452	0.678					0.352
Nonlinear	0.060	0.161	0.229	0.476					0.301
Linear Equation:									
Intercept	0.225	0.215	0.315	0.150					0.227
Slope	0.0000	-0.0044	-0.0078	0.0025					-0.0032
Slope Std Error	0.0059	0.0029	0.0082	0.0032					0.0031
LOWER LAYER (CLAYEY LAYER, ~90-120 cm)									
Means For:									
0 Mg/ha	0.300	No Sample	A 0.138	A 0.158	Not Analyzed	A 0.155	A 0.087	No Sample	A 0.132
10	0.300		A 0.217	A 0.183		A 0.078	A 0.093		A 0.138
20	0.500		A 0.167	A 0.200		A 0.088	A 0.108		A 0.144
LSD	----		0.285	0.179		0.119	0.027		0.065
ANOVA									
P(Treatment)	----		0.634	0.874		0.294	0.319		0.961
P(Trends):									
Linear	----		0.630	0.615		0.214	0.151		0.779
Nonlinear	----		0.443	0.953		0.338	0.721		0.996
Linear Equation:									
Intercept	0.269		0.154	0.160		0.140	0.085		0.131
Slope	0.0092		0.0017	0.0021		-0.0033	0.0010		0.0008
Slope Std Error	0.0045		0.0045	0.0038		0.0031	0.0007		0.0017

Table A-8. Data Analysis for Polonium-210 in Soil from PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

	Pre-PG	Post-Application							
		Col. 1	**Col. 2**	**Col. 3**	**Col. 4**	**Col. 5**	**Col. 6**	**Col. 7**	**Overall**
	5/20/93	**9/9/93**	**2/15/94**	**12/12/94**	**3/1/95**	**6/20/96**	**2/17/97**	**8/24/98**	**1993-1998**
SURFACE LAYER (0-5 cm)									
Means For:									
0 Mg/ha	A 0.617	B 0.550	A 0.417	B 0.583	A 0.983	A 0.870	B 0.785	B 0.850	C 0.705
10	A 0.550	BA 0.933	A 0.733	A 1.183	A 0.833	A 1.363	B 0.985	B 1.250	B 1.012
20	A 0.517	A 1.100	A 0.683	BA 1.100	A 1.083	A 1.655	A 1.533	A 2.488	A 1.303
LSD	0.490	0.486	0.630	0.584	0.414	0.911	0.538		0.227
<u>ANOVA</u>									
P(Treatment)	0.899	0.077	0.508	0.091	0.431	0.184	0.029	< 0.001	< 0.001
P(Trends):									
Linear	0.659	0.030	0.368	0.074	0.602	0.079	0.011	< 0.001	< 0.001
Nonlinear	0.932	0.579	0.471	0.163	0.242	0.767	0.424	0.054	0.936
Linear Equation:									
Intercept	0.565	0.586	0.478	0.697	0.917	0.903	0.727	0.713	0.708
Slope	-0.0022	0.0275	0.0133	0.0310	0.0050	0.0393	0.0374	0.0813	0.0307
Slope Std Error	0.0106	0.0105	0.0134	0.0132	0.0092	0.0162	0.0116	0.0156	0.0058
INTERMEDIATE LAYER A (5-10 cm)									
Means For:									
0 Mg/ha					A 0.292	A 0.425	A 0.348	A 0.800	A 0.434
10					A 0.258	A 0.498	A 0.377	A 0.750	A 0.440
20					A 0.392	A 0.460	A 0.486	A 0.875	A 0.530
LSD	No	No	No	No	0.238	0.199	0.162	0.676	0.178
<u>ANOVA</u>	Sample	Sample	Sample	Sample					
P(Treatment)					0.458	0.688	0.158	0.903	0.480
P(Trends):									
Linear					0.371	0.682	0.069	0.795	0.281
Nonlinear					0.389	0.464	0.591	0.727	0.586
Linear Equation:									
Intercept					0.242	0.463	0.320	0.771	0.421
Slope					0.0063	0.0006	0.0093	0.0038	0.0045
Slope Std Error					0.0064	0.0039	0.0040	0.0121	0.0045

Continued ...

Table A-8. Data Analysis for Polonium-210 in Soil...(Myakka), Continued.

	Pre-PG	Post-Application							
	5/20/93	Col. 1 9/9/93	Col. 2 2/15/94	Col. 3 12/12/94	Col. 4 3/1/95	Col. 5 6/20/96	Col. 6 2/17/97	Col. 7 8/24/98	Overall 1993-1998
INTERMEDIATE LAYER B (10-15 cm)									
Means For:									
0 Mg/ha					A 0.092	A 0.293	A 0.255	A 0.275	A 0.217
10					A 0.092	A 0.240	A 0.243	A 0.350	A 0.218
20					A 0.192	A 0.273	A 0.172	A 0.350	A 0.237
LSD	No	No	No	No	0.123	0.102	0.132	0.236	0.082
ANOVA	Sample	Sample	Sample	Sample					
P(Treatment)					0.164	0.489	0.726	0.685	0.844
P(Trends):									
Linear					0.101	0.648	0.456	0.466	0.610
Nonlinear					0.321	0.284	0.815	0.669	0.783
Linear Equation:									
Intercept					0.075	0.278	0.264	0.288	0.214
Slope					0.0050	-0.0010	-0.0040	0.0038	0.0010
Slope Std Error					0.0025	0.0022	0.0035	0.0049	0.0020
INTERMEDIATE LAYER C (15-30 cm)									
Means For:									
0 Mg/ha					A 0.075				A 0.075
10					A 0.058				A 0.058
20					A 0.100				A 0.100
LSD	No	No	No	No	0.091	No	No	No	0.091
ANOVA	Sample	Sample	Sample	Sample		Sample	Sample	Sample	
P(Treatment)					0.604				0.604
P(Trends):									
Linear					0.553				0.553
Nonlinear					0.427				0.427
Linear Equation:									
Intercept					0.065				0.065
Slope					0.0013				0.0013
Slope Std Error					0.0020				0.0020

Continued ...

Table A-8. Data Analysis for Polonium-210 in Soil...(Myakka), Continued.

	Pre-PG	Post-Application							
		Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Overall
	5/20/93	9/9/93	2/15/94	12/12/94	3/1/95	6/20/96	2/17/97	8/24/98	1993-1998
INTERMEDIATE LAYER D (5 cm to Spodic)									
Means For:									
0 Mg/ha	A 0.292	A 0.200	A 0.240	A 0.175					A 0.203
10	A 0.167	A 0.117	A 0.133	A 0.142					B 0.131
20	A 0.275	A 0.133	A 0.230	A 0.192					BA 0.182
LSD	0.226	0.119	0.227	0.120	No Sample	No Sample	No Sample	No Sample	0.071
<u>ANOVA</u>									
P(Treatment)	0.438	0.297	0.516	0.652					0.120
P(Trends):									
Linear	0.873	0.239	0.801	0.764					0.592
Nonlinear	0.213	0.304	0.276	0.393					0.047
Linear Equation:									
Intercept	0.253	0.183	0.202	0.162					0.182
Slope	-0.0008	-0.0033	-0.0005	0.0006					-0.0012
Slope Std Error	0.0056	0.0025	0.0046	0.0025					0.0018
LOWER LAYER (First 10cm of Spodic Horizon)									
Means For:									
0 Mg/ha	A 0.242	A 0.210	A 0.238	A 0.242		A 0.108	A 0.229		A 0.209
10	A 0.267	A 0.150	A 0.160	A 0.233		A 0.110	A 0.304		A 0.205
20	A 0.158	A 0.138	A 0.330	A 0.267		A 0.103	A 0.277		A 0.233
LSD	0.203	0.309	0.348	0.227	Not Analyzed	0.053	0.516	No Sample	0.126
<u>ANOVA</u>									
P(Treatment)	0.485	0.776	0.710	0.944		0.940	0.815		0.900
P(Trends):									
Linear	0.381	0.552	0.445	0.811		0.824	0.567		0.721
Nonlinear	0.417	0.737	0.427	0.818		0.797	0.806		0.774
Linear Equation:									
Intercept	0.264	0.205	0.188	0.235		0.109	0.266		0.206
Slope	-0.0042	-0.0037	0.0051	0.0013		-0.0003	0.0013		0.0011
Slope Std Error	0.0050	0.0042	0.0072	0.0053		0.0015	0.0115		0.0031

Table A-9. Rn Flux from PG-Treated Florida Land Cropped to Bahiagrass --Non-Spodic Soil (Malabar).

Sampling Year, Collection No., & Sampling Date	Radon Flux, pCi m^{-2} s^{-1}, for Indicated Mg ha^{-1} Treatment Level			
	0 (C_{ext})	0 (C_{int})	10	20
Pre-PG Application				
0. 04/13/93	NM	0.041	0.037	0.041
Post-PG Application				
Initial 1. 05/25/93	0.057	0.045	0.056	0.065
Yr 1 (1993-1994)				
2. 09/28/93	0.048	0.031	0.049	0.068
3. 12/27/93	0.058	0.038	0.070	0.105
4. 02/28/94	0.028	0.035	0.044	0.066
5. 05/09/94	0.097	0.041	0.053	0.056
Mean	0.058	0.036	0.054	0.074
Yr 2 (1994-1995)				
6. 10/26/94	0.014	0.026	0.037	0.066
7. 01/02/95	0.026	0.038	0.075	0.101
8. 03/28/95	0.000	0.010	0.013	0.029
Mean	0.013	0.024	0.041	0.065
Yr 3 (1995-1996)				
9. 11/20/95	0.018	0.017	0.026	0.044
10. 02/12/96	0.045	0.027	0.046	0.052
11. 05/15/96	0.003	0.008	0.010	0.004
Mean	0.022	0.017	0.027	0.033
Yr 4 (1996-1997)				
12. 07/24/96	0.000	0.003	0.006	0.003
13. 10/21/96	0.013	0.014	0.037	0.043
14. 02/18/97	0.014	0.049	0.052	0.088
15. 06/04/97	0.048	0.058	0.089	0.110
Mean	0.025	0.031	0.046	0.061
Yr 5 (1997-1998)				
16. 08/26/97	0.025	0.022	0.043	0.066
17. 01/05/98	0.015	0.013	0.045	0.070
18. 03/03/98	0.013	0.027	0.063	0.094
19. 06/08/98	0.043	0.033	0.029	0.049
Mean	0.024	0.024	0.045	0.070
Final				
20. 08/28/98	0.015	0.011	0.019	0.031

Notes:

- PG Application 5/25/93
- C_{ext} = External Control = Untreated plots outside of the treatment array.
  C_{int} = Internal Control = Untreated plots within the treatment array
- Dates are starting dates for 24-hr collection periods.
- Data points represent means of 12 replicates, except for C_{ext} which are means of 6 replicates for years 1 & 2, and 4 replicates for subsequent years.

Table A-10. Rn Flux from PG-Treated Florida Land Cropped to Bahiagrass --Spodic Soil (Myakka).

Sampling Year, Collection No., & Sampling Date	Radon Flux, pCi m^{-2} s^{-1}, for Indicated Mg ha^{-1} Treatment Level			
	0 (C_{ext})	0 (C_{int})	10	20
Pre-PG Application				
0. 04/28/93	NM	0.022	0.027	0.025
Post-PG Application				
Initial 1. 06/01/93	0.012	0.020	0.033	0.039
Yr 1 (1993-1994)				
2. 10/04/93	0.023	0.028	0.060	0.073
3. 01/10/94	0.013	0.023	0.048	0.061
4. 04/06/94	0.017	0.023	0.044	0.056
Mean	0.018	0.025	0.051	0.063
Yr 2 (1994-1995)				
5. 10/30/94	0.008	0.009	0.033	0.058
6. 01/24/95	0.002	0.015	0.058	0.097
7. 04/11/95	0.002	0.013	0.019	0.034
Mean	0.004	0.012	0.036	0.063
Yr 3 (1995-1996)				
8. 11/27/95	0.020	0.017	0.051	0.063
9. 02/14/96	0.010	0.009	0.031	0.049
10. 05/09/96	0.005	0.010	0.012	0.017
Mean	0.012	0.012	0.031	0.043
Yr 4 (1996-1997)				
11. 07/29/96	0.023	0.004	0.009	0.022
12. 10/14/96	0.008	0.018	0.033	0.045
13. 02/11/97	0.025	0.023	0.035	0.039
14. 06/16/97	0.013	0.034	0.080	0.116
Mean	0.017	0.020	0.039	0.055
Yr 5 (1997-1998)				
15. 09/08/97	0.010	0.010	0.028	0.033
16. 01/06/98	0.020	0.018	0.042	0.061
17. 03/31/98	0.020	0.008	0.045	0.059
18. 06/29/98	0.020	0.014	0.033	0.040
Mean	0.018	0.013	0.037	0.048
Final				
19. 08/24/98	0.003	0.008	0.032	0.048

Notes:

- PG Application 6/01/93
- C_{ext} = External Control = Untreated plots outside of the treatment array.
  C_{int} = Internal Control = Untreated plots within the treatment array
- Dates are starting dates for 24-hr collection periods.
- Data points represent means of 12 replicates, except for C_{ext} which are means of 6 replicates for years 1 & 2, and 4 replicates for subsequent years.

Table A-11. Data Analysis for Rn Flux from PG-Treated Florida Land Cropped to Bahiagrass--Non-Spodic Soil (Malabar).

	Pre-PG	Post-Application							
		Initial	Year 1	Year 2	Year 3	Year 4	Year 5	Final	Overall
	4/13/93	5/25/93	(1993-94)	(1994-95)	(1995-96)	(1996-97)	(1997-98)	8/28/98	1993-1998
No. of Collections	1	1	4	3	3	4	4	1	20
Means For:									
0 Mg/ha	A 0.0408	B 0.0450	C 0.0363	C 0.0244	B 0.0172	B 0.0313	C 0.0238	B 0.0108	C 0.0273
10	A 0.0367	A 0.0558	B 0.0543	B 0.0414	BA 0.0272	BA 0.0458	B 0.0450	B 0.0192	B 0.0430
20	A 0.0408	A 0.0650	A 0.0735	A 0.0653	A 0.0333	A 0.0608	A 0.0698	A 0.0308	A 0.0604
LSD	0.0057	0.0108	0.0090	0.0152	0.0107	0.0167	0.0121	0.0110	0.0056
ANOVA									
P(Treatment)	0.237	0.004	< 0.001	< 0.001	0.013	0.003	< 0.001	0.004	< 0.001
P(Trends):									
Linear	1.000	0.001	< 0.001	< 0.001	0.004	0.001	< 0.001	0.001	< 0.001
Nonlinear	0.094	0.855	0.983	0.603	0.678	0.977	0.739	0.720	0.750
Linear Equation:									
Intercept	0.0394	0.0453	0.0360	0.0233	0.0179	0.0312	0.0232	0.0103	0.0270
Slope	0.00000	0.00100	0.00186	0.00204	0.00081	0.00148	0.00230	0.00100	0.00166
Slope Std Error	0.00020	0.00045	0.00024	0.00038	0.00027	0.00042	0.00032	0.00032	0.00015

Table A-12. Data Analysis for Rn Flux from PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

	Pre-PG	Post-Application							
	4/28/93	Initial 6/1/93	Year 1 (1993-94)	Year 2 (1994-95)	Year 3 (1995-96)	Year 4 (1996-97)	Year 5 (1997-98)	Final 8/24/98	Overall 1993-1998
No. of Collections	1	1	3	3	3	4	4	1	19
Means For:									
0 Mg/ha	A 0.0217	B 0.0200	C 0.0242	C 0.0126	C 0.0119	C 0.0196	C 0.0125	C 0.0075	C 0.0159
10	A 0.0267	A 0.0325	B 0.0508	B 0.0364	B 0.0311	B 0.0394	B 0.0367	B 0.0317	B 0.0381
20	A 0.0250	A 0.0392	A 0.0633	A 0.0631	A 0.0428	A 0.0554	A 0.0483	A 0.0483	A 0.0532
LSD	0.0069	0.0092	0.0076	0.0076	0.0100	0.0131	0.0085	0.0121	0.0044
ANOVA									
P(Treatment)	0.325	0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
P(Trends):									
Linear	0.325	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Nonlinear	0.257	0.456	0.035	0.823	0.393	0.744	0.096	0.465	0.071
Linear Equation:									
Intercept	0.0228	0.0210	0.0265	0.0121	0.0132	0.0202	0.0146	0.0088	0.0171
Slope	0.00017	0.00096	0.00196	0.00252	0.00154	0.00179	0.00179	0.00204	0.00186
Slope Std Error	0.00020	0.00023	0.00019	0.00031	0.00026	0.00032	0.00022	0.00031	0.00011

Table A-13. Gamma Radiation over PG-Treated Florida Land Cropped to Bahiagrass --Non-Spodic Soil (Malabar).

Collection No., Sampling Period, & [Number of days in Sampling Period]	Gamma Radiation Exposure Rate, mR h^{-1} for Indicated Mg ha^{-1} Treatment Level							
	0 (C_{ext})		0 (C_{int})		10		20	
PRE- PG APPLICATION								
0. 04/07/93 - 05/10/93 [33]			4.23					
POST-PG APPLICATION								
Yr 1 (1993-1994)								
1. 05/25/93 - 07/29/93 [65]	4.97		4.92		5.05		5.18	
2. 08/06/93 - 10/05/93 [60]	5.21		5.26		5.33		5.64	
3. 10/06/93 - 12/09/93 [64]	5.05		5.14		5.12		5.40	(11)
4. 02/10/94 - 04/11/94 [60]	5.14		5.32		5.32		5.49	
Time Wt'd Mean [249]	5.09		5.15		5.20		5.42	
Yr 2 (1994-1995)								
5. 04/13/94 - 06/20/94 [68]	4.99		6.27	(11)	6.15	(11)	6.51	(10)
6. 06/21/94 - 08/08/94 [48]	6.18		5.95	(11)	5.97		6.20	
7. 08/10/94 - 11/01/94 [83]	NM		6.10		6.43		5.99	
8. 11/02/94 - 12/23/94 [51]	6.54		6.00		6.08		5.58	
9. 12/27/94 - 02/22/95 [57]	7.44		6.57		6.51	(11)	6.66	
Time Wt'd Mean [307]	6.22		6.18		6.25		6.19	
Yr 3 (1995-1996)								
10. 11/22/95 - 02/06/96 [76]	7.04	(3)	5.90	(5)	6.42	(5)	6.01	(4)
11. 02/07/96 - 05/20/96 [103]	6.74	(3)	6.35		6.58		5.58	
12. 05/23/96 - 07/22/96 [60]	7.70	(3)	6.40		6.81		6.48	(5)
13. 07/24/96 - 09/30/96 [68]	6.91	(3)	6.80		6.65	(5)	6.88	
Time Wt'd Mean [307]	7.04		6.35		6.60		6.15	
Yr 4 (1996-1997)								
14. 10/29/96 - 01/24/97 [87]	8.17		7.91	(5)	7.78		7.54	
15. 02/03/97 - 04/18/97 [74]	8.17		7.91	(5)	7.78		7.60	
16. 04/21/97 - 05/23/97 [32]	6.98		7.77		7.45	(4)	7.96	
17. 06/04/97 - 08/11/97 [68]	7.12		8.12		7.76		7.50	
Time Wt'd Mean [261]	7.75		7.93		7.71		7.63	

Notes:
- PG Application 5/25/93
- C_{ext} = External Control = Untreated plots outside of the treatment array.
  C_{int} = Internal Control = Untreated plots within the treatment array
- Data points for collections 0-9 represent means of 12 replicate plots unless indicated otherwise by number in ( ), except for C_{ext} which are means of 6 replicates.
  Data points for collections 10-17 represent means of 6 replicate plots unless indicated otherwise by number in ( ), except for C_{ext} which are means of 4 replicates.
- Collections 0-13 involved 1 EIC/plot; collections 14-17 involved 2 EIC/plot
- NM = Not measured.

Table A-14. Gamma Radiation over PG-Treated Florida Land Cropped to Bahiagrass --Spodic Soil (Myakka).

Collection No., Sampling Period, & [Number of days in Sampling Period]	Gamma Radiation Exposure Rate, mR h^{-1} for Indicated Mg ha^{-1} Treatment Level							
	0 (C_{ext})		0 (C_{int})		10		20	
PRE- PG APPLICATION								
0. 04/08/93 - 05/11/93 [33]			4.19					
POST-PG APPLICATION								
Yr 1 (1993-1994)								
1. 06/01/93 - 08/01/93 [61]	4.69		4.65		4.79		4.97	(11)
2. 08/07/93 - 10/13/93 [67]	4.73		5.01		5.29	(11)	5.37	(11)
3. 10/14/93 - 12/15/93 [62]	5.62		5.75		5.90		5.84	(11)
4. 02/28/94 - 04/25/94 [56]	6.38	(5)	6.28		6.20		6.41	
Time Wt'd Mean [246]	5.32		5.40		5.53		5.63	
Yr 2 (1994-1995)								
5. 04/26/94 - 07/06/94 [71]	6.05	(5)	6.65		6.47		6.72	
6. 07/07/94 - 09/14/94 [69]	5.27	(4)	5.97	(11)	6.13		6.00	(10)
7. 10/17/94 - 12/05/94 [49]	5.42	(2)	5.93	(11)	6.03		5.69	
8. 12/06/94 - 02/13/95 [69]	5.27	(4)	6.28	(11)	6.55	(11)	6.14	
Time Wt'd Mean [258]	5.51		6.23		6.32		6.18	
Yr 3 (1995-1996)								
9. 11/30/95 - 02/07/96 [70]	6.92		7.20		7.41	(5)	7.17	
10. 02/12/96 - 05/29/96 [107]	6.53		6.55		7.10	(4)	6.68	(5)
11. 06/07/96 - 07/22/96 [45]	6.79		8.02		7.70	(3)	8.11	
12. 07/25/96 - 10/01/96 [68]	6.78		7.01		6.99		7.28	(5)
Time Wt'd Mean [290]	6.72		7.04		7.24		7.16	
Yr 4 (1996-1997)								
13. 10/29/96 - 02/10/97 [104]	6.01		7.13		8.07		7.71	(5)
14. 02/14/97 - 04/25/97 [70]	6.44		7.59		7.21	(3)	6.57	
15. 04/29/97 - 06/11/97 [43]	5.65		6.79	(5)	7.74	(5)	6.41	(5)
16. 06/12/97 - 07/23/97 [41]	6.02	(3)	7.13		7.70		6.83	
Time Wt'd Mean [258]	6.07		7.20		7.72		7.04	

Notes:

- PG Application 6/01/93
- C_{ext} = External Control = Untreated plots outside of the treatment array.
  C_{int} = Internal Control = Untreated plots within the treatment array
- Data points for collections 0-8 represent means of 12 replicate plots unless indicated otherwise by number in ( ), except for C_{ext} which are means of 6 replicates.
  Data points for collections 9-16 represent means of 6 replicate plots unless indicated otherwise by number in ( ), except for C_{ext} which are means of 4 replicates.
- Collections 0-12 involved 1 EIC/plot; collections 13-16 involved 2 EIC/plot
- NM = Not measured.

Table A-15. Data Analysis for Gamma Radiation over PG-Treated Florida Land Cropped to Bahiagrass--Non-Spodic Soil (Malabar).

	Post-Application					
	Year 1 (1993-94)	Year 2 (1994-95)	Year 3 (1995-96)	Year 4 (1996-97)	Overall Years 2-4	Overall Years 1-4
No. of Collections	4	5	4	4	13	17
Means For:						
0 Mg/ha	B 5.16	A 6.18	A 6.38	A 7.92	B 6.51	A 6.14
10	B 5.19	A 6.22	A 6.62	A 7.71	A 6.82	A 6.37
20	A 5.43	A 6.18	A 6.48	A 7.61	BA 6.68	A 6.31
LSD	0.16	0.24	0.41	0.39	0.27	0.24
ANOVA						
P(Treatment)	0.002	0.897	0.662	0.473	0.079	0.158
P(Trends):						
Linear	0.002	0.952	0.603	0.239	0.158	0.134
Nonlinear	0.133	0.644	0.458	0.744	0.078	0.228
Linear Equation:						
Intercept	5.126	6.194	6.443	7.897	6.581	6.186
Slope	0.0132	-0.0001	0.0092	-0.0155	0.0092	0.0088
Slope Std Error	0.0045	0.0063	0.0072	0.0105	0.0072	0.0064

Table A-16. Data Analysis for Gamma Radiation over PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

	Post-Application					
	Year 1 (1993-94)	Year 2 (1994-95)	Year 3 (1995-96)	Year 4 (1996-97)	Overall Years 2-4	Overall Years 1-4
No. of Collections	4	4	4	4	12	16
Means For:						
0 Mg/ha	A 5.42	A 6.22	A 7.19	BA 7.27	B 6.53	B 6.21
10	A 5.55	A 6.29	A 7.25	A 7.81	A 6.99	A 6.53
20	A 5.66	A 6.14	A 7.34	B 6.89	B 6.66	BA 6.36
LSD	0.30	0.26	0.42	0.57	0.29	0.25
ANOVA						
P(Treatment)	0.249	0.508	0.713	0.005	0.008	0.045
P(Trends):						
Linear	0.096	0.395	0.413	0.193	0.466	0.288
Nonlinear	0.991	0.428	0.972	0.002	0.002	0.024
Linear Equation:						
Intercept	5.424	6.256	7.188	7.512	6.651	6.285
Slope	0.0121	-0.0038	0.0074	-0.0197	0.0069	0.0080
Slope Std Error	0.0074	0.0068	0.0100	0.0156	0.0079	0.0067

Table A-17. Radionuclides in Water from PG-Treated Florida Land Cropped to Bahiagrass--Non-Spodic Soil (Malabar).

Collection No. & Sampling Date	Concentration, pCi g^{-1}, for Indicated Radionuclide and Mg ha^{-1} Treatment Level								
	^{226}Ra			^{210}Pb			^{210}Po		
	0	10	20	0	10	20	0	10	20
RUNOFF WATER									
1. 06/28/93	NS	NS	NS	NS	NS	NS	NS	NS	NS
2. 08/03/94	NS	NS	NS	NS	NS	NS	NS	NS	NS
3a 01/17/95	0.73	1.10	1.15	0.73	1.14	0.56	0.53	0.55	0.72
4. 06/06/95	NS	NS	NS	NS	NS	NS	NS	NS	NS
5. 04/01/96	0.21 (2)	0.34 (2)	0.51 (3)	1.01 (2)	1.32 (2)	1.05 (3)	0.32 (2)	0.51 (2)	0.25 (3)
6. 04/24/97	0.04 (5)	0.09 (3)	0.22	-1.29 (5)	-1.02 (3)	-1.94	0.14	0.10 (3)	0.10
7. 09/23/98	0.20 (1)	0.35 (2)	0.80 (2)	0.05 (1)	0.05 (2)	0.23 (2)	1.00 (1)	1.15 (2)	0.33 (2)
COLLECTED AT 35-45 cm BELOW THE SURFACE									
1. 06/28/93	1.00	1.58 (4)	1.43	0.61	0.79 (4)	1.08	0.41	0.23 (4)	0.45
2. 08/03/94	0.32 (5)	0.14 (5)	0.42	1.62	2.43	2.73	0.28	0.56	0.79
3. 02/03/95	0.77	0.71	0.57	1.68	2.50	2.03	0.75	0.89	1.00
4. 06/06/95	ND	ND (3)	0.25 (3)	0.70	0.38 (3)	1.22 (3)	0.25	0.42 (3)	0.77 (3)
5. 04/01/96	0.29	0.20	0.29	0.96	1.18	1.97	0.15	0.09	1.01 (3)
6. 04/24/97	0.50	0.18 (3)	0.64	-1.02	0.16 (3)	-0.25	0.08	0.11 (3)	0.09
7. 09/23/98	0.08	0.05	0.24	0.05	0.29	1.55	0.48	0.31	0.25
COLLECTED AT 80-90 cm BELOW THE SURFACE									
1. 06/28/93	1.02	1.60	1.28	0.57	0.70	0.77	0.06	ND	ND
2. 08/03/94	0.78	0.53	1.08	ND	ND	ND	0.30	0.43	0.52 (5)
3. 02/03/95	0.93	0.87	0.93	0.90	1.33	1.73	0.29	0.17	0.57
4. 06/06/95	0.86	0.65 (3)	0.20 (3)	0.39	0.18 (3)	0.45 (3)	0.31	0.22 (3)	0.22 (3)
5. 04/01/96	0.63 (3)	0.41	0.25 (3)	1.06 (3)	0.74	1.04 (2)	0.63 (3)	0.21	0.62 (3)
6. 04/24/97	0.21 (1)	0.70 (2)	0.35 (1)	-2.10 (1)	-0.63 (2)	-0.15 (2)	9.50 (1)	0.06 (2)	0.06 (2)
7. 09/23/98	0.30 (2)	0.45	0.52 (3)	0.18 (2)	0.06	0.80 (3)	0.95 (2)	0.19	0.28 (3)

Notes:
- PG Application 5/25/93
- Reported concentrations are the means of 6 replicate plots for collections 1-3 and 4 replicate plots for collections 4-7 unless indicated otherwise by number in ( )
- NS = No Sample, ND = "Non-detectible". Results for all samples in this set were below the limit of detection.

Table A-18. Radionuclides in Water from PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

Collection No. & Sampling Date	Concentration, pCi g^{-1}, for Indicated Radionuclide and Mg ha^{-1} Treatment Level								
	^{226}Ra			^{210}Pb			^{210}Po		
	0	10	20	0	10	20	0	10	20
RUNOFF WATER									
1. 06/29/93	NS	NS	NS	NS	NS	NS	NS	NS	NS
2. 10/03/94	NS	NS	NS	NS	NS	NS	NS	NS	NS
3. 01/26/95	NS	NS	NS	NS	NS	NS	NS	NS	NS
4. 06/07/95	0.88	1.96	2.10	0.35	0.38	0.33	0.77 (3)	2.45	5.40
5. 04/01/96	0.50	0.66	1.31 (3)	-0.32	0.07	1.38	1.17	0.42	0.70
6. 04/24/97	0.09 (6)	0.24 (5)	0.18 (5)	-2.22 (6)	-2.54 (5)	-2.08 (5)	0.23 (5)	0.23	0.19 (5)
7. 09/23/98	0.05 (1)	0.18 (2)	0.20 (1)	0.05 (1)	0.05 (2)	0.05 (1)	0.85 (1)	0.80 (1)	1.10 (1)
COLLECTED AT 35-45 cm BELOW THE SURFACE									
1. 06/29/93	1.52 (5)	1.86 (5)	1.80	1.96 (5)	2.70 (5)	2.60	0.50 (5)	0.49 (5)	0.38
2. 10/03/94	0.17	0.38	0.14	2.35	1.98	2.68	0.67	0.53	0.54
3. 01/26/95	0.94	0.59	0.75	2.48	1.82	1.96	0.68	0.60	0.93
4. 06/07/95	0.34	0.83	0.90	1.19	0.89	0.81	0.21	0.13	0.21
5. 04/01/96	0.14	0.28	0.13	2.35	0.03	0.90	0.19	0.25	0.16
6. 04/24/97	0.20 (6)	0.46 (6)	0.17 (6)	-1.11 (6)	-1.38 (6)	-1.92 (6)	0.12 (6)	0.20 (6)	0.16 (6)
7. 09/23/98	0.18	0.05	0.18	1.39	0.10	1.70	0.30	0.18	0.38
COLLECTED AT 80-90 cm BELOW THE SURFACE									
1. 06/29/93	1.35	1.07	1.32	0.97	0.59	0.58	0.10	0.16	0.09
2. 10/03/94	0.58	0.34	0.55	0.73	0.98	1.85	0.33	0.33	0.59
3. 01/26/95	0.93	0.89	1.28	2.14	0.83	1.54	0.45	0.51	0.52
4. 06/07/95	0.95	1.17 (3)	1.35	0.41	1.05 (3)	0.88	0.54	0.77 (3)	1.35
5. 04/01/96	0.12 (3)	0.58	0.11	1.31 (3)	-0.77	0.80 (3)	0.34 (3)	0.46	0.68
6. 04/24/97	0.33 (6)	0.54 (5)	0.38 (3)	-2.21 (6)	-1.45 (5)	-2.23 (3)	0.09 (5)	0.07 (5)	0.11 (3)
7. 09/23/98	0.23	0.30 (3)	0.21	1.06	1.60 (3)	1.69	0.23	0.37 (3)	0.53

Notes:
- PG Application 6/01/93
- Reported concentrations are the means of 6 replicate plots for collections 1-3 and 4 replicate plots for collections 4-7 unless indicated otherwise by number in ( )
- NS = No Sample

Table A-19. Data Analysis for Radium-226 in Water from PG-Treated Florida Land Cropped to Bahiagrass--Non-Spodic Soil (Malabar).

	Post-Application										
	Col. 1 6/29/93	**Col. 2 8/3/94**	**Col. 3a 1/17/95**	**Col. 3 2/3/95**	**Col. 4 6/6/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1995-96**	**Overall 1997-98**	**Overall 1993-98**
RUNOFF WATER											
Means For:											
0 Mg/ha			A 0.725			A 0.205	B 0.043	A 0.200	A 0.595	B 0.069	A 0.370
10			A 1.100			A 0.335	BA 0.088	A 0.350	A 0.909	BA 0.193	A 0.633
20			A 1.150			A 0.513	A 0.223	A 0.800	A 0.938	A 0.415	A 0.729
LSD			0.983			0.359	0.148	0.734	0.675	0.313	0.420
<u>ANOVA</u>	No Sample	No Sample		No Sample	No Sample						
P(Treatment)			0.591			0.103	0.082	0.086	0.511	0.114	0.219
P(Trends):											
Linear			0.358			0.054	0.039	0.056	0.300	0.049	0.093
Nonlinear			0.680			0.564	0.374	0.259	0.621	0.528	0.669
Linear Equation:											
Intercept			0.779			0.196	0.006	0.114	0.643	0.037	0.412
Slope			0.0213			0.0156	0.0104	0.0321	0.0169	0.0183	0.0170
Slope Std Error			0.0213			0.0039	0.0024	0.0078	0.0167	0.0064	0.0117
COLLECTED AT 35-45 cm BELOW THE SURFACE											
Means For:											
0 Mg/ha	A 1.000	A 0.320		A 0.767	A 0.050	A 0.290	A 0.500	B 0.075			A 0.481
10	A 1.575	A 0.140		A 0.708	A 0.050	A 0.195	A 0.183	B 0.050			A 0.446
20	A 1.433	A 0.417		A 0.567	A 0.250	A 0.285	A 0.638	A 0.238			A 0.603
LSD	0.560	0.291		0.620	0.226	0.192	0.714	0.136			0.263
<u>ANOVA</u>			No Sample								
P(Treatment)	0.157	0.077		0.766	0.123	0.447	0.488	0.030	Not Applicable	Not Applicable	0.432
P(Trends):											
Linear	0.090	0.308		0.489	0.078	0.951	0.877	0.027			0.313
Nonlinear	0.348	0.040		0.866	0.246	0.223	0.262	0.069			0.417
Linear Equation:											
Intercept	1.090	0.242		0.781	0.024	0.258	0.395	0.040			0.450
Slope	0.0217	0.0055		-0.0100	0.0096	0.0001	0.0069	0.0081			0.0066
Slope Std Error	0.0132	0.0118		0.0128	0.0039	0.0100	0.0200	0.0032			0.0068

Continued ...

Table A-19. Data Analysis for Radium-226 in Water ... (Malabar), Continued.

	Post-Application										
	Col. 1 6/29/93	**Col. 2 8/3/94**	**Col. 3a 1/17/95**	**Col. 3 2/3/95**	**Col. 4 6/6/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1995-96**	**Overall 1997-98**	**Overall 1993-98**
COLLECTED AT 80-90 cm BELOW THE SURFACE											
Means For:											
0 Mg/ha	A 1.017	BA 0.783		A 0.933	A 0.863	A 0.627	0.210	A 0.300			A 0.805
10	A 1.600	B 0.525		A 0.867	A 0.650	A 0.405	0.700	A 0.450			A 0.797
20	A 1.283	A 1.083		A 0.933	A 0.200	A 0.253	0.350	A 0.517			A 0.824
LSD	0.679	0.552		0.491	1.485	0.676	----	0.882	Not Applicable	Not Applicable	0.281
ANOVA											
P(Treatment)	0.209	0.128	No Sample	0.941	0.720	0.311	----	0.878			0.995
P(Trends):											
Linear	0.402	0.254		1.000	0.565	0.150	----	0.648			0.929
Nonlinear	0.119	0.086		0.734	0.600	0.984	----	0.906			0.962
Linear Equation:											
Intercept	1.167	0.668		0.911	0.893	0.620	1.050	0.323			0.799
Slope	0.0133	0.0087		0.0000	-0.0326	-0.0205	-0.0350	0.0105			0.0009
Slope Std Error	0.0181	0.0155		0.0130	0.0240	0.0153	0.0173	0.0126			0.0077

Table A-20. Data Analysis for Radium-226 in Water from PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

	Post-Application									
	Col. 1 6/29/93	**Col. 2 10/3/94**	**Col. 3 1/26/95**	**Col. 4 6/7/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1995-96**	**Overall 1997-98**	**Overall 1993-98**
RUNOFF WATER										
Means For:										
0 Mg/ha				A 0.875	A 0.495	A 0.093	A 0.050	A 0.685	A 0.083	A 0.384
10				A 1.958	A 0.663	A 0.244	A 0.175	A 1.310	A 0.224	A 0.803
20				A 2.100	A 1.313	A 0.184	A 0.200	A 1.763	A 0.187	A 1.035
LSD				2.183	1.319	0.277	1.834	1.179	0.198	0.708
ANOVA	No Sample	No Sample	No Sample							
P(Treatment)				0.384	0.291	0.493	0.581	0.205	0.299	0.137
P(Trends):										
Linear				0.219	0.160	0.590	0.397	0.081	0.253	0.048
Nonlinear				0.565	0.523	0.299	0.902	0.834	0.289	0.953
Linear Equation:										
Intercept				0.514	0.419	0.088	0.082	0.446	0.087	0.293
Slope				0.0923	0.0396	0.0053	0.0091	0.0704	0.0060	0.0415
Slope Std Error				0.0435	0.0286	0.0060	0.0064	0.0267	0.0047	0.0179
COLLECTED AT 35-45 cm BELOW THE SURFACE										
Means For:										
0 Mg/ha	A 1.520	A 0.167	A 0.942	A 0.338	A 0.140	A 0.201	A 0.175			A 0.516
10	A 1.860	A 0.375	A 0.592	A 0.825	A 0.275	A 0.463	A 0.050			A 0.642
20	A 1.800	A 0.142	A 0.750	A 0.900	A 0.128	A 0.172	A 0.175			A 0.611
LSD	0.750	0.307	0.562	0.740	0.251	0.459	0.144			0.322
ANOVA										
P(Treatment)	0.580	0.226	0.413	0.211	0.346	0.336	0.125	Not Applicable	Not Applicable	0.707
P(Trends):										
Linear	0.337	0.859	0.465	0.112	0.907	0.891	1.000			0.541
Nonlinear	0.731	0.094	0.271	0.461	0.162	0.151	0.050			0.573
Linear Equation:										
Intercept	1.589	0.240	0.857	0.406	0.187	0.293	0.133			0.542
Slope	0.0134	-0.0013	-0.0096	0.0281	-0.0006	-0.0014	0.0000			0.0047
Slope Std Error	0.0177	0.0068	0.0169	0.0152	0.0057	0.0116	0.0046			0.0080

Continued ...

Table A-20. Data Analysis for Radium-226 in Water...(Myakka), Continued.

	Post-Application									
	Col. 1 6/29/93	**Col. 2 10/3/94**	**Col. 3 1/26/95**	**Col. 4 6/7/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1995-96**	**Overall 1997-98**	**Overall 1993-98**
COLLECTED AT 80-90 cm BELOW THE SURFACE										
Means For:										
0 Mg/ha	A 1.352	A 0.583	A 0.925	A 0.950	B 0.120	A 0.327	A 0.225			A 0.691
10	A 1.067	A 0.342	A 0.892	A 1.167	A 0.578	A 0.540	A 0.300			A 0.703
20	A 1.317	A 0.550	A 1.283	A 1.350	B 0.108	A 0.380	A 0.213			A 0.810
LSD	0.670	0.674	0.575	0.509	0.446	0.530	0.555			0.302
ANOVA										
P(Treatment)	0.601	0.697	0.288	0.196	0.087	0.562	0.905	Not Applicable	Not Applicable	0.354
P(Trends):										
Linear	0.910	0.914	0.195	0.087	0.251	0.932	0.954			0.485
Nonlinear	0.328	0.411	0.364	0.801	0.050	0.304	0.673			0.751
Linear Equation:										
Intercept	1.263	0.508	0.854	0.955	0.347	0.375	0.247			0.685
Slope	-0.0018	-0.0017	0.0179	0.0200	-0.0011	0.0051	-0.0006			0.0064
Slope Std Error	0.0158	0.0154	0.0200	0.0167	0.0203	0.0117	0.0085			0.0077

Table A-21. Data Analysis for Lead-210 in Water from PG-Treated Florida Land Cropped to Bahiagrass--Non-Spodic Soil (Malabar).

	Post-Application										
	Col. 1 6/29/93	**Col. 2 8/3/94**	**Col. 3a 1/17/95**	**Col. 3 2/3/95**	**Col. 4 6/6/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1995-96**	**Overall 1997-98**	**Overall 1993-98**
RUNOFF WATER											
Means For:											
0 Mg/ha			A 0.725			A 1.010	A -1.288	A 0.050	A 0.796	A -1.065	A -0.001
10			A 1.142			A 1.320	A -1.023	A 0.050	A 1.186	A -0.594	A 0.502
20			A 0.558			A 1.047	A -1.935	A 0.225	A 0.721	A -1.215	A -0.053
LSD			0.953			3.608	2.606	2.568	0.810	1.734	1.118
<u>ANOVA</u>	No Sample	No Sample		No Sample	No Sample						
P(Treatment)			0.406			0.757	0.513	0.612	0.481	0.674	0.539
P(Trends):											
Linear			0.705			0.508	0.315	0.426	0.883	0.450	0.922
Nonlinear			0.207			0.959	0.618	0.839	0.237	0.662	0.272
Linear Equation:											
Intercept			0.892			1.113	-1.246	0.000	0.941	-0.932	0.226
Slope			-0.0083			0.0001	-0.0255	0.0100	-0.0046	-0.0059	-0.0066
Slope Std Error			0.0234			0.0428	0.0466	0.0091	0.0199	0.0406	0.0263
COLLECTED AT 35-45 cm BELOW THE SURFACE											
Means For:											
0 Mg/ha	A 0.608	B 1.617		A 1.675	A 0.700	A 0.955	B -1.023	A 0.050			B 0.769
10	A 0.788	BA 2.433		A 2.500	A 0.383	A 1.180	A 0.157	A 0.288			BA 1.341
20	A 1.083	A 2.733		A 2.033	A 1.217	A 1.968	BA -0.248	A 1.550			A 1.571
LSD	0.704	0.905		1.744	1.708	2.001	0.915	2.565			0.643
<u>ANOVA</u>			No Sample								
P(Treatment)	0.262	0.051		0.589	0.490	0.475	0.141	0.369	Not Applicable	Not Applicable	0.052
P(Trends):											
Linear	0.131	0.020		0.657	0.467	0.262	0.113	0.202			0.017
Nonlinear	0.562	0.479		0.363	0.360	0.705	0.185	0.593			0.625
Linear Equation:											
Intercept	0.594	1.644		1.890	0.550	0.814	-0.807	-0.121			0.775
Slope	0.0238	0.0588		0.0179	0.0233	0.0647	0.0388	0.0750			0.0430
Slope Std Error	0.0145	0.0198		0.0424	0.0319	0.0397	0.0259	0.0553			0.0163

Continued ...

Table A-21. Data Analysis for Lead-210 in Water...(Malabar), Continued.

	Post-Application										
	Col. 1 6/29/93	**Col. 2 8/3/94**	**Col. 3a 1/17/95**	**Col. 3 2/3/95**	**Col. 4 6/6/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1995-96**	**Overall 1997-98**	**Overall 1993-98**
COLLECTED AT 80-90 cm BELOW THE SURFACE											
Means For:											
0 Mg/ha	A 0.567	0.050		A 0.900	A 0.388	A 1.060	-2.100	A 0.175			A 0.431
10	A 0.700	0.050		A 1.333	A 0.183	A 0.735	-0.625	A 0.063			A 0.484
20	A 0.767	0.050		A 1.725	A 0.450	A 1.035	-0.155	A 0.800			A 0.741
LSD	0.598	----		2.061	0.628	3.667	----	2.066			0.540
ANOVA											
P(Treatment)	0.756	----	No	0.682	0.453	0.948	----	0.561	Not	Not	0.509
P(Trends):			Sample						Applicable	Applicable	
Linear	0.473	----		0.393	0.273	0.912	----	0.627			0.288
Nonlinear	0.889	----		0.980	0.599	0.779	----	0.368			0.643
Linear Equation:											
Intercept	0.578	0.050		0.907	0.326	0.946	-1.700	-0.057			0.456
Slope	0.0100	0.0000		0.0413	0.0021	-0.0041	0.1075	0.0351			0.0149
Slope Std Error	0.0143	0.0000		0.0452	0.0147	0.0457	0.0771	0.0333			0.0133

Table A-22. Data Analysis for Lead-210 in Water from PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

	Post-Application									
	Col. 1 6/29/93	**Col. 2 10/3/94**	**Col. 3 1/26/95**	**Col. 4 6/7/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1995-96**	**Overall 1997-98**	**Overall 1993-98**
RUNOFF WATER										
Means For:										
0 Mg/ha				A 0.350	A -0.320	A -2.217	0.050	A 0.015	A -1.650	A -0.818
10				A 0.375	A 0.073	A -2.536	0.050	A 0.224	A -1.797	A -0.719
20				A 0.325	A 1.383	A -2.080	0.050	A 0.854	A -1.725	A -0.251
LSD				0.781	1.762	1.618	----	0.879	1.455	1.146
ANOVA										
P(Treatment)	No	No	No	0.988	0.121	0.914	----	0.142	0.872	0.525
P(Trends):	Sample	Sample	Sample							
Linear				0.940	0.056	0.699	----	0.060	0.643	0.305
Nonlinear				0.896	0.490	0.891	----	0.568	0.825	0.635
Linear Equation:										
Intercept				0.445	-0.489	-2.310	0.050	-0.064	-1.652	-0.797
Slope				-0.0062	0.0899	0.0026	0.0000	0.0416	-0.0120	0.0202
Slope Std Error				0.0144	0.0429	0.0486	0.0000	0.0239	0.0467	0.0323
COLLECTED AT 35-45 cm BELOW THE SURFACE										
Means For:										
0 Mg/ha	A 1.960	A 2.350	A 2.475	A 1.188	A 2.348	A -1.113	BA 1.388			A 1.479
10	A 2.700	A 1.983	A 1.817	A 0.888	B 0.025	A -1.380	B 0.100			A 0.916
20	A 2.600	A 2.683	A 1.958	A 0.813	BA 0.895	A -1.917	A 1.700			A 1.266
LSD	1.951	2.352	2.095	0.912	1.857	1.232	1.302			0.917
ANOVA										
P(Treatment)	0.909	0.806	0.768	0.595	0.057	0.372	0.051	Not	Not	0.463
P(Trends):								Applicable	Applicable	
Linear	0.681	0.759	0.595	0.353	0.104	0.177	0.579			0.659
Nonlinear	0.919	0.573	0.634	0.739	0.051	0.784	0.020			0.247
Linear Equation:										
Intercept	2.104	2.172	2.342	1.150	1.815	-1.068	0.906			1.326
Slope	0.0308	0.0167	-0.0258	-0.0188	-0.0726	-0.0402	0.0156			-0.0104
Slope Std Error	0.0462	0.0474	0.0473	0.0343	0.0588	0.0246	0.0417			0.0227

Continued ...

Table A-22. Data Analysis for Lead-210 in Water...(Myakka), Continued.

	Post-Application									
	Col. 1 6/29/93	**Col. 2 10/3/94**	**Col. 3 1/26/95**	**Col. 4 6/7/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1995-96**	**Overall 1997-98**	**Overall 1993-98**
COLLECTED AT 80-90 cm BELOW THE SURFACE										
Means For:										
0 Mg/ha	A 0.967	A 0.725	A 2.142	A 0.413	A 1.310	A -2.207	A 1.063			A 0.560
10	A 0.592	A 0.975	B 0.825	A 1.050	A -0.768	A -1.450	A 1.600			A 0.363
20	A 0.575	A 1.850	BA 1.542	A 0.875	A 0.800	A -2.233	A 1.688			A 0.930
LSD	0.888	1.598	1.172	1.644	3.144	3.293	2.491			0.803
ANOVA										
P(Treatment)	0.559	0.301	0.087	0.718	0.295	0.621	0.782	Not Applicable	Not Applicable	0.354
P(Trends):										
Linear	0.349	0.148	0.280	0.480	0.689	0.584	0.527			0.385
Nonlinear	0.615	0.626	0.050	0.736	0.149	0.435	0.823			0.251
Linear Equation:										
Intercept	0.907	0.621	1.803	0.523	0.741	-2.009	1.124			0.447
Slope	-0.0196	0.0563	-0.0300	0.0231	-0.0355	0.0085	0.0313			0.0175
Slope Std Error	0.0201	0.0312	0.0377	0.0274	0.0782	0.0673	0.0444			0.0203

Table A-23. Data Analysis for Polonium-210 in Water from PG-Treated Florida Land Cropped to Bahiagrass--Non-Spodic Soil (Malabar).

	Post-Application											
	Col. 1 6/29/93	**Col. 2 8/3/94**	**Col. 3a 1/17/95**	**Col. 3 2/3/95**	**Col. 4 6/6/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1993-96**	**Overall 1997-98**	**Overall 1996-98**	**Overall 1993-98**
RUNOFF WATER												
Means For:												
0 Mg/ha			A 0.525			A 0.320	A 0.143	A 1.000			A 0.316	A 0.412
10			A 0.550			A 0.510	A 0.103	A 1.150			A 0.519	A 0.533
20			A 0.717			A 0.250	A 0.103	A 0.325			A 0.201	A 0.407
LSD			0.702			0.501	0.155	2.568			0.406	0.357
ANOVA	No Sample	No Sample		No Sample	No Sample							
P(Treatment)			0.807			0.297	0.806	0.178	Not Applic-able	Not Applic-able	0.248	0.677
P(Trends):												
Linear			0.557			0.628	0.580	0.120			0.193	0.882
Nonlinear			0.801			0.170	0.776	0.322			0.289	0.388
Linear Equation:												
Intercept			0.501			0.399	0.137	1.279			0.406	0.454
Slope			0.0096			-0.0048	-0.0020	-0.0407			-0.0067	-0.0005
Slope Std Error			0.0145			0.0070	0.0022	0.0314			0.0094	0.0085
COLLECTED AT 35-45 cm BELOW THE SURFACE												
Means For:												
0 Mg/ha	A 0.408	A 0.275		A 0.750	A 0.250	A 0.148	A 0.080	A 0.475	B 0.392	A 0.277		A 0.365
10	A 0.225	A 0.558		A 0.892	A 0.417	A 0.093	A 0.110	A 0.313	BA 0.488	A 0.226		A 0.427
20	A 0.450	A 0.792		A 1.000	A 0.767	A 1.010	A 0.090	A 0.250	A 0.783	A 0.170		A 0.629
LSD	0.677	0.552		1.217	0.959	1.500	0.078	0.672	0.353	0.329		0.284
ANOVA			No Sample									
P(Treatment)	0.794	0.164		0.901	0.409	0.346	0.996	0.713	0.090	0.574	Not Applic-able	0.154
P(Trends):												
Linear	0.882	0.064		0.657	0.213	0.252	0.945	0.444	0.036	0.330		0.065
Nonlinear	0.520	0.910		0.973	0.803	0.371	0.967	0.840	0.523	0.717		0.569
Linear Equation:												
Intercept	0.357	0.347		0.756	0.226	-0.006	0.086	0.458	0.362	0.278		0.354
Slope	0.0021	0.0238		0.0125	0.0254	0.0406	0.0005	-0.0113	0.0194	-0.0054		0.0128
Slope Std Error	0.0147	0.0159		0.0221	0.0131	0.0285	0.0017	0.0134	0.0087	0.0075		0.0072

Continued ...

Table A-23. Data Analysis for Polonium-210 in Water...(Malabar), Continued.

	Post-Application											
	Col. 1 6/29/93	**Col. 2 8/3/94**	**Col. 3a 1/17/95**	**Col. 3 2/3/95**	**Col. 4 6/6/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1993-96**	**Overall 1997-98**	**Overall 1996-98**	**Overall 1993-98**
COLLECTED AT 80-90 cm BELOW THE SURFACE												
Means For:												
0 Mg/ha	A 0.058	A 0.300		A 0.292	A 0.313	A 0.627	----	A 0.950	A 0.281	B 0.950		A 0.331
10	A 0.050	A 0.433		A 0.167	A 0.217	A 0.208	0.050	A 0.188	A 0.215	A 0.143		A 0.201
20	A 0.050	A 0.520		A 0.567	A 0.217	A 0.620	0.055	A 0.283	A 0.383	A 0.192		A 0.349
LSD	0.015	0.687		0.424	0.575	1.028	----	1.346	0.217	0.613		0.208
<u>ANOVA</u>			No Sample									
P(Treatment)	0.402	0.832		0.150	0.697	0.303	----	0.387	0.325	0.090	Not Applic-able	0.292
P(Trends):												
Linear	0.249	0.569		0.179	0.484	0.919	----	0.347	0.425	0.109		0.929
Nonlinear	0.496	0.874		0.142	0.680	0.146	----	0.320	0.205	0.100		0.119
Linear Equation:												
Intercept	0.057	0.308		0.204	0.300	0.425	0.060	0.716	0.243	0.637		0.277
Slope	-0.0004	0.0111		0.0138	-0.0050	0.0084	-0.0005	-0.0294	0.0049	-0.0285		0.0019
Slope Std Error	0.0003	0.0128		0.0111	0.0093	0.0292	0.0043	0.0219	0.0056	0.0164		0.0054

Table A-24. Data Analysis for Polonium-210 in Water from PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

	Post-Application										
	Col. 1 6/29/93	**Col. 2 10/3/94**	**Col. 3 1/26/95**	**Col. 4 6/7/95**	**Col. 5 4/1/96**	**Col. 6 4/24/97**	**Col. 7 9/23/98**	**Overall 1993-96**	**Overall 1997-98**	**Overall 1996-98**	**Overall 1993-98**
RUNOFF WATER											
Means For:											
0 Mg/ha				C 0.767	A 1.173	A 0.226	0.850			A 0.684	A 0.701
10				B 2.450	A 0.423	A 0.230	0.800			A 0.379	A 1.016
20				A 5.400	A 0.700	A 0.190	1.100			A 0.485	A 1.889
LSD				1.193	1.119	0.261	----			0.524	1.332
<u>ANOVA</u>											
P(Treatment)	No Sample	No Sample	No Sample	0.001	0.322	0.795	----	Not Applic-able	Not Applic-able	0.362	0.148
P(Trends):											
Linear				< 0.001	0.341	0.658	----			0.277	0.072
Nonlinear				0.068	0.242	0.629	----			0.357	0.443
Linear Equation:											
Intercept				0.500	1.041	0.232	0.818			0.625	0.607
Slope				0.2350	-0.0355	-0.0018	0.0109			-0.0102	0.0614
Slope Std Error				0.0544	0.0279	0.0045	0.0457			0.0129	0.0325
COLLECTED AT 35-45 cm BELOW THE SURFACE											
Means For:											
0 Mg/ha	A 0.500	A 0.667	A 0.675	A 0.213	A 0.190	A 0.123	A 0.300	A 0.486	A 0.194		A 0.403
10	A 0.490	A 0.525	A 0.600	A 0.125	A 0.250	A 0.197	A 0.175	A 0.428	A 0.188		A 0.359
20	A 0.383	A 0.542	A 0.925	A 0.213	A 0.163	A 0.162	A 0.375	A 0.485	A 0.247		A 0.419
LSD	0.444	0.527	0.707	0.285	0.167	0.100	0.435	0.226	0.154		0.177
<u>ANOVA</u>											
P(Treatment)	0.748	0.811	0.580	0.702	0.470	0.304	0.556	0.848	0.687	Not Applic-able	0.802
P(Trends):											
Linear	0.467	0.609	0.449	1.000	0.701	0.412	0.687	0.902	0.483		0.913
Nonlinear	0.891	0.707	0.483	0.419	0.259	0.193	0.331	0.576	0.618		0.513
Linear Equation:											
Intercept	0.517	0.640	0.608	0.183	0.215	0.141	0.246	0.467	0.183		0.386
Slope	-0.0060	-0.0063	0.0125	0.0000	-0.0014	0.0019	0.0038	-0.0001	0.0027		0.0008
Slope Std Error	0.0101	0.0109	0.0162	0.0051	0.0038	0.0024	0.0077	0.0058	0.0035		0.0045

Continued ...

Table A-24. Data Analysis for Polonium-210 in Water...(Myakka), Continued.

	Post-Application										
	Col. 1 6/29/93	Col. 2 10/3/94	Col. 3 1/26/95	Col. 4 6/7/95	Col. 5 4/1/96	Col. 6 4/24/97	Col. 7 9/23/98	Overall 1993-96	Overall 1997-98	Overall 1996-98	Overall 1993-98
COLLECTED AT 80-90 cm BELOW THE SURFACE											
Means For:											
0 Mg/ha	A 0.100	A 0.325	A 0.450	A 0.535	A 0.337	A 0.091	A 0.225	A 0.336	A 0.150		B 0.287
10	A 0.158	A 0.333	A 0.508	A 0.767	A 0.458	A 0.067	A 0.367	A 0.405	A 0.179		BA 0.350
20	A 0.092	A 0.592	A 0.517	A 1.350	A 0.675	A 0.106	A 0.525	A 0.589	A 0.345		A 0.537
LSD	0.147	0.546	0.885	1.141	0.591	0.104	0.326	0.280	0.211		0.222
ANOVA											
P(Treatment)	0.565	0.491	0.983	0.218	0.378	0.454	0.130	0.186	0.143	Not	0.073
P(Trends):										Applic-	
Linear	0.902	0.302	0.870	0.112	0.186	0.269	0.055	0.079	0.052	able	0.028
Nonlinear	0.300	0.569	0.943	0.520	0.866	0.598	0.793	0.613	0.956		0.512
Linear Equation:											
Intercept	0.121	0.283	0.458	0.489	0.301	0.081	0.223	0.317	0.130		0.265
Slope	-0.0004	0.0133	0.0033	0.0406	0.0160	0.0004	0.0150	0.0126	0.0095		0.0122
Slope Std Error	0.0032	0.0104	0.0175	0.0240	0.0143	0.0028	0.0053	0.0070	0.0048		0.0056

Table A-25. Radionuclides in Bahiagrass Forage Grown on PG-Treated Florida Land--Non-Spodic Soil (Malabar).

Harvest Date		Concentration, pCi g^{-1}, for Indicated Radionuclide and Mg ha^{-1} Treatment Level								
		^{226}Ra			^{210}Pb			^{210}Po		
		0	10	20	0	10	20	0	10	20
1993 Regrowth	**06/30/93**	0.22	0.20	0.18	0.38	0.24	0.35	0.25	0.25	0.35
	08/02/93	0.28	0.25	0.22	0.60	0.60	0.45	0.52	0.48	0.35
	09/13/93	0.11	0.22	0.17	0.18	0.18	0.29	0.30	0.30	0.35
	Mean	0.20	0.22	0.19	0.39	0.34	0.36	0.36	0.34	0.35
1993 Mature	**12/02/93**	0.15	0.24	0.37	0.53	0.67	0.65	0.38	0.42	0.43
1994 Regrowth	**04/20/94**	0.09	0.13	0.15	0.38	0.23	0.27	0.16	0.08	0.12
	05/03/94	0.09	0.13	0.18	0.55	0.68	0.53	0.38	0.20	0.38
	06/27/94	0.06	0.11	0.17	0.23	0.07	0.09	0.23	0.22	0.30
	07/21/94	0.07	0.09	0.10	0.14	0.15	0.13	0.12	0.16	0.16
	Mean	0.08	0.11	0.15	0.33	0.28	0.25	0.22	0.16	0.24
1994 Mature	**12/07/94**	0.08	0.25	0.22	0.78	0.85	0.90	0.53	0.63	0.70
1995		No Data								
1996 Regrowth	**Composite**	0.12	0.19	0.28	0.56	0.61	0.64	0.18	0.20	0.19
1996 Mature	**11/01/96**	0.06	0.19	0.31	0.77	0.71	0.84	0.30	0.29	0.32
1997 Regrowth	**Composite**	0.02 (4)	0.13 (4)	0.20 (4)	0.45 (4)	0.45 (4)	0.39 (4)	0.23 (3)	0.28 (4)	0.26 (4)
1997 Mature	**11/05/97**	0.05 (5)	0.12 (5)	0.20 (5)	1.64 (5)	1.45 (5)	0.99 (5)	0.62 (5)	0.59 (5)	0.46 (5)
1998 Regrowth	**Composite**	0.05 (4)	0.05 (4)	0.16 (4)	0.43 (4)	0.05 (4)	0.06 (4)	0.19 (3)	0.11 (4)	0.23 (4)
1998 Mature	**10/13/98**	0.05 (4)	0.06 (4)	0.20 (4)	1.64 (4)	2.83 (4)	0.88 (4)	0.33 (4)	0.46 (4)	0.35 (4)

Notes:

- PG Application 5/25/93
- Data points represent means of 6 replicate plots unless indicated otherwise by number in ( )

Table A-26. Radionuclides in Bahiagrass Forage Grown on PG-Treated Florida Land--Spodic Soil (Myakka).

Harvest	Date	Concentration, pCi g^{-1}, for Indicated Radionuclide and Mg ha^{-1} Treatment Level								
		^{226}Ra			^{210}Pb			^{210}Po		
		0	10	20	0	10	20	0	10	20
1993 Regrowth	**07/12/93**	0.13	0.82	0.95	0.52	1.48	1.48	0.42	1.07	1.27
	08/09/93	0.13	0.16	0.10	0.42	0.35	0.30	0.17	0.13	0.28
	09/21/93	0.12	0.18	0.14	0.39	0.39	0.32	0.19	0.37	0.28
	Mean	0.12	0.39	0.40	0.44	0.74	0.70	0.26	0.52	0.61
1993 Mature	**11/19/93**	0.14	0.33	0.33	0.75	0.98	0.98	0.33	0.55	0.57
1994 Regrowth	**05/03/94**	0.10	0.25	0.38	0.85	1.03	1.07	0.27	0.35	0.30
	06/08/94	0.07	0.05	0.07	0.41	0.30	0.50	0.33	0.38	0.23
	07/11/94	0.05	0.07	0.07	0.15	0.23	0.13	0.11	0.17	0.28
	Mean	0.07	0.12	0.17	0.47	0.52	0.57	0.24	0.30	0.27
1994 Mature	**12/07/94**	0.07	0.14	0.17	1.05	1.27	1.68	0.40	0.72	0.73
1995		No Data								
1996 Regrowth	**Composite**	0.10	0.12	0.21	0.50	0.52	0.64	0.14	0.15	0.16
1996 Mature	**11/01/96**	0.02	0.16	0.21	0.80	0.86	0.71	0.37	0.44	0.39
1997 Regrowth	**Composite**	0.05 (4)	0.07 (4)	0.08 (4)	0.52 (4)	0.51 (4)	0.56 (4)	0.19 (4)	0.19 (4)	0.17 (4)
1997 Mature	**11/12/97**	0.06 (5)	0.10 (5)	0.20 (5)	1.92 (5)	1.56 (5)	1.41 (5)	0.75 (5)	0.64 (5)	0.66 (5)
1998 Regrowth	**Composite**	0.08 (4)	0.09 (4)	0.16 (4)	0.15 (4)	0.18 (4)	0.19 (4)	0.33 (4)	0.25 (4)	0.30 (4)
1998 Mature	**10/13/98**	0.10 (4)	0.13 (4)	0.21 (4)	0.39 (4)	0.59 (4)	0.58 (4)	0.33 (4)	0.43 (4)	0.60 (4)

Notes:
- PG Application 6/01/93
- Data points represent means of 6 replicate plots unless indicated otherwise by number in ( )

Table A-27. Data Analysis for Radium-226 in Bahiagrass Forage Grown on PG-Treated Florida Land--Non-Spodic Soil (Malabar).

	1993 Regrowth Individual Collections			Regrowth Overall	Mature 1993	1994 Regrowth Individual Collections				Regrowth Overall
	6/30/93	8/2/93	9/13/93	1993	12/2/93	4/20/94	5/3/94	6/27/94	7/21/94	1994
Means For:										
0 Mg/ha	A 0.217	A 0.275	A 0.108	A 0.200	B 0.150	A 0.092	A 0.092	B 0.058	A 0.067	B 0.077
10	A 0.200	A 0.250	A 0.217	A 0.222	BA 0.242	A 0.133	A 0.125	BA 0.108	A 0.092	BA 0.115
20	A 0.183	A 0.217	A 0.167	A 0.189	A 0.367	A 0.150	A 0.175	A 0.167	A 0.100	A 0.148
LSD	0.091	0.218	0.124	0.084	0.133	0.063	0.107	0.102	0.070	0.038
ANOVA										
P(Treatment)	0.724	0.839	0.200	0.718	0.014	0.157	0.263	0.108	0.564	0.002
P(Trends):										
Linear	0.433	0.565	0.320	0.790	0.005	0.067	0.113	0.040	0.315	< 0.001
Nonlinear	1.000	0.962	0.132	0.444	0.753	0.622	0.845	0.919	0.766	0.900
Linear Equations:										
(All Treatments)										
Intercept	0.217	0.276	0.135	0.209	0.144	0.096	0.089	0.057	0.069	0.078
Slope	-0.0017	-0.0029	0.0029	-0.0006	0.0108	0.0029	0.0042	0.0054	0.0017	0.0035
Slope Std Error	0.0022	0.0047	0.0031	0.0021	0.0037	0.0013	0.0022	0.0025	0.0014	0.0010
(0 to 10)										
Intercept	0.217	0.275	0.108	0.200	0.150	0.092	0.092	0.058	0.067	0.077
Slope	-0.0017	-0.0025	0.0108	0.0022	0.0092	0.0042	0.0033	0.0050	0.0025	0.0038
Slope Std Error	0.0040	0.0110	0.0068	0.0046	0.0047	0.0023	0.0035	0.0040	0.0026	0.0015
(10 to 20)										
Intercept	0.217	0.283	0.267	0.256	0.117	0.117	0.075	0.050	0.083	0.081
Slope	-0.0017	-0.0033	-0.0050	-0.0033	0.0125	0.0017	0.0050	0.0058	0.0008	0.0033
Slope Std Error	0.0048	0.0069	0.0069	0.0035	0.0090	0.0031	0.0051	0.0062	0.0033	0.0023

Continued ...

Table A-27. Data Analysis for Radium-226 in Bahiagrass...(Malabar), Continued.

	Mature 1994 11/30/94	1995	Regrowth 1996 Composite	Mature 1996 11/1/96	Regrowth 1997 Composite	Mature 1997 11/5/97	Regrowth 1998 Composite	Mature 1998 10/13/98	Regrowth Overall 1993-98	Mature Overall 1993-98
Means For:										
0 Mg/ha	B 0.083		A 0.115	B 0.057	A 0.019	A 0.049	B 0.050	A 0.050	B 0.115	C 0.081
10	A 0.250		A 0.186	BA 0.187	A 0.133	A 0.119	B 0.050	A 0.063	BA 0.154	B 0.182
20	A 0.217		A 0.280	A 0.314	A 0.199	A 0.201	A 0.163	A 0.200	A 0.180	A 0.266
LSD	0.110	No	0.242	0.136	0.229	0.174	0.111	0.256	0.043	0.068
ANOVA		Sample								
P(Treatment)	0.016		0.351	0.006	0.231	0.192	0.075	0.348	0.013	< 0.001
P(Trends):										
Linear	0.022		0.159	0.002	0.103	0.078	0.047	0.201	0.003	< 0.001
Nonlinear	0.042		0.904	0.982	0.778	0.934	0.201	0.516	0.742	0.774
Linear Equations:										
(All Treatments)										
Intercept	0.117		0.111	0.057	0.035	0.047	0.031	0.029	0.117	0.084
Slope	0.0067		0.0083	0.0129	0.0085	0.0076	0.0056	0.0075	0.0033	0.0093
Slope Std Error	0.0026		0.0048	0.0030	0.0046	0.0037	0.0024	0.0053	0.0011	0.0017
(0 to 10)										
Intercept	0.083		0.115	0.057	0.026	0.049	0.050	0.050	0.115	0.081
Slope	0.0167		0.0071	0.0130	0.0107	0.0071	0.0000	0.0013	0.0039	0.0101
Slope Std Error	0.0044		0.0093	0.0045	0.0022	0.0065	0.0000	0.0013	0.0022	0.0025
(10 to 20)										
Intercept	0.283		0.092	0.059	0.067	0.038	-0.063	-0.075	0.127	0.098
Slope	-0.0033		0.0094	0.0128	0.0066	0.0082	0.0113	0.0138	0.0026	0.0084
Slope Std Error	0.0053		0.0105	0.0070	0.0103	0.0088	0.0055	0.0134	0.0021	0.0040

Table A-28. Data Analysis for Radium-226 in Bahiagrass Forage Grown on PG-Treated Florida Land--Spodic Soil (Myakka).

	1993 Regrowth Individual Collections			Regrowth Overall	Mature 1993	1994 Regrowth Individual Collections			Regrowth Overall	Mature 1994
	7/12/93	8/9/93	9/21/93	1993	11/19/93	5/3/94	6/8/94	7/11/94	1994	12/7/94
Means For:										
0 Mg/ha	B 0.125	A 0.125	A 0.117	B 0.122	B 0.142	B 0.100	A 0.067	A 0.050	B 0.072	B 0.067
10	A 0.817	A 0.158	A 0.183	A 0.386	A 0.333	A 0.250	A 0.050	A 0.067	BA 0.122	A 0.142
20	A 0.950	A 0.100	A 0.142	A 0.397	A 0.333	A 0.383	A 0.067	A 0.067	A 0.172	A 0.167
LSD	0.297	0.105	0.076	0.225	0.136	0.140	0.025	0.025	0.087	0.063
ANOVA										
P(Treatment)	< 0.001	0.487	0.191	0.028	0.015	0.004	0.285	0.285	0.078	0.014
P(Trends):										
Linear	< 0.001	0.607	0.479	0.018	0.010	0.001	1.000	0.174	0.025	0.006
Nonlinear	0.036	0.287	0.096	0.199	0.099	0.882	0.122	0.418	1.000	0.333
Linear Equations:										
(All Treatments)										
Intercept	0.218	0.140	0.135	0.164	0.174	0.103	0.061	0.053	0.072	0.075
Slope	0.0413	-0.0013	0.0013	0.0138	0.0096	0.0142	0.0000	0.0008	0.0050	0.0050
Slope Std Error	0.0071	0.0031	0.0018	0.0054	0.0046	0.0034	0.0006	0.0006	0.0021	0.0015
(0 to 10)										
Intercept	0.125	0.125	0.117	0.122	0.142	0.100	0.067	0.050	0.072	0.067
Slope	0.0692	0.0033	0.0067	0.0264	0.0192	0.0150	-0.0017	0.0017	0.0050	0.0075
Slope Std Error	0.0111	0.0073	0.0032	0.0085	0.0089	0.0034	0.0011	0.0011	0.0025	0.0029
(10 to 20)										
Intercept	0.683	0.217	0.225	0.375	0.333	0.117	0.033	0.067	0.072	0.117
Slope	0.0133	-0.0058	-0.0042	0.0011	0.0000	0.0133	0.0017	0.0000	0.0050	0.0025
Slope Std Error	0.0146	0.0072	0.0032	0.0131	0.0104	0.0086	0.0011	0.0015	0.0051	0.0034

Continued ...

Table A-28. Data Analysis for Radium-226...(Myakka), Continued.

	1995	Regrowth 1996 Composite	Mature 1996 11/1/96	Regrowth 1997 Composite	Mature 1997 11/12/97	Regrowth 1998 Composite	Mature 1998 10/13/98	Regrowth Overall# 1993-98	Mature Overall 1993-98
Means For:									
0 Mg/ha		A 0.095	B 0.015	A 0.049	B 0.059	B 0.080	A 0.100	B 0.087	B 0.075
10		A 0.119	A 0.155	A 0.068	B 0.097	B 0.093	A 0.125	BA 0.127	A 0.176
20		A 0.207	A 0.206	A 0.082	A 0.201	A 0.163	A 0.213	A 0.154	A 0.225
LSD	No	0.148	0.091	0.060	0.090	0.032	0.171	0.043	0.064
ANOVA	Sample								
P(Treatment)		0.255	0.002	0.458	0.017	0.001	0.312	0.010	< 0.001
P(Trends):									
Linear		0.124	0.001	0.232	0.007	0.001	0.159	0.003	< 0.001
Nonlinear		0.585	0.231	0.919	0.354	0.042	0.625	0.717	0.349
Linear Equations:									
(All Treatments)									
Intercept		0.084	0.030	0.050	0.048	0.070	0.090	0.089	0.084
Slope		0.0056	0.0095	0.0016	0.0071	0.0041	0.0056	0.0033	0.0075
Slope Std Error		0.0029	0.0029	0.0014	0.0019	0.0015	0.0036	0.0011	0.0016
(0 to 10)									
Intercept		0.095	0.015	0.049	0.059	0.080	0.100	0.092	0.075
Slope		0.0023	0.0140	0.0019	0.0038	0.0125	0.0025	0.0118	0.0101
Slope Std Error		0.0038	0.0062	0.0020	0.0036	0.0033	0.0069	0.0037	0.0032
(10 to 20)									
Intercept		0.030	0.105	0.054	-0.008	0.023	0.038	0.171	0.127
Slope		0.0088	0.0051	0.0014	0.0104	0.0070	0.0088	0.0039	0.0049
Slope Std Error		0.0069	0.0069	0.0030	0.0036	0.0334	0.0084	0.0056	0.0036

Notes:
Regrowth Overall 1993-1998 Analysis Excludes First Harvest

Table A-29. Data Analysis for Lead-210 in Bahiagrass Forage Grown on PG-Treated Florida Land--Non-Spodic Soil (Malabar).

	1993 Regrowth Individual Collections			Regrowth Overall	Mature 1993	1994 Regrowth Individual Collections				Regrowth Overall	Mature 1994
	6/30/93	8/2/93	9/13/93	1993	12/2/93	4/20/94	5/3/94	6/27/94	7/21/94	1994	11/30/94
Means For:											
0 Mg/ha	A 0.383	A 0.600	A 0.183	A 0.389	A 0.533	A 0.383	A 0.550	A 0.233	A 0.142	A 0.327	A 0.783
10	A 0.242	A 0.600	A 0.175	A 0.339	A 0.667	A 0.233	A 0.683	B 0.067	A 0.150	A 0.283	A 0.853
20	A 0.350	A 0.450	A 0.292	A 0.364	A 0.650	A 0.267	A 0.533	B 0.092	A 0.125	A 0.254	A 0.900
LSD	0.188	0.265	0.225	0.162	0.222	0.261	0.152	0.084	0.112	0.138	0.162
ANOVA											
P(Treatment)	0.259	0.381	0.464	0.825	0.380	0.436	0.100	0.003	0.882	0.570	0.316
P(Trends):											
Linear	0.700	0.235	0.309	0.757	0.268	0.343	0.811	0.004	0.748	0.294	0.140
Nonlinear	0.117	0.483	0.491	0.593	0.404	0.388	0.037	0.015	0.711	0.903	0.897
Linear Equations:											
(All Treatments)											
Intercept	0.342	0.625	0.163	0.376	0.558	0.353	0.597	0.201	0.147	0.325	0.786
Slope	-0.0017	-0.0075	0.0054	-0.0013	0.0058	-0.0058	-0.0008	-0.0071	-0.0008	-0.0036	0.0058
Slope Std Error	0.0051	0.0060	0.0050	0.0039	0.0058	0.0052	0.0050	0.0022	0.0024	0.0033	0.0034
(0 to 10)											
Intercept	0.383	0.600	0.183	0.389	0.533	0.383	0.550	0.233	0.142	0.327	0.783
Slope	-0.0142	0.0000	-0.0008	-0.0050	0.0133	-0.0150	0.0133	-0.0167	0.0008	-0.0044	0.0067
Slope Std Error	0.0100	0.0134	0.0085	0.0085	0.0108	0.0119	0.0101	0.0035	0.0049	0.0071	0.0053
(10 to 20)											
Intercept	0.133	0.750	0.058	0.314	0.683	0.200	0.833	0.042	0.175	0.313	0.800
Slope	0.0108	-0.0150	0.0117	0.0025	-0.0017	0.0033	-0.0150	0.0025	-0.0025	-0.0029	0.0050
Slope Std Error	0.0098	0.0096	0.0109	0.0073	0.0114	0.0070	0.0082	0.0026	0.0048	0.0068	0.0072

Continued ...

Table A-29. Data Analysis for Lead-210...(Malabar), Continued.

	Regrowth Overall 1993-94	Mature Overall 1993-94	1995	Regrowth 1996 Composite	Mature 1996 11/1/96	Regrowth 1997 Composite	Mature 1997 11/5/97	Regrowth 1998 Composite	Mature 1998 10/13/98	Regrowth Overall 1996-98	Mature Overall 1996-98
Means For:											
0 Mg/ha	A 0.354	A 0.658		A 0.558	BA 0.772	A 0.447	A 1.642	A 0.425	BA 1.638	A 0.488	BA 1.293
10	A 0.307	A 0.758		A 0.610	B 0.705	A 0.454	A 1.446	A 0.050	A 2.825	A 0.405	A 1.517
20	A 0.301	A 0.775		A 0.638	A 0.839	A 0.389	A 0.994	A 0.063	B 0.888	A 0.402	B 0.904
LSD	0.103	0.170	No	0.262	0.133	0.091	0.694	0.600	1.693	0.220	0.596
ANOVA			Sample								
P(Treatment)	0.543	0.331		0.794	0.130	0.236	0.149	0.295	0.079	0.668	0.122
P(Trends):											
Linear	0.314	0.172		0.513	0.292	0.168	0.064	0.190	0.320	0.432	0.194
Nonlinear	0.652	0.568		0.913	0.079	0.307	0.637	0.397	0.040	0.671	0.109
Linear Equations:											
(All Treatments)											
Intercept	0.347	0.672		0.562	0.739	0.483	1.685	0.360	2.158	0.482	1.169
Slope	-0.0026	0.0058		0.0040	0.0033	-0.0044	-0.0324	-0.0181	-0.0375	-0.0047	-0.0129
Slope Std Error	0.0025	0.0040		0.0047	0.0037	0.0017	0.0163	0.0121	0.0423	0.0055	0.0103
(0 to 10)											
Intercept	0.354	0.658		0.558	0.772	0.474	1.642	0.425	1.638	0.498	1.168
Slope	-0.0046	0.0100		0.0051	-0.0068	-0.0020	-0.0196	-0.0375	0.1188	-0.0092	-0.0126
Slope Std Error	0.0054	0.0074		0.0072	0.0080	0.0040	0.0262	0.0298	0.0735	0.0110	0.0216
(10 to 20)											
Intercept	0.313	0.742		0.581	0.571	0.519	1.898	0.038	4.76250	0.408	1.174
Slope	-0.0006	0.0017		0.0029	0.0134	-0.0065	-0.0452	0.0013	-0.1938	-0.0003	-0.0132
Slope Std Error	0.0050	0.0079		0.0108	0.0069	0.0029	0.0345	0.0013	0.0457	0.0103	0.0193

Table A-30. Data Analysis for Lead-210 in Bahiagrass Forage Grown on PG-Treated Florida Land--Spodic Soil (Myakka)

	1993 Regrowth Individual Collections			Regrowth Overall	Mature 1993	1994 Regrowth Individual Collections			Regrowth Overall	Mature 1994
	7/12/93	8/9/93	9/21/93	1993	11/19/93	5/3/94	6/8/94	7/11/94	1994	12/7/94
Means For:										
0 Mg/ha	B 0.517	A 0.417	A 0.392	A 0.442	A 0.750	A 0.850	A 0.408	A 0.150	A 0.469	B 1.050
10	A 1.483	A 0.350	A 0.392	A 0.742	A 0.983	A 1.033	A 0.300	A 0.225	A 0.519	BA 1.267
20	A 1.483	A 0.300	A 0.317	A 0.700	A 0.983	A 1.067	A 0.500	A 0.133	A 0.567	A 1.683
LSD	0.467	0.169	0.331	0.358	0.279	0.625	0.225	0.191	0.308	0.429
ANOVA										
P(Treatment)	0.001	0.343	0.846	0.199	0.148	0.715	0.189	0.545	0.818	0.023
P(Trends):										
Linear	0.001	0.155	0.624	0.153	0.092	0.457	0.384	0.850	0.529	0.008
Nonlinear	0.024	0.901	0.776	0.273	0.307	0.764	0.108	0.289	0.992	0.562
Linear Equations:										
(All Treatments)										
Intercept	0.678	0.414	0.404	0.499	0.367	0.875	0.357	0.178	0.470	0.450
Slope	0.0483	-0.0058	-0.0038	0.0129	0.0117	0.0108	0.0046	-0.0008	0.0049	0.0167
Slope Std Error	0.0118	0.0037	0.0063	0.0085	0.0045	0.0117	0.0053	0.0042	0.0073	0.0099
(0 to 10)										
Intercept	0.517	0.417	0.392	0.442	0.750	0.850	0.408	0.150	0.469	1.050
Slope	0.0967	-0.0067	0.0000	0.0300	0.0233	0.0183	-0.0108	0.0075	0.0050	0.0217
Slope Std Error	0.0206	0.0064	0.0137	0.0151	0.0135	0.0273	0.0097	0.0085	0.0147	0.0168
(10 to 20)										
Intercept	1.483	0.400	0.467	0.783	0.983	1.000	0.100	0.317	0.472	0.850
Slope	0.0000	-0.0050	-0.0075	-0.0042	0.0000	0.0033	0.0200	-0.0092	0.0047	0.0417
Slope Std Error	0.0220	0.0076	0.0139	0.0204	0.0126	0.0231	0.0097	0.0093	0.0153	0.0231

Continued ...

Table A-30. Data Analysis for Lead-210...(Myakka), Continued.

	Regrowth Overall# 1993-94	Mature Overall 1993-94	1995	Regrowth 1996 Composite	Mature 1996 11/1/96	Regrowth 1997 Composite	Mature 1997 11/12/97	Regrowth 1998 Composite	Mature 1998 10/13/98	Regrowth Overall 1996-98	Mature Overall 1996-98
Means For:											
0 Mg/ha	A 0.443	B 0.900		A 0.496	A 0.801	A 0.517	A 1.916	A 0.150	A 0.388	A 0.403	A 1.063
10	A 0.460	BA 1.125		A 0.520	A 0.856	A 0.510	A 1.562	A 0.175	A 0.588	A 0.419	A 1.020
20	A 0.463	A 1.333		A 0.637	A 0.714	A 0.557	A 1.410	A 0.188	A 0.575	A 0.486	A 0.909
LSD	0.191	0.312	No	0.315	0.212	0.151	0.732	0.142	0.736	0.208	0.447
ANOVA			Sample								
P(Treatment)	0.975	0.029		0.580	0.357	0.729	0.315	0.811	0.767	0.695	0.773
P(Trends):											
Linear	0.835	0.008		0.340	0.377	0.542	0.149	0.542	0.556	0.425	0.489
Nonlinear	0.936	0.950		0.711	0.258	0.635	0.723	0.905	0.698	0.773	0.859
Linear Equations:											
(All Treatments)											
Intercept	0.446	0.903		0.481	0.390	0.508	0.726	0.152	0.313	0.395	1.074
Slope	0.0010	0.0217		0.0071	0.0010	0.0020	-0.0044	0.0019	0.0138	0.0041	-0.0077
Slope Std Error	0.0047	0.0077		0.0083	0.0017	0.0030	0.0052	0.0070	0.0050	0.0052	0.0106
(0 to 10)											
Intercept	0.443	0.900		0.496	0.801	0.517	1.916	0.150	0.983	0.403	1.063
Slope	0.0017	0.0225		0.0024	0.0055	-0.0007	-0.0354	0.0025	0.0000	0.0016	-0.0043
Slope Std Error	0.0093	0.0120		0.0112	0.0101	0.0074	0.0309	0.0118	0.0126	0.0085	0.0234
(10 to 20)											
Intercept	0.457	0.917		0.403	0.999	0.464	1.714	0.163	0.600	0.352	1.131
Slope	0.0003	0.0208		0.0117	-0.0143	0.0047	-0.0152	0.0013	-0.0013	0.0067	-0.0111
Slope Std Error	0.0099	0.0169		0.0195	0.0100	0.0073	0.0223	0.0161	0.0274	0.0114	0.0176

Notes:
\# Regrowth Overall 1993-94 Analysis Excludes First Harvest

Table A-31. Data Analysis for Polonium-210 in Bahiagrass Forage Grown on PG-Treated Florida Land--Non-Spodic Soil (Malabar).

	1993 Regrowth Individual Collections			Regrowth Overall	Mature 1993	1994 Regrowth Individual Collections				Regrowth Overall	Mature 1994
	6/30/93	8/2/93	9/13/93	1993	12/2/93	4/20/94	5/3/94	6/27/94	7/21/94	1994	11/30/94
Means For:											
0 Mg/ha	B 0.250	A 0.517	A 0.300	A 0.356	A 0.383	A 0.158	A 0.383	A 0.233	A 0.117	A 0.223	A 0.533
10	B 0.250	A 0.483	A 0.300	A 0.344	A 0.417	A 0.075	A 0.200	A 0.217	A 0.158	A 0.158	A 0.633
20	A 0.350	A 0.350	A 0.350	A 0.350	A 0.433	A 0.117	A 0.383	A 0.300	A 0.158	A 0.240	A 0.700
LSD	0.094	0.389	0.102	0.124	0.230	0.093	0.248	0.131	0.123	0.091	0.419
ANOVA											
P(Treatment)	0.061	0.615	0.480	0.984	0.886	0.188	0.214	0.361	0.693	0.209	0.682
P(Trends):											
Linear	0.039	0.362	0.302	0.928	0.638	0.343	1.000	0.282	0.468	0.714	0.397
Nonlinear	0.201	0.748	0.544	0.876	0.927	0.115	0.087	0.348	0.672	0.085	0.921
Linear Equations:											
(All Treatments)											
Intercept	0.233	0.533	0.292	0.353	0.386	0.138	0.322	0.217	0.124	0.200	0.539
Slope	0.0050	-0.0083	0.0025	-0.0003	0.0025	-0.0021	0.0000	0.0033	0.0021	0.0008	0.0083
Slope Std Error	0.0028	0.0072	0.0023	0.0030	0.0054	0.0029	0.0058	0.0033	0.0034	0.0023	0.0087
(0 to 10)											
Intercept	0.250	0.517	0.300	0.356	0.383	0.158	0.383	0.233	0.117	0.223	0.533
Slope	0.0000	-0.0033	0.0000	-0.0011	0.0033	-0.0083	-0.0183	-0.0017	0.0042	-0.0060	0.0100
Slope Std Error	0.0048	0.0171	0.0052	0.0069	0.0081	0.0058	0.0125	0.0064	0.0047	0.0044	0.0114
(10 to 20)											
Intercept	0.150	0.617	0.250	0.339	0.400	0.033	0.017	0.133	0.158	0.085	0.567
Slope	0.0100	-0.0133	0.0050	0.0006	0.0017	0.0042	0.0183	0.0083	0.0000	0.0077	0.0067
Slope Std Error	0.0061	0.0116	0.0043	0.0049	0.0116	0.0040	0.0065	0.0070	0.0081	0.0040	0.0199

Continued ...

Table A-31. Data Analysis for Polonium-210...(Malabar), Continued.

	Regrowth Overall 1993-94	Mature Overall 1993-94	1995	Regrowth 1996 Composite	Mature 1996 11/1/96	Regrowth 1997 Composite	Mature 1997 11/5/97	Regrowth 1998 Composite	Mature 1998 10/13/98	Regrowth Overall 1996-98	Mature Overall 1996-98
Means For:											
0 Mg/ha	A 0.280	A 0.458		B 0.175	A 0.300	A 0.233	A 0.623	A 0.188	A 0.325	A 0.192	A 0.414
10	A 0.240	A 0.525		A 0.195	A 0.292	A 0.280	A 0.587	A 0.113	A 0.463	A 0.196	A 0.436
20	A 0.287	A 0.567		BA 0.185	A 0.324	A 0.255	A 0.461	A 0.225	A 0.350	A 0.216	A 0.377
LSD	0.078	0.240	No	0.016	0.054	0.050	0.213	0.136	0.560	0.053	0.151
ANOVA			Sample								
P(Treatment)	0.450	0.651		0.052	0.426	0.165	0.244	0.201	0.820	0.624	0.725
P(Trends):											
Linear	0.857	0.363		0.177	0.347	0.476	0.118	0.525	0.917	0.379	0.615
Nonlinear	0.212	0.903		0.035	0.368	0.083	0.595	0.099	0.552	0.690	0.536
Linear Equations:											
(All Treatments)											
Intercept	0.265	0.463		0.180	0.294	0.248	0.638	0.156	0.367	0.189	0.428
Slope	0.0004	0.0054		0.0005	0.0012	0.0009	-0.0081	0.0019	0.0013	0.0012	-0.0019
Slope Std Error	0.0020	0.0054		0.0005	0.0012	0.0010	0.0041	0.0038	0.0103	0.0013	0.0036
(0 to 10)											
Intercept	0.280	0.458		0.175	0.300	0.233	0.623	0.188	0.325	0.192	0.414
Slope	-0.0039	0.0067		0.0020	-0.0008	0.0047	-0.0037	-0.0075	0.0138	0.0003	0.0021
Slope Std Error	0.0042	0.0077		0.0009	0.0022	0.0013	0.0047	0.0060	0.0251	0.0026	0.0081
(10 to 20)											
Intercept	0.194	0.483		0.204	0.261	0.305	0.712	0.000	0.575	0.175	0.495
Slope	0.0046	0.0042		-0.0010	0.0032	-0.0025	-0.0125	0.0113	-0.0113	0.0021	-0.0059
Slope Std Error	0.0035	0.0122		0.0009	0.0025	0.0017	0.0104	0.0070	0.0234	0.0027	0.0075

Table A-32. Data Analysis for Polonium-210 in Bahiagrass Forage Grown on PG-Treated Florida Land--Spodic Soil (Myakka).

	1993 Regrowth Individual Collections			Regrowth Overall	Mature 1993	1994 Regrowth Individual Collections			Regrowth Overall	Mature 1994
	7/12/93	8/9/93	9/21/93	1993	11/19/93	5/3/94	6/8/94	7/11/94	1994	12/7/94
Means For:										
0 Mg/ha	B 0.417	BA 0.167	A 0.192	B 0.258	B 0.333	A 0.267	A 0.333	B 0.108	A 0.236	A 0.400
10	A 1.067	B 0.133	A 0.367	BA 0.522	A 0.550	A 0.350	A 0.383	B 0.167	A 0.300	A 0.717
20	A 1.267	A 0.283	A 0.283	A 0.611	A 0.567	A 0.300	A 0.233	A 0.283	A 0.272	A 0.733
LSD	0.289	0.150	0.203	0.283	0.180	0.175	0.211	0.110	0.108	0.362
ANOVA										
P(Treatment)	< 0.001	0.112	0.209	0.041	0.029	0.583	0.316	0.015	0.497	0.117
P(Trends):										
Linear	< 0.001	0.113	0.339	0.016	0.016	0.681	0.317	0.005	0.505	0.067
Nonlinear	0.073	0.146	0.133	0.475	0.184	0.351	0.251	0.510	0.330	0.311
Linear Equations:										
(All Treatments)										
Intercept	0.492	0.136	0.235	0.288	0.789	0.289	0.367	0.099	0.251	1.017
Slope	0.0425	0.0058	0.0046	0.0176	0.0117	0.0017	-0.0050	0.0088	0.0018	0.0317
Slope Std Error	0.0068	0.0040	0.0047	0.0067	0.0067	0.0040	0.0059	0.0024	0.0027	0.0105
(0 to 10)										
Intercept	0.417	0.167	0.192	0.258	0.333	0.267	0.333	0.108	0.236	0.400
Slope	0.0650	-0.0033	0.0175	0.0264	0.0217	0.0083	0.0050	0.0058	0.0064	0.0317
Slope Std Error	0.0113	0.0037	0.0083	0.0110	0.0098	0.0083	0.0134	0.0037	0.0060	0.0174
(10 to 20)										
Intercept	0.867	-0.017	0.450	0.433	0.533	0.400	0.533	0.050	0.328	0.700
Slope	0.0200	0.0150	-0.0083	0.0089	0.0017	-0.0050	-0.0150	0.0117	-0.0028	0.0017
Slope Std Error	0.0140	0.0093	0.0097	0.0160	0.0075	0.0081	0.0086	0.0052	0.0047	0.0235

Continued ...

Table A-32. Data Analysis for Polonium-210...(Myakka), Continued.

	Regrowth Overall# 1993-94	Mature Overall 1993-94	1995	Regrowth 1996 Composite	Mature 1996 11/1/96	Regrowth 1997 Composite	Mature 1997 11/12/97	Regrowth 1998 Composite	Mature 1998 10/13/98	Regrowth Overall 1996-98	Mature Overall 1996-98
Means For:											
0 Mg/ha	A 0.213	B 0.367		A 0.136	A 0.370	A 0.193	A 0.746	A 0.325	A 0.325	A 0.206	A 0.484
10	A 0.280	A 0.633		A 0.152	A 0.438	A 0.187	A 0.642	A 0.250	A 0.425	A 0.190	A 0.503
20	A 0.277	A 0.650		A 0.157	A 0.389	A 0.173	A 0.658	A 0.300	A 0.600	A 0.202	A 0.535
LSD	0.081	0.203	No	0.028	0.074	0.042	0.232	0.266	0.275	0.077	0.143
ANOVA			Sample								
P(Treatment)	0.187	0.012		0.268	0.158	0.527	0.561	0.789	0.121	0.907	0.762
P(Trends):											
Linear	0.123	0.008		0.130	0.579	0.290	0.407	0.826	0.050	0.917	0.469
Nonlinear	0.323	0.156		0.602	0.069	0.785	0.508	0.531	0.713	0.670	0.912
Linear Equations:											
(All Treatments)											
Intercept	0.225	0.408		0.138	0.834	0.194	1.882	0.304	0.423	0.201	0.481
Slope	0.0032	0.0142		0.0010	-0.0044	-0.0010	-0.0253	-0.0013	0.0094	-0.0002	0.0026
Slope Std Error	0.0021	0.0055		0.0006	0.0047	0.0009	0.0139	0.0051	0.0132	0.0018	0.0034
(0 to 10)											
Intercept	0.213	0.367		0.136	0.370	0.193	0.746	0.325	0.325	0.206	0.484
Slope	0.0067	0.0267		0.0016	0.0068	-0.0006	-0.0104	-0.0075	0.0100	-0.0016	0.0019
Slope Std Error	0.0042	0.0099		0.0013	0.0033	0.0022	0.0129	0.0099	0.0127	0.0036	0.0076
(10 to 20)											
Intercept	0.283	0.617		0.148	0.487	0.201	0.626	0.200	0.250	0.178	0.470
Slope	-0.0003	0.0017		0.0005	-0.0049	-0.0014	0.0016	0.0050	0.0175	0.0012	0.0033
Slope Std Error	0.0040	0.0123		0.0010	0.0033	0.0012	0.0051	0.0119	0.0085	0.0037	0.0051

Notes:

\# Regrowth Overall 1993-94 Analysis Excludes First Harvest

Table A-33. Airborne Rn over PG-Treated Florida Land Cropped to Bahiagrass --Non-Spodic Soil (Malabar).

Collection No., Sampling Period, & [Number of days in Sampling Period]	Airborne Radon Exposure Rate, pCi L^{-1} for Indicated Mg ha^{-1} Treatment Level									
	0 ($C_{ext,o}$)		0 ($C_{ext,i}$)		0 (C_{int})		10		20	
PRE- PG APPLICATION										
0. 04/07/93 - 05/10/93 [33]					0.14					
POST-PG APPLICATION										
Yr 1 (1993-1994)										
1. 05/25/93 - 07/29/93 [65]	0.14	(3)	0.17	(6)	0.17		0.23		0.22	
2. 08/06/93 - 10/05/93 [60]	0.34	(4)	0.27	(5)	0.23	(10)	0.30		0.27	
3. 10/06/93 - 12/09/93 [64]	0.36	(5)	0.21	(6)	0.27		0.31		0.31	
4. 02/10/94 - 04/11/94 [60]	0.40	(4)	0.27	(6)	0.29		0.29		0.29	
Time Wt'd Mean [249]	0.31		0.23		0.24		0.28		0.27	
Yr 2 (1994-1995)										
5. 04/13/94 - 06/20/94 [68]	0.45	(4)	0.41	(5)	0.30	(11)	0.27		0.24	
6. 06/21/94 - 08/08/94 [48]	0.33	(5)	0.27	(6)	0.11		0.14		0.12	
7. 08/10/94 - 11/01/94 [83]	NM		NM		0.24		0.14	(10)	0.13	
8. 11/02/94 - 12/23/94 [51]	0.07	(6)	0.23	(5)	0.11		0.10		0.14	
9. 12/27/94 - 02/22/95 [57]	0.05	(3)	0.15	(4)	0.07	(10)	0.07	(10)	0.05	
Time Wt'd Mean [307]	0.23		0.27		0.18		0.15		0.14	
Yr 3 (1995-1996)										
10. 11/22/95 - 02/06/96 [76]	0.14	(1)	0.12	(4)	0.13	(5)	0.12		0.09	
11. 02/07/96 - 05/20/96 [103]	0.29	(4)	0.17	(4)	0.17	(4)	0.12	(5)	0.20	
12. 05/23/96 - 07/22/96 [60]	0.31	(2)	0.13	(4)	0.36	(4)	0.14	(3)	0.16	(4)
13. 07/24/96 - 09/30/96 [68]	0.72	(2)	0.26	(2)	0.19	(2)	0.28	(5)	0.19	(5)
Time Wt'd Mean [307]	0.35		0.17		0.20		0.16		0.16	
Yr 4 (1996-1997)										
14. 10/29/96 - 01/24/97 [87]	0.10	(3)	0.30	(2)	0.12	(2)	0.03	(4)	0.09	(4)
15. 02/03/97 - 04/18/97 [74]	0.33	(2)	0.11	(3)	0.36	(4)	0.48	(5)	0.26	(3)
16. 04/21/97 - 05/23/97 [32]	0.37	(4)	0.28	(4)	0.21	(4)	0.48	(5)	0.48	(4)
17. 06/04/97 - 08/11/97 [68]	0.44	(2)	0.13	(4)	0.13	(2)	0.36		0.56	(5)
Time Wt'd Mean [261]	0.29		0.20		0.20		0.30		0.31	

Notes:

- PG Application 5/25/93
- $C_{ext,o}$ = Outside chimney measurements from External Control Stations.
  $C_{ext,i}$ = Inside chimney measurements from External Control Stations.
  C_{int} = Internal Control = Untreated plots within contiguous treatment array.
- Data points for collections 0-9 represent means of 12 replicate plots (or stations) unless indicated otherwise by number in ( ), except for C_{ext} which are means of 6 replicates.
  Data points for collections 10-17 represent means of 6 replicate plots (or stations) unless indicated otherwise by number in ( ), except for C_{ext} which are means of 4 replicates.
- Collections 0-9 involved 3 EIC/plot (or station) except for $C_{ext,o}$ with 1 EIC/station; collections 10-17 involved 2 EIC/plot (or station) .
- NM = Not measured.

Table A-34. Airborne Rn over PG-Treated Florida Land Cropped to Bahiagrass --Spodic Soil (Myakka).

Collection No., Sampling Period, & [Number of days in Sampling Period]	Airborne Radon Exposure Rate , pCi L^{-1} for Indicated Mg ha^{-1} Treatment Level				
	0 ($C_{ext,o}$)	0 ($C_{ext,i}$)	0 (C_{int})	10	20
PRE- PG APPLICATION					
0. 04/08/93 - 05/11/93 [33]			0.16		
POST-PG APPLICATION					
Yr 1 (1993-1994)					
1. 06/01/93 - 08/07/93 [67]	0.17 (5)	0.13 (6)	0.21	0.20	0.22
2. 08/07/93 - 10/13/93 [67]	0.30 (4)	0.41 (5)	0.36 (11)	0.38	0.23 (11)
3. 10/14/93 - 12/15/93 [62]	0.31 (4)	0.26 (6)	0.32	0.29	0.32
4. 02/28/94 - 04/25/94 [56]	0.14 (3)	0.32 (6)	0.32 (11)	0.43	0.21 (11)
Time Wt'd Mean [252]	0.23	0.28	0.30	0.32	0.24
Yr 2 (1994-1995)					
5. 04/26/94 - 07/06/94 [71]	0.59 (6)	0.37 (6)	0.34	0.34	0.36
6. 07/07/94 - 09/14/94 [69]	0.23 (4)	0.23 (3)	0.19	0.19	0.28 (11)
7. 10/17/94 - 12/05/94 [49]	0.24 (2)	0.27 (2)	0.13	0.15	0.24
8. 12/06/94 - 02/14/95 [70]	NM	NM	0.13	0.16	0.22
Time Wt'd Mean [259]	0.37	0.29	0.20	0.22	0.28
Yr 3 (1995-1996)					
9. 11/30/95 - 02/07/96 [70]	0.12 (3)	0.04 (3)	0.11	0.12 (4)	0.06 (4)
10. 02/12/96 - 05/29/96 [107]	0.36 (4)	0.10 (2)	0.24 (5)	0.06 (4)	0.17
11. 06/07/96 - 07/22/96 [45]	0.41 (4)	0.13 (4)	0.09	0.15 (5)	0.19
12. 07/25/96 - 10/01/96 [68]	0.18 (4)	0.33 (4)	0.25	0.33	0.19
Time Wt'd Mean [290]	0.27	0.14	0.19	0.15	0.15
Yr 4 (1996-1997)					
13. 10/29/96 - 02/10/97 [104]	0.27 (4)	0.33 (4)	0.13	0.42 (3)	0.36
14. 02/14/97 - 04/25/97 [70]	0.17 (2)	NM	0.20 (4)	0.15 (3)	0.21 (3)
15. 04/29/97 - 06/11/97 [43]	0.62 (3)	0.25 (4)	0.13 (3)	0.02 (1)	0.11 (3)
16. 06/12/97 - 07/23/97 [41]	0.22 (3)	0.50 (2)	0.03 (2)	0.68 (1)	0.33 (4)
Time Wt'd Mean [258]	0.30	0.35	0.13	0.32	0.27

Notes:

- PG Application 6/01/93
- $C_{ext,o}$ = Outside chimney measurements from External Control Stations.
  $C_{ext,i}$ = Inside chimney measurements from External Control Stations.
  C_{int} = Internal Control = Untreated plots within contiguous treatment array.
- Data points for collections 0-8 represent means of 12 replicate plots (or stations) unless indicated otherwise by number in ( ), except for C_{ext} which are means of 6 replicates.
  Data points for collections 9-16 represent means of 6 replicate plots (or stations) unless indicated otherwise by number in ( ), except for C_{ext} which are means of 4 replicates.
- Collections 0-8 involved 3 EIC/plot (or station) except for $C_{ext,o}$ with 1 EIC/station; collections 9-16 involved 2 EIC/plot (or station) .
- NM = Not measured.

Table A-35. Data Analysis for Airborne Rn over PG-Treated Florida Land Cropped to Bahiagrass--Non-Spodic Soil (Malabar).

	Post-Application				
	Year 1 (1993-94)	**Year 2 (1994-95)**	**Year 3 (1995-96)**	**Year 4 (1996-97)**	**Overall 1993-1998**
No. of Collections	4	5	4	4	17
Means For:					
0 Mg/ha	A 0.244	A 0.163	A 0.191	A 0.247	A 0.195
10	A 0.270	A 0.140	A 0.146	A 0.339	A 0.206
20	A 0.269	A 0.139	A 0.159	A 0.378	A 0.209
LSD	0.040	0.041	0.080	0.236	0.030
ANOVA					
P(Treatment)	0.418	0.429	0.472	0.725	0.625
P(Trends):					
Linear	0.293	0.264	0.412	0.468	0.372
Nonlinear	0.426	0.505	0.363	0.738	0.707
Linear Equation:					
Intercept	0.007	0.159	0.179	0.259	0.196
Slope	0.0012	-0.0012	-0.0014	0.0064	0.0007
Std error(slope)	0.0010	0.0010	0.0020	0.0060	0.0008

Table A-36. Data Analysis for Airborne Rn over PG-Treated Florida Land Cropped to Bahiagrass--Spodic Soil (Myakka).

	Post-Application				
	Year 1 (1993-94)	Year 2 (1994-95)	Year 3 (1995-96)	Year 4 (1996-97)	Overall 1993-1998
No. of Collections	4	4	4	4	16
Means For:					
0 Mg/ha	A 0.292	B 0.190	A 0.187	A 0.283	A 0.225
10	A 0.291	B 0.211	A 0.160	A 0.297	A 0.242
20	B 0.237	A 0.270	A 0.165	A 0.248	A 0.244
LSD	0.053	0.045	0.102	0.343	0.035
ANOVA					
P(Treatment)	0.049	0.001	0.895	0.930	0.450
P(Trends):					
Linear	0.032	< 0.001	0.683	0.904	0.234
Nonlinear	0.233	0.251	0.815	0.720	0.673
Linear Equation:					
Intercept	0.301	0.184	0.182	0.288	0.227
Slope	-0.0028	0.0040	-0.0011	-0.0017	0.0010
Slope Std Error	0.0013	0.0011	0.0024	0.0069	0.0009

APPENDIX B

WORKSHEETS FOR THE RADIOLOGICAL ASSESSMENT

APPENDIX B

WORKSHEETS FOR THE RADIOLOGICAL ASSESSMENT

The purpose of this appendix is to organize and present reference data and factors to support the radiological assessment of the long-term application of PG to forage lands.

BASELINE VALUES

One criterion of the significance of a projected radiological characteristic resulting from a proposed practice is how it compares to pre-existing baseline or background values and their spatial variations. Baseline data for the various measured parameters at a number of field sites at the Ona Research Station are tabulated and analyzed in Worksheets B-1 through B-3. Data identified as “Phase 1" are taken from Rechcigl and others (1996).

Worksheet B-1. Background Data for Radionuclides in Surface Layer Soil, Ona Vicinity.

Site	Concentration, pCi g^{-1}		
	^{226}Ra	^{210}Pb	^{210}Po
0-5 cm (0-2 in) Layer (Minimum Sampling)			
Phase 1 bahiagrass test plots	0.55	0.61	0.53
Phase 1 ryegrass test plots	0.43	0.76	0.38
Phase 2/3 Malabar test plots	0.49	1.12	0.81
Phase 2/3 Myakka test plots	0.30	0.72	0.65
Mean (N=4)	**0.442**	**0.802**	**0.592**
Minimum	0.30	0.61	0.38
Maximum	0.55	1.12	0.81
Standard Deviation	**0.107**	**0.221**	**0.182**
Phase 1 values are from 0-15 cm samples.			
Phase 2/3 values are from 0-5 cm samples.			
0-15 cm (0-6 in) Layer (Tilling/Root Zone)			
Phase 1 bahiagrass test plots	0.55	0.61	0.53
Phase 1 ryegrass test plots	0.43	0.76	0.38
Phase 2/3 Malabar test plots	0.34	0.49	0.47
Phase 2/3 Myakka test plots	0.23	0.64	0.49
Mean (N=4)	**0.388**	**0.625**	**0.455**
Minimum	0.23	0.49	0.38
Maximum	0.55	0.76	0.53
Standard Deviation	**0.136**	**0.111**	**0.062**
Phase 1 values are from 0-15 cm samples.			
Phase 2/3 values are means of three 5-cm layers, 0 to 15 cm.			

Continued ..

Worksheet B-1. Continued.			
0-61 cm (0-2 ft) Layer (Rn Modeling Layer)			
Phase 1 bahiagrass test plots	0.58	0.48	0.36
Phase 1 ryegrass test plots	0.63	0.68	0.59
Phase 2/3 Malabar test plots	0.39	0.47	0.29
Phase 2/3 Myakka test plots	0.32	0.30	0.25
Mean (N=4)	**0.480**	**0.482**	**0.362**
Minimum	0.32	0.30	0.25
Maximum	0.63	0.68	0.59
Standard Deviation	**0.148**	**0.155**	**0.154**

Phase 1 values are means of four 15-cm layers, 0 to 60 cm.
Phase 2/3 values are depth-weighted means of five layers.

Worksheet B-2. Background Data for Rn Flux and Gamma Radiation, Ona Vicinity.

Site	Rn Flux, pCi m^{-2} s^{-1}	Gamma Exposure Rate, µR hr^{-1}
Phase 1 bahiagrass test plots	0.031	4.81
Phase 1 bahiagrass External Control 1	--	5.23
Phase 1 bahiagrass External Control 2	--	5.92
Phase 1 ryegrass test plots	0.022	5.45
Phase 1 ryegrass External Control 1	--	5.39
Phase 1 ryegrass External Control 2	--	5.69
Phase 2/3 Malabar test plots	0.027	6.19
Phase 2/3 Malabar External Control	0.035	6.55
Phase 2/3 Myakka test plots	0.016	6.22
Phase 2/3 Myakka External Control	0.019	5.90
Mean	**0.0250**	**5.735**
Minimum	0.016	4.81
Maximum	0.035	6.55
Standard Deviation	**0.0073**	**0.525**
	(N = 6)	(N = 10)

Worksheet B-3. Background Data for Radionuclides in Groundwater and Forages, Ona Vicinity.

Site	Concentration, pCi unit^{-1}		
	^{226}Ra	^{210}Pb	^{210}Po
RUNOFF WATER (pCi L^{-1})			
Phase 1 bahiagrass test plots	0.19	0.45	0.44
Phase 1 ryegrass test plots	NS	NS	NS
Phase 2/3 Malabar test plots	0.34	0.40	0.42
Phase 2/3 Myakka test plots	0.38	0.01	0.72
Mean (N=3)	**0.303**	**0.287**	**0.527**
Minimum	0.19	0.01	0.42
Maximum	0.38	0.45	0.72
Standard Deviation	**0.100**	**0.241**	**0.168**
SHALLOW GROUNDWATER (pCi L^{-1})			
Phase 1 bahiagrass test plots	0.60	0.44	0.82
Phase 1 bahiagrass External Control	0.46	0.32	0.45
Phase 1 ryegrass test plots	0.85	0.49	0.49
Phase 1 ryegrass External Control	0.52	0.67	0.49
Phase 2/3 Malabar test plots	0.65	0.60	0.59
Phase 2/3 Myakka test plots	0.60	1.02	0.26
Mean (N=6)	**0.612**	**0.590**	**0.517**
Minimum	0.46	0.32	0.26
Maximum	0.85	1.02	0.82
Standard Deviation	**0.132**	**0.244**	**0.183**
MATURE HAY (pCi g^{-1})			
Phase 1 bahiagrass test plots	0.03	1.33	0.57
Phase 2/3 Malabar test plots	0.08	1.04	0.43
Phase 2/3 Myakka test plots	0.08	1.00	0.44
Mean (N=3)	**0.063**	**1.123**	**0.480**
Minimum	0.03	1.00	0.43
Maximum	0.08	1.33	0.57
Standard Deviation	**0.029**	**0.180**	**0.078**
REGROWTH FORAGE (pCi g^{-1})			
Phase 1 bahiagrass test plots	0.05	0.93	0.33
Phase 2/3 Malabar test plots	0.12	0.43	0.23
Phase 2/3 Myakka test plots	0.09	0.42	0.22
Mean (N=3)	**0.087**	**0.593**	**0.260**
Minimum	0.05	0.42	0.22
Maximum	0.12	0.93	0..33
Standard Deviation	**0.035**	**0.292**	**0.061**

PROJECTION OF INDOOR RADON CONCENTRATIONS

One of the major radiological questions with regard to the long-term application of PG to land concerns what indoor Rn concentrations might occur in future structures built on PG-treated land. In this study, Rn flux was measured as the primary indicator of the source term for Rn of soil origin. Projection of future indoor Rn concentrations involves projecting the future Rn flux level expected to result from the proposed PG treatment practice and then estimating the expected resultant indoor Rn concentration. Indoor Rn concentrations are modeled by a variety of methods including:

1) Empirical models relating indoor Rn to a simple suite of soil measurements (such as ^{226}Ra profile, soil gas Rn concentration, or Rn flux); and

2) Radon entry models using soil Rn source characteristics (^{226}Ra profile and/or soil gas Rn), soil properties affecting Rn transport (such as permeability, density, moisture, etc.), and house characteristics (such as coupling to the ground, floor penetrations, pressure differentials, air exchange rate, etc.).

The method chosen for this project was that of predicting indoor Rn from simple, empirically-derived Rn/Rn flux relationships. A number of equations developed from several different data sets were used. These included both linear models (linear regression of the untransformed data) and power function models (back-transformed from the linear regression of the log-transformed data sets). The majority of the equations were developed in unpublished work at the University of Florida in the 1980's using a Florida data set and several sets of data from the literature. For this current study, an additional set of Florida data collected in the 1990's as part of the Florida Radon Research Program (FRRP) was analyzed by linear regression (Worksheet B-4). The several models used and the predicted indoor Rn concentrations are summarized in Worksheet B-5.

The incremental (PG-attributable) indoor Rn concentration predicted by the linear models is independent of the baseline Rn flux. However, predicting the incremental indoor Rn concentration by the power function models requires the specification of a baseline Rn flux. As the baseline Rn flux is increased, the incremental indoor Rn predicted by the power function models decreases. The low baseline Rn flux characteristic of the Ona research site (0.025 pCi m^{-2} s^{-1}) was used in the calculations, giving high-side conservatism. The models result in a range of projected values for the same PG-treatment practice; the power function models predicted higher incremental indoor Rn concentrations than the linear models. The models are crude and they have obvious short-comings; however, it is felt that they present an order of magnitude of the effect to be expected. The geometric mean PG-attributable indoor Rn value was chosen to carry forward in the assessment process.

Worksheet B-4. Empirical Relationship of Indoor Rn and Soil Rn Flux, Florida houses.

REGRESSION EQUATIONS

Linear Form:

$C_{Rn} = 2.44 + 0.475\ J$ $\quad R^2 = 0.64$

Linear Regression on Ln-transformed Data:

$\ln(C_{Rn}) = 1.094 + 0.344 \ln(J)$ or $C_{Rn} = 2.99\ J^{0.344}$ $\quad R^2 = 0.66$

Where C_{Rn} = Indoor Rn concentration, pCi L^{-1}, and
J = Soil Rn flux, pCi $m^{-2}\ s^{-1}$.

DATA

House No.	SSV System	Foundation	Rn Flux, pCi $m^{-2}\ s^{-1}$	Indoor Rn pCi L^{-1}
E-30	None	SSW	0.50 ± 0.35	2.7 ± 0.8
E-31		SSW	0.38 ± 0.11	1.6 ± 0.4
E-34		SSW	0.61 ± 0.93	2.1 ± 0.1
E-35		SSW	1.02 ± 1.34	5.8 ± 2.0
E-36		SSW	0.36 ± 0.17	1.9 ± 0.4
E-37		SSW	0.38 ± 0.13	1.9 ± 0.4
E-38		SSW	0.35 ± 0.11	2.2 ± 0.8
E-39		Mono	4.62 ± 2.81	3.2 ± 1.1
E-40		SSW	3.74 ± 3.78	4.4 ± 0.6
E-41		SSW	3.76 ± 3.74	5.0 ± 1.3
E-42		SSW	0.76 ± 0.17	2.1 ± 0.1
C-14	Not Stated	Mono	4.57 ± 4.57	6.0 ± 1.6
E-32		SSW	0.48 ± 0.17	2.3 ± 0.0
E-45		Mono	0.52 ± 0.30	4.0 ± 1.7
D-06		Mono	5.40 ± 3.20	3.0 ± 0.5
D-08		Mono	16.8 ± 24.2	6.2 ± 2.2
D-10		Mono	5.31 ± 2.76	5.7 ± 1.5
D-11		Mono	17.1 ± 10.2	14.8 ± 3.6

Data from EPA -600/R-95-161, Nov 1995 (Nielson et al., 1995)
SSV = Sub-slab ventilation system.
Foundations: SSW = Slab in stem wall; Mono = Monolithic slab.

Worksheet B-5. Projection of Indoor Rn Concentrations over PG-treated Lands.

SCENARIO

PG treatment: 0.4 MG ha^{-1} annually for 100 yrs.; 40 MG ha^{-1} cumulative.

Projected PG-attributable Rn flux, 100th yr: $\Delta J = 0.072$ pCi m^{-2} s^{-1} (see Table 16).

INDOOR RN PROJECTIONS BY VARIOUS MODELS

Model	Indoor Rn Concentration, pCi L^{-1}		
	C_{Rn} for $J = 0.097$	C_{BL} for $J_{BL} = 0.025$	ΔC_{Rn} for $\Delta J = 0.072$
PF-1	0.594	0.318	0.28
PF-2	0.326	0.164	0.16
PF-3	0.249	0.098	0.15
PF-4	1.340	0.084	0.50
L-1	2.092	2.076	0.02
L-2	2.486	2.452	0.03

Summary for $\Delta J = 0.072$ pCi m^{-2} s^{-1}: ΔC_{Rn} = 0.02 to 0.5 pCi L^{-1};

Geometric mean ΔC_{Rn} = 0.11 pCi L^{-1}.

MODELS

A. Models from unpublished University of Florida work (1988):

PF-1: Data set #1, 31 Florida houses. $C_{Rn} = 1.74\ J^{0.461}$

PF-2: Data set #2, seven pairs of data from the literature, U.S. houses.
$C_{Rn} = 1.07\ J^{0.509}$

PF-3: Data set #3, 40 pairs of data from the literature, Norway and Denmark.
$C_{Rn} = 1.23\ J^{0.685}$

L-1: Data set #2, linear form
$C_{Rn} = 2.07 + 0.232\ J$; or $\Delta C_{Rn} = 0.232\ \Delta J$

B. Analysis of data from EPA-600/R-95-161 (1995),18 Florida houses:
(See Worksheet B-4)

L-2: $C_{Rn} = 2.44 + 0.475\ J$; or $\Delta C_{Rn} = 0.475\ \Delta J$

PF-4: $C_{Rn} = 2.99\ J^{0.344}$

Where C_{Rn} = Indoor Rn concentration, pCi L^{-1};
and J = Soil surface Rn flux, pCi m^{-2} s^{-1}.

FORAGE-BEEF TISSUE-HUMAN PATHWAY

One potential route of radiation exposure to humans as a result of treating agricultural lands with PG involves the use of food products derived from animals consuming forage from PG-treated land. Since this study addressed PG treatment of lands used to produce pasture and forage for beef animals; beef products are the relevant route to humans.

Assessment of this exposure pathway involves three steps: (1) determining radionuclide levels in animal tissues consumed by humans, (2) estimating intake of radionuclides by humans consuming these animal products, and (3) using radionuclide intake values to estimate radiation dose and risk. Since no actual animal feeding experiments were conducted and there were no actual measurements of radionuclide levels in beef, it is necessary to model the projected radionuclide concentrations in beef consuming forages from PG-treated land. The first two steps, predicting radionuclides levels in animal tissue and estimating intake of radionuclides by humans requires further review before the assessment can proceed.

Radionuclide Concentrations in Tissue of Beef Fed with Forage from PG-Treated Lands

Radionuclide concentrations in animal tissue at any point in time reflect the prior radionuclide intake history. This assessment will use the simplifying assumption that there has been a continuous, chronic intake and that there is a steady-state equilibrium between animal tissue and intake. The assessment for this study will use the Transfer Factor (also called Transfer Coefficient) approach which relates concentration in tissue to daily radionuclide intake quantity. The concentration, pCi kg^{-1}, of the *i*th radionuclide in beef is estimated by:

$$C_{beef,i} = F_{beef,i}\, C_{forage,i}\, Q_{feed}$$

where

$F_{beef,i}$ = element-dependent transfer factor, the fraction of the daily intake that is transferred to a unit of meat (quantity kg^{-1} per quantity d^{-1}; or simply d kg^{-1}),
$C_{forage,i}$ = concentration of radionuclide i in forage (pCi kg^{-1}), and
Q_{feed} = feed consumed daily by animal on a dry matter basis (kg d^{-1}).

Thus, given a projected radionuclide concentration in feed, the process requires selection of values of Q_{feed} to calculate the daily radionuclide intake by the reference animal and values of $F_{beef,i}$ to convert the radionuclide intake to expected concentration in beef.

Animal diets will vary depending upon factors such as breed and age of the animal, the type of feeding program, and the type, availability, palatability of the feed. Worksheet B-6 summarizes some reported values of Q_{feed} for beef cattle and presents the value selected for this assessment.

The transfer factors relating a given intake by an animal and the concentration in meat exhibit considerable variability (NCRP 1999). Worksheet B-7 summarizes some reported values of F_{beef} for Ra, Pb, and Po. The values selected for this assessment are those from the most recent publication and represent high-side conservatism.

Worksheet B-6. Forage Intake by Beef Animals.

Data Source	Feed Intake, kg d^{-1}	
	Wet Wt.	Dry Wt.
Halbert et al (1990); review of various literature sources	63 (40-100)*	11 (9-14)*
Kennedy and Strenge (1992)	44 (forage & grain)	12
NCRP (1999), pg. 105	- -	7-8
Table 5.8	- -	8 (4-12)*
Brown (1999)†	- -	10 (9-11)*
Selected for this assessment	- -	**10**

*No.'s in ( ) indicate range of values in the report.
†Personal communication, W.F. Brown, Professor, Animal Science, University of Florida.(February 11, 1999). The daily dry matter consumption for a beef animal would be on the order of 2-2.5% of its live body weight. For a 545 kg (1000 lb) animal this calculates to be 9.1 to 11.4 kg d^{-1}.

Worksheet B-7. Feed to Tissue Transfer Coefficients, Beef.

Data Source	Transfer Factor, d kg^{-1}		
	Ra	Pb	Po
Halbert , et al. (1990)	6.8×10^{-4} ($5\text{-}9.9 \times 10^{-4}$)*	- -	- -
Kennedy and Strenge (1992)	2.5×10^{-4}	3.0×10^{-4}	3.0×10^{-4}
NCRP (1984)	5.0×10^{-4} (ND to 2.0×10^{-3})*	- -	- -
NCRP (1996, 1999)	1×10^{-3} (2.0)†	8×10^{-4} (2.0)†	5×10^{-3} (2.0)†
Till and Meyer (1990)	5.1×10^{-4}	4×10^{-4}	4.5×10^{-3}
Selected for this Assessment	**1×10^{-3}**	**8×10^{-4}**	**5×10^{-3}**

*No.'s in ( ) indicate range of values in the report.
† No. in ( ) is geometric standard deviation (GSD) assigned in NCRP Report No. 129.

Radionuclide Intake by Humans via Consumption of Beef Fed with Forage from PG-Treated Lands

The PG-attributable radiation dose (and risk) from the ingestion of beef products is a function of the intake of PG-attributable radionuclides. In turn, the projected intake of a radionuclide is determined by its concentration in the food product and the quantity of the product consumed (sometimes referred to as the "usage factor"). Selecting a realistic usage factor for this case is a difficult, highly subjective task. For this assessment, the reference individual will be an adult whose major source of meat is beef from animals for which the feed prior to slaughter was primarily grazing, forage, and/or hay from PG-treated lands. Worksheet B-8 summarizes some reported values of beef and meat usage factors. Note that the beef and red meat factors range from 21 to 59 kg y^{-1} and total (and/or non-specified) meat factors range from 50 to 100 kg y^{-1}.

Worksheet B-8. Usage Factors for Meat Consumption by Humans.

Meat Category	Annual Average Per Capita Consumption, kg y^{-1} (Wet Weight), from Various Data Sources						
	EPA *	Guidry et al.. (1990)	Kennedy & Strenge (1992)	NCRP (1996, 1999)	NRC (1977)†	UNSCEAR (1993)†	USDA(1994) †
Red Meat	- -	- -	- -	- -	- -	- -	52
Beef	32.0	47.2	59	- -	- -	- -	- -
Pork	10.3	14.4	- -	- -	- -	- -	- -
Poultry	11.4	- -	9	- -	- -	- -	28
Other Meat	9.2	25.2	- -	- -	- -	- -	- -
Not spec.	- -	- -	- -	100‡	95	50	- -
Sum of above	62.9	86.8	68	100	95	50	80

__Selected for this study__**: Screening value to assess consumption of beef fed on forages from PG-treated land = 50 kg y^{-1}.**

*From USEPA Office of Radiation Programs daily values in Table 11-10 of EPA (1996).

† These sources are summarized in NCRP (1999), Table 5.1. UNSCEAR and NRC values are for adult; the reference also has values for child and infant.

‡NCRP single generic meat value suggested for screening doses.

A value of 50 kg y^{-1} was selected for this assessment, giving a reference individual for which a major portion of the dietary meat is beef fed exclusively by forage from PG-treated land. This should produce an overestimate of the PG-attributable radionuclide intake; the typical individual is not likely to consume beef from exclusively range-fed animals in this great a quantity. Generally these animals would go to a feed lot for finishing before slaughter and receive feeds with lower concentrations of radionuclides; radionuclide concentrations in tissue at time of slaughter should be lower than projected for range-fed animals.

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APPENDIX C

RN FLUX MEASUREMENT SYSTEM INTERCOMPARISONS

APPENDIX C

RN FLUX MEASUREMENT SYSTEM INTERCOMPARISONS

At the present time there are no readily-accessible Rn flux standard sources and no on-going formal Rn flux measurement intercomparison programs. Therefore, the investigators conducted several *ad hoc* intercomparisons with other available Rn flux measurement systems to evaluate the system used in this study.

EXPERIMENTAL CONDITIONS

Experimental conditions are summarized in Table C-1. The Large Area Activated Charcoal Canister (LAACC) system used in the research study (LAACC-P in the table) was compared to the quite similar system of the Florida Department of Health and Rehabilitative Services (HRS) (LAACC-H) and, for various exercises, one or another of two versions of systems using electret ionization chamber (EIC) detectors.

Two types of Rn flux source were used: test beds and field plots. The test beds consisted of various depths of PG in wooden trays on tables in a well-ventilated greenhouse at the Ona Research Center. The field plots were the Malabar site PG-treated plots used in the research study. The field plots provided intercomparison under the conditions used for the research study. The indoor test beds were included as well to provide a more powerful intercomparison. Test bed Rn flux values, approximately an order of magnitude higher than for the field plots, were expected to have lower relative variation and, being less susceptible to variations in environmental conditions such as rainfall, soil moisture content, water table level, wind velocity, etc., were expected to be more constant with time than field plot values.

Exercises were conducted twice, October 1996 and February 1997, for each of the two Rn source types. Replication and other deployment conditions are summarized in the third section of Table C-1.

RESULTS

Systems Comparison, October 1996 Exercises

For the test bed exercise, the two LAACC systems and the EIC-passive system were codeployed. Results are plotted in Figure C-1 and summarized with statistical analyses in Table C-2. Individual results are presented in Annex CA-1. All three systems reported increasing Rn flux levels with increasing PG depth, but as suggested by the figure and verified by the statistical testing, each reported a different series of results ($P<0.001$ for both the PG beds). The magnitude ranking of the results reported by the three systems was:

LAACC-H > EIC-passive > LAACC-P.

For the two LAACC methods, System P results for the two PG depths were about 40% of the results reported by System H.

Table C-1. Experimental Conditions for Rn Flux Intercomparison Experiments.

Measurement Systems

1. LAACC-P. Large Area Activated Charcoal Canister (LAACC) method. Canisters, charcoal, counting, and calculations were provided by Pembroke Laboratories, Inc., Ft. Meade, FL. Preparation, deployment, and retrieval of canisters, transfer of charcoal to the shipping/counting containers, and transport of containerized charcoal to the counting laboratory were performed by University of Florida (UF), research personnel, Ona, FL.
2. LAACC-H. LAACC method. Entire system by Florida Department of Health and Rehabilitative Service (HRS), Office of Radiation Control, Orlando, FL. (HRS is now the Florida Department of Health.)
3. EIC-Flow. Electret Ionization Chamber (EIC) method with a pair of EICs in an air-purged flow-through collection chamber. Deployment and readout by UF research personnel and by representatives of Rad Elec Inc., Frederick, MD.
4. EIC-Passive. EIC method with the EIC coupled directly to the ground surface through a Rn-permeable diaphragm. Deployment and readout by UF and Rad Elec.

Rn Flux Sources (Both involve PG with a ^{226}Ra concentration of 21.6 pCi g^{-1}.)

1. Test Beds . Wooden trays, 61 cm (2 ft) x 91 cm (3 ft), filled to various depths with PG, placed on tables in a well-ventilated greenhouse at the Ona Research Center.

Bed Depths (3):	0 cm (Blank)	3.8 cm (1.5 in)	7.6 cm (3.0 in).
^{226}Ra*:	0 pCi m^{-2}	8.1 x 10^5 pCi m^{-2}	1.6 x 10^6 pCi m^{-2}

*(Assuming a PG bulk density of 1.0 g cm^{-3})

2. Field: PG-treated Research plots (pasture treated by surface application of PG).

PG treatment levels (3):	0 Mg ha^{-1}	10 Mg ha^{-1}	20 Mg ha^{-1}
^{226}Ra -- natural content plus:	0 pCi m^{-2}	2.1 x 10^4 pCi m^{-2}	4.3 x 10^4 pCi m^{-2}

Deployment Plan

1. Test Beds (3 trays/bed depth).	10/21-22/96	2/18-19/97
Bed Depths (source levels)	3	2 (0 & 3.8 cm)
Devices deployed per source level:		
LAACC-P	3 (1/tray)	6 (2/tray)**
LAACC-H	3 (1/tray)	6 (2/tray)
EIC-flow	none	3 (1/tray)
EIC-passive	3 (1/tray)	none

**(2/97 Test Bed exercises included multifactor experiment)

2. Field (12 plots per treatment level), 10/21-22/96 & 2/18-19/97

Treatment levels: 3 (both exercises)

Devices deployed per treatment level (both exercises):

LAACC-P	12 (1/plot)
LAACC-H	12 (1/plot)
EIC-flow	6 (1/plot on subset of 6 plots)

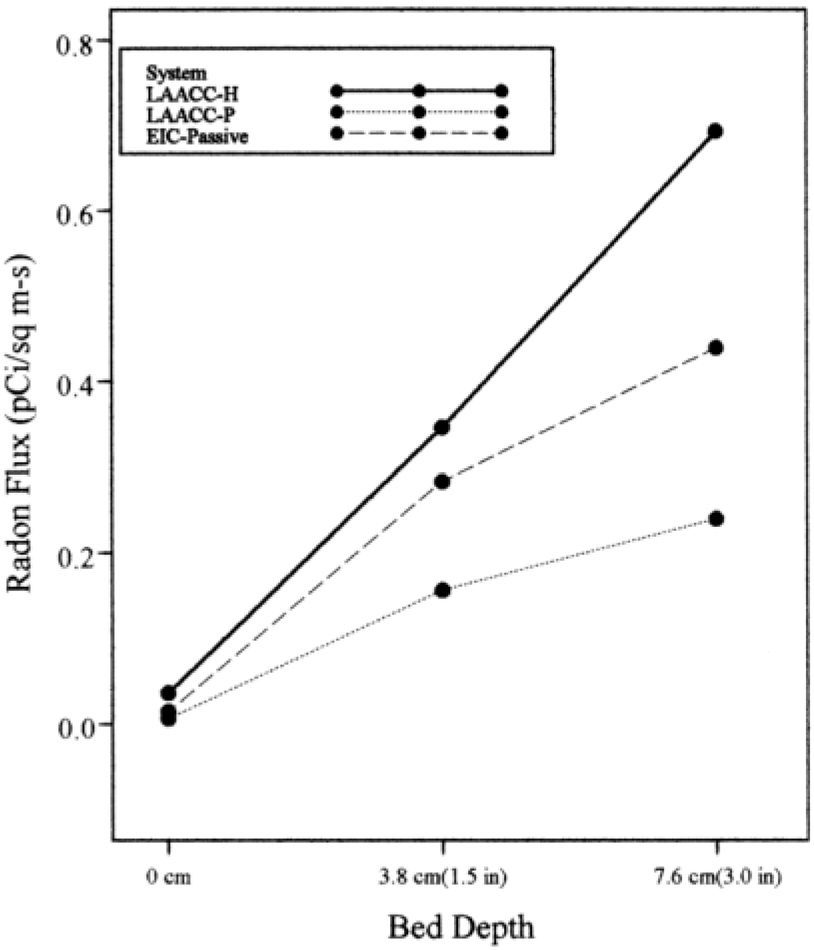

Figure C-1. Rn Flux Measurement Intercomparison, Test Bed Experiment, October 1996.

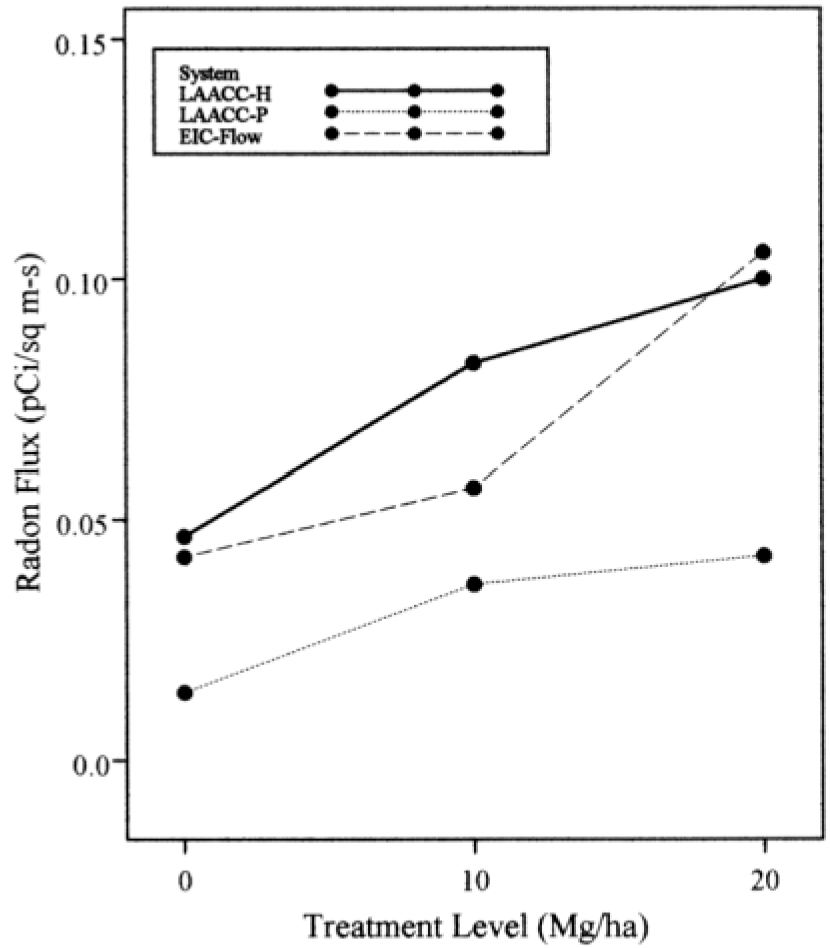

Figure C-2. Rn Flux Measurement Intercomparison, Field Experiment, October 1996.

Table C-2. Comparison of Rn Flux Measurement Systems, Test Bed Exercise, October 21-22, 1996.

	Blank Bed	3.8-cm Bed	7.6-cm Bed
Means, pCi m^{-2} s^{-1} for:			
LAACC-H	0.037 a	0.347 a	0.693 a
EIC-Passive	0.015 b	0.283 b	0.440 b
LAACC-P	0.007 b	0.157 c	0.240 c
ANOVA			
P(System)	0.039	<0.001	<0.001

Notes:
- LAACC means based on 3 replicates (3 trays x 1 canister/tray).
- EIC means based on 2 replicates (2 trays x 1 EIC/tray).
- Means with the same letter code (a, b, or c) are not significantly different at the $P \leq 0.05$ Level.

For the field test, the two LAACC systems and the EIC-flow system were codeployed. Results for the field exercise are plotted in Figure C-2 and summarized in Table C-3. Individual results are presented in Annex CA-2. The three systems all reported increasing Rn flux levels with increasing PG treatment level, but each reported a different series of results (P, System <0.001). The ranking of the magnitude of results reported by the three systems was:

$$\text{LAACC-H} \geq \text{EIC-flow} > \text{LAACC-P}.$$

The EIC-flow system reported results approaching those of the LAACC-H system. For the two LAACC methods, the System P results were about 39% of the system H results (ranging from 30% to 45% for the various treatment levels).

The differences between the results for the two LAACC systems is of particular note. The two systems used identical canister configurations and charcoal quantities, and they used very similar charcoal handling, counting, and Rn flux calculation procedures. It was concluded that the differences were likely due to (1) differences in Rn collection and retention efficiencies of different batches of charcoal, (2) a difference in standardization between the two counting laboratories, or (3) some other, subtle difference in procedures.

Calibration Comparison

To compare the calibration between the two counting laboratories, a ^{226}Ra-spiked sample prepared and standardized by Laboratory H was provided to Laboratory P for counting and calculation of the ^{226}Ra content. The results were as follows:

(Activity reported by Lab P)/(Activity assigned by Lab H) = 3632 pCi/3330 pCi = 1.087.

Table C-3. Comparison of Rn Flux Measurement Systems, Field Exercise, October 21-22, 1996.

	0 Mg ha^{-1}	10 Mg ha^{-1}	20 Mg ha^{-1}	Overall
Means, pCi m^{-2} s^{-1} for:				
LAACC-H	0.047 a	0.082 a	0.100 a	- -
EIC-Flow	0.042 a	0.057 (5)b	0.105 (5)a	- -
LAACC-P	0.014 b	0.037 b	0.042 b	- -
ANOVA				
P(Treatment)	- -	- -	- -	<0.001
P(System)	- -	- -	- -	<0.001
P(Treat x System)	- -	- -	- -	0.058

Notes:

- LAACC means based on 12 replicates (12 plots x 1 canister/plot).
- EIC means based on 6 replicates (6 plots x 1 EIC/plot) except where indicated (5).
- Means with the same letter code (a, b, or c) are not significantly different at the $P \leq 0.05$ Level.

The results reported by Laboratory P were about 109% of (i.e., quite comparable to) those of Laboratory H, rather than the 39-40% as obtained in the October 1996 test bed and field experiments.

This finding indicates that the counting procedures, radioactivity standardizations, and initial parts of the calculation procedures were comparable between the two laboratories. It suggests that the differences observed in the October 1996 intercomparisons were related to differences in either (1) Rn collection and/or retention efficiency of the respective charcoals, (2) later calculational steps (such as corrections for radioactive decay of Rn during collection, holding, or counting), or (3) some other subtle, unidentified technique feature.

After the October tests, Laboratory P (the commercial laboratory providing services to the project) exhausted its supply of activated charcoal and began use of a new batch, thus presenting the investigators with an additional, unanticipated variable.

Multifactor Comparison

The February 1997 exercises included a test bed experiment designed to test three variables in the LAACC method:

1. Charcoal
2. Analytical laboratory
3. Run number (order in counting rotation and delay until counting)

Canisters were deployed on the blank beds and the 3.8-cm (1.5-in) beds. Two pairs of charcoal canisters, one prepared by each of the two participating laboratories, were co-deployed on each of the three replicate beds at each of the two test levels. Each canister was analyzed and reported out by both laboratories. One member of each pair was analyzed first by the preparing ("home") laboratory and secondly by the other ("alternate") laboratory and the other member of the pair was analyzed first by the "alternate" laboratory and secondly by the "home" laboratory. (In the data analysis, the first and second counts are designated "Run 1" and "Run 2," respectively.) The results of this exercise are summarized in Table C-4; the individual data are tabulated in Annex CA-3.

Table C-4. Test of Charcoal, Laboratory, and Counting Order as Variables in LAACC Rn Flux Measurement -- 3.8-cm PG Test Bed, February, 1997.

A. Means (Rn Flux, pCi m^{-2} s^{-1})

Charcoal Source	Canister Set*	Analysis by Lab P	Analysis by Lab H	Average
Lab P	PP	0.318 (1)**	0.316 (2)	0.317
	PH	0.278 (2)	0.271 (1)	0.274
	Avg	0.298	0.294	0.296
Lab H	HH	0.378 (2)	0.369 (1)	0.374
	HP	0.425 (1)	0.389 (2)	0.402
	Avg	0.401	0.379	0.390
Both sources	Overall Avg	0.350	0.336	0.343

*Three canisters/set.
PP: P charcoal, 1st count by lab P (Canisters P43, P45, P47).
PH: P charcoal, 1st count by lab H (Canisters P44, P46, P48).
HH: H charcoal, 1st count by lab H (Canisters H43, H45, H47).
HP: H charcoal, 1st count by lab P (Canisters H44, H46, H48).
** No.'s in ( ) indicate whether result is from Run 1 or Run 2 (i.e., 1st or 2nd count).

B. ANOVA

Source	P-value
Charcoal	<0.001
Lab	0.007
Run	NS
Charcoal x Lab	0.039
Charcoal x Run	0.064
Run x Lab	0.021
Charcoal x Lab x Run	NS

From the Analysis of Variance (ANOVA) it can be seen that the charcoal batch is an important variable (P = <0.001). The overall average flux value for the 3.8-cm bed as measured by the Lab P charcoal (0.30 pCi m^{-2} s^{-1}) was 76% of the overall value measured by the Lab H charcoal (0.39 pCi m^{-2} s^{-1}).

The laboratory performing the analysis had some effect (P = 0.007). However, the effect was small; the overall average from all canisters on the 3.8-cm PG bed as reported by Laboratory P was 104% of the value reported by Laboratory H. There were some sporadic interaction effects that have little impact on the conclusions. These included Lab x Charcoal interaction (P = 0.039) -- the differences were significant for Lab H charcoal but not for Lab P charcoal, and Lab x Run interaction (P = 0.021) -- Lab P results were greater than Lab H results for Run 1 but the differences were not significant for Run 2.

The position in counting order (i.e., Run No.) was not significant as a main effect. The lack of a consistent overall effect for Run No. indicates that the extra handling and counting and a day's difference in holding time did not affect the reported results. There were some marginal interaction effects. These included Run x Charcoal (P = 0.064) where Run 1 results were slightly higher than Run 2 results for Lab H charcoal but slightly lower (not significant) for Lab P charcoal. The other was the Run x Lab interaction mentioned in the preceding paragraph. The Run 1 to Run 2 difference between the two laboratories suggests a possible slight difference in how the two laboratories document time markers and/or correct for radioactive decay during collection, holding, and counting, but the effect does not appear to be appreciable.

In conclusion, the major effect for the differences in the Rn flux values reported by the two LAACC systems appears to be the charcoal batch; analytical differences between the two laboratories appear to be small, and variations of one day more or less in the time between Rn collection and charcoal counting have little effect on the result.

Systems Comparison, February 1997 Exercise

Test bed LAACC results for the respective laboratories using their own charcoal provide a comparison similar to the October 1996 exercise. Results are presented in Figure C-3 and summarized in Table C-5. Individual data are presented in Annex CA-3. The three systems all responded to the PG source (only one non-zero PG depth was used for this exercise); but the LAACC-H system reported higher results than the other two systems (P, System = 0.002). For the two LAACC systems, the system P results were about 79% of the results reported by system H.

Results for the field exercise are plotted in Figure C-4 and summarized in Table C-6. Individual results are presented in Annex CA-2. The three systems all reported increasing Rn flux levels with increasing PG treatment level, but each reported a different series of results (P, System = 0.0004). The LAACC-H system reported the highest results and had the most linear response with treatment level. The Rn flux vs. PG treatment level slope was similar for the two LAACC systems; overall the LAACC-P system results were 78% of the LAACC-H results and the differences between the two LAACC systems were not statistically significant for the untreated and the 20 Mg ha^{-1} plots.

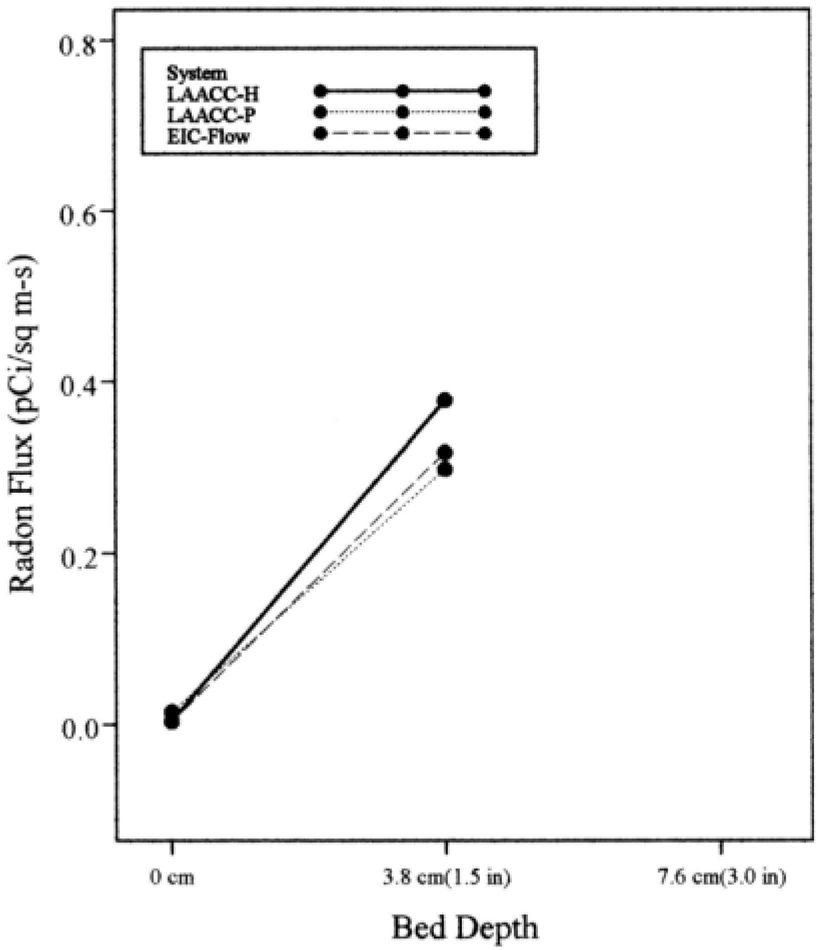

Figure C-3. **Rn Flux Measurement Intercomparison, Test Bed Experiment, February 1997.**

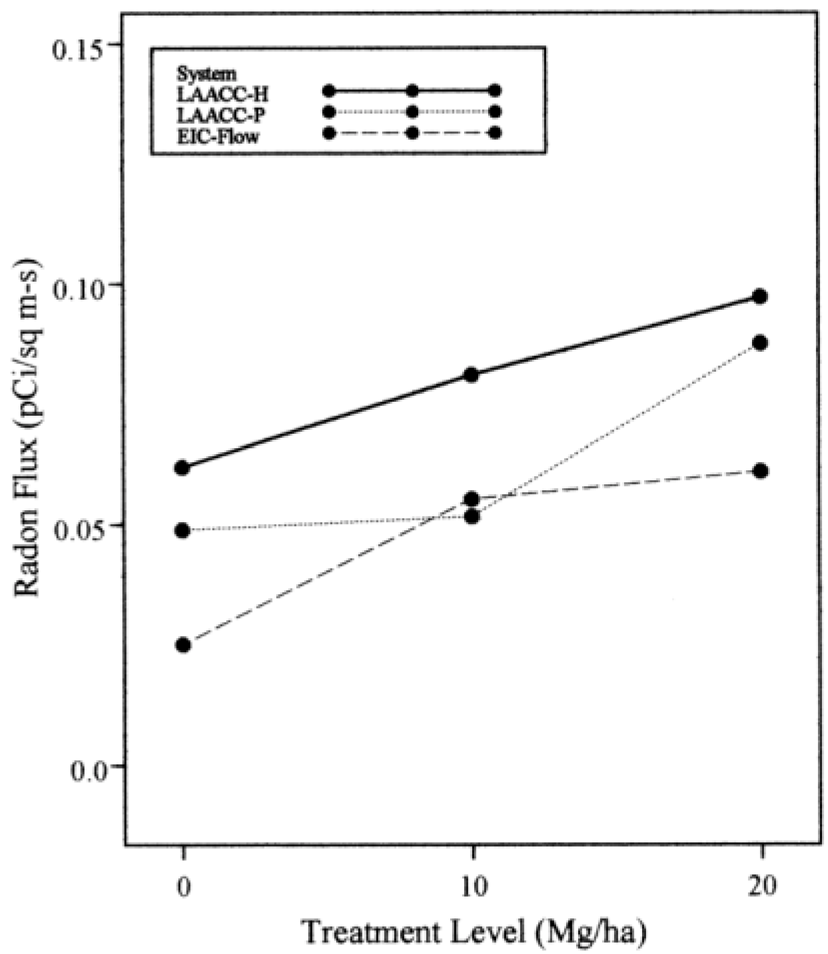

Figure C-4. **Rn Flux Measurement Intercomparison, Field Experiment, February 1997.**

Table C-5. Comparison of Rn Flux Measurement Systems, Test Bed Exercise, February 18-19, 1997.

	Blank Bed	3.8-cm Bed	7.6-cm Bed
Means, pCi m^{-2} s^{-1} for:			
LAACC-H	0.005 a	0.379 a	NM
EIC-Flow	0.004 a	0.317 b	NM
LAACC-P	0.015 a	0.298 b	NM
ANOVA			
P(System)	NS	0.002	NM

Notes:
- LAACC means based on 6 replicates (3 trays x 2 canister/tray).
- EIC means based on 3 replicates (3 trays x 1 EIC/tray).
- Means with the same letter code (a, b, or c) are not significantly different at the $P \leq 0.05$ Level.
- NM = Not measured; NS = Not significant at $P = \leq 0.10$ level.

Table C-6. Comparison of Rn Flux Measurement Systems, Field Exercise, February 18-19, 1997.

	0 Mg ha^{-1}	10 Mg ha^{-1}	20 Mg ha^{-1}	Overall
Means, pCi m^{-2} s^{-1} for:				
LAACC-H	0.062 a	0.081 a	0.097 a	- -
LAACC-P	0.049 a	0.052 b	0.088 a	- -
EIC-Flow	0.025 b	0.055 b	0.061 b	- -
ANOVA				
P(Treatment)	- -	- -	- -	0.0001
P(System)	- -	- -	- -	0.0004
P(Treat x System)	- -	- -	- -	NS

Notes:
- LAACC means based on 12 replicates (12 plots x 1 canister/plot).
- EIC means based on 6 replicates (6 plots x 1 EIC/plot).
- Means with the same letter code (a, b, or c) are not significantly different at the $P\leq 0.05$ Level.

NS = Not significant at $P = \leq 0.10$ level.

Overall Results

All systems responded in a generally linear fashion to increasing Rn flux as provided by the increasing depths/additions of PG. However, the different systems gave different results with the LAACC-H system generally reporting the highest Rn flux levels.

The major perturbation was in the difference between the October 1996 and February 1997 LAACC-P results (coincident with a change in charcoal batch) and, in particular, the magnitude of the October 1996 results. The LAACC-P results were considerably lower that those for the other two systems in October (LAACC-P/LAACC-H = 0.34-0.40 for Field and Test Bed, respectively); but were more comparable to the other systems in February (LAACC-P/LAACC-H = 0.78-0.79 for Field and Test Bed, respectively). If the Test Beds are taken to be relatively constant Rn sources (the LAACC-H Oct/Feb ratio = 0.92), then the October 1996 LAACC-P results were low compared to February 1997 (Oct/Feb ratio = 0.53) and compared to the overall results for the other systems.

CONCLUSIONS AND RECOMMENDATIONS

General Conclusions

1. All the tested systems responded in a generally linear fashion to increasing Rn flux as provided by the increasing depths/additions of PG.
2. The different systems gave different results (system differences were statistically significant for most of the comparison points) with the LAACC-H system generally reporting the highest Rn flux levels.
3. With regard to the LAACC method, charcoal (and its Rn collection/retention efficiency) can be a major variable; this charcoal batch effect is a source of uncertainty when a specific calibration for the particular batch is not known.
4. The relatively constant LAACC-H Test Bed results from the October 1996 exercise to the February 1997 exercise suggest that the LAACC method is reproducible within the same charcoal batch.

Conclusions with Regard to the 1993-1998 UF Study of PG on Forage Lands

1. The differences between the October 1996 LAACC-P, the February 1997 LAACC-P, and the October-February LAACC-H test bed results indicate that a degree of uncertainty in Rn flux results due to variations in charcoal efficiency should be recognized for this study.
2. Since the intercomparison exercises were conducted during a small portion of the 1993-1998 time span, it is not possible to verify the full range of variation or reconstruct the exact pattern of variation during 1993-1998 study.

   Charcoal batch was not expected to be a significant factor; the initial intercomparison exercises were conducted to provide a "spot-check" test of whether the system in use produced comparable results to other systems. The October 1996 exercises examined a batch of charcoal at the end of its use span, the number of different batches of *charcoal used by the contractor laboratory during the course of the study could not be determined, and no information is available on any performance or capacity specifications that might have been associated with the various batches of charcoal.*

3. While the seasonal pattern of Rn flux was sufficiently recurring to be a real effect, any overall time trend underlying the superimposed cyclic pattern is likely confounded with the charcoal efficiency effect.

   The apparent underlying Rn flux time trend showed a significant overall decrease over the period April 1993 through February 1997; reported levels then increased sufficiently so that there was no overall decrease for the 1993-1998 period. The 1997 "reversal" is generally coincident with the use of a new batch of charcoal and it is possible that some portion of the underlying trend observed for the 1993-1998 period may be due to changes in charcoal batch and/or changes in efficiency for charcoal held in storage.

Recommendations

The fact that charcoal batch (and its Rn collection and retention efficiency) is an important variable in the LAACC method of Rn flux measurement leads to several recommendations for future measurements by this method:

1. Ideally, there should be an absolute Rn flux calibration source and individual measurement laboratories should have a constant Rn flux reference source to document reproducibility with time and to intercompare charcoal batches.
2. In the absence of absolute Rn flux calibration facilities, future LAACC Rn flux measurement programs should have some form of constant Rn flux reference source to make comparisons and assure consistency in results, especially if different charcoal batches are used within and/or between laboratories.

ANNEXES TO APPENDIX C

DATA FOR RN FLUX MEASUREMENT SYSTEM INTERCOMPARISONS

Annex CA-1. Rn Flux Measurement Intercomparison, Test Bed Exercise, October 21-22, 1996.

Bed Depth and Source Tray	Rn Flux, pCi m^{-2} s^{-1}		
	LAACC-P	LAACC-H	EIC-Passive
0 cm (Blank)			
0-1	0.01	0.03	0.01
0-2	0.00	0.03	0.02
0-3	0.01	0.05	--
Avg	0.007	0.037	0.015
3.8 cm (1.5 in)			
15-1	0.13	0.34	0.28
15-2	0.17	0.34	0.30
15-3	0.17	0.36	0.27
Avg	0.157	0.347	0.283
7.6 cm (3.0 in)			
30-1	0.21	0.73	0.40
30-2	0.20	0.67	0.40
30-3	0.31	0.68	0.52
Avg	0.240	0.693	0.440

Annex CA-2. Rn Flux Measurement Intercomparison, Field Exercises, October 21-22, 1996 and February 18-19, 1997.

PG Level, Replicate	Rn Flux, pCi m^{-2} s^{-1}					
	October 1996 Exercise			February 1997 Exercise		
	LAACC-P	LAACC-H	EIC-Flow	LAACC-P	LAACC-H	EIC-Flow
0 Mg ha^{-1}						
1	0.00	0.05	0.07	0.017	0.044	0.013
2	0.01	0.04	0.04	0.060	0.046	-0.002
3	0.00	0.05	0.01	0.026	0.035	0.015
4	0.00	0.05	0.04	0.013	0.037	0.022
5	0.00	0.05	0.03	0.013	0.047	-0.004
6	0.02	0.04	0.03	0.020	0.029	0.018
7	0.04	0.05	- -	0.085	0.055	- -
8	0.05	0.06	- -	0.078	0.066	- -
9	0.03	0.06	- -	0.027	0.113	- -
10	0.01	0.03	- -	0.100	0.067	- -
11	0.01	0.04	- -	0.055	0.079	- -
12	0.00	0.04	- -	0.094	0.128	- -
Avg	0.014	0.047	0.037	0.0490	0.0622	0.0102
10 Mg ha^{-1}						
1	0.02	0.08	(0.32)*	0.035	0.055	0.020
2	0.02	0.06	0.04	0.016	0.107	0.028
3	0.02	0.07	0.09	0.010	0.072	0.084
4	0.02	0.08	0.03	0.024	0.036	0.023
5	0.00	0.07	0.07	0.081	0.098	0.067
6	0.04	0.08	0.02	0.032	0.048	0.021
7	0.03	0.08	- -	0.047	0.055	- -
8	0.05	0.11	- -	0.063	0.082	- -
9	0.17	0.09	- -	0.040	0.115	- -
10	0.02	0.09	- -	0.134	0.056	- -
11	0.03	0.08	- -	0.085	0.080	- -
12	0.02	0.10	- -	0.054	0.168	- -
Avg	0.037	0.083	0.050	0.0518	0.0810	0.0405
20 Mg ha^{-1}						
1	0.04	0.10	0.10	0.036	0.071	0.021
2	0.02	0.07	0.04	0.123	0.063	0.091
3	0.01	0.11	0.09	0.072	0.050	0.077
4	0.04	0.09	(0.27)*	0.053	0.080	0.029
5	0.06	0.12	0.13	0.130	0.155	0.055
6	0.03	0.07	0.14	0.018	0.044	0.004
7	0.03	0.13	- -	0.115	0.090	- -
8	0.05	0.06	- -	0.144	0.103	- -
9	0.09	0.14	- -	0.093	0.111	- -
10	0.05	0.10	- -	0.108	0.104	- -
11	0.05	0.10	- -	0.089	0.131	- -
12	0.04	0.11	- -	0.071	0.164	- -
Avg	0.042	0.100	0.100	0.0877	0.0972	0.0462

*Outlying data point not included in Avg. or in statistical analysis.

Annex CA-3. Rn Flux Measurement Intercomparison, Test Bed Exercise, February 18-19, 1997 (Page 1 of 2).

Source Tray	LAACC, Lab P Charcoal				LAACC, Lab H Charcoal				EIC-Flow
	Canister	Rn flux, pCi m^{-2} s^{-1}			Canister	Rn flux, pCi m^{-2} s^{-1}			Rn flux, pCi m^{-2} s^{-1}
		Lab P Analysis	Lab H Analysis	Avg		Lab P Analysis	Lab H Analysis	Avg	
0-cm (Blank) Bed Depth									
0-1	P37 P38	0.000 (1) 0.036 (2)	0.001 (2) 0.006 (1)	0.0005 0.0210	H37 H38	0.003 (2) 0.018 (1)	0.007 (1) 0.003 (2)	0.0050 0.0105	0.010
0-2	P39 P40	0.002 (1) 0.017 (2)	0.002 (2) 0.007 (1)	0.0020 0.0120	H39 H40	0.000 (2) 0.019 (1)	0.004 (1) 0.001 (2)	0.0020 0.0100	0.000
0-3	P41 P42	0.001 (1) 0.035 (2)	0.002 (2) 0.003 (1)	0.0015 0.0190	H41 H42	0.013 (2) 0.023 (1)	0.006 (1) 0.008 (2)	0.0095 0.0155	0.001
	1st Ct Avg 2nd Ct Avg 2-Ct Avg	0.0010 0.0293 <u>0.0152</u>	0.0053 0.0017 0.0035	0.0032 0.0155 0.0094	1st Ct Avg 2nd Ct Avg 2-Ct Avg	0.0200 0.0053 0.0127	0.0057 0.0040 <u>0.0048</u>	0.0128 0.0047 0.0088	 <u>0.0037</u>

Note: No.'s. In ( ) indicate whether 1st or 2nd count (run) of the particular sample.

Continued ...

Annex CA-3. Rn Flux Measurement Intercomparison, Test Bed Exercise, February 18-19, 1997 B (Page 2 of 2).

Source Tray	LAACC, Lab P Charcoal				LAACC, Lab H Charcoal				EIC-Flow
	Canister	Rn flux, pCi m^{-2} s^{-1}			Canister	Rn flux, pCi m^{-2} s^{-1}			Rn flux, pCi m^{-2} s^{-1}
		Lab P Analysis	Lab H Analysis	Avg		Lab P Analysis	Lab H Analysis	Avg	
3.8-cm (1.5-in) Bed Depth									
15-1	P43	0.350 (1)	0.356 (2)	0.3530	H43	0.380 (2)	0.366 (1)	0.3730	0.345
	P44	0.267 (2)	0.261 (1)	0.2640	H44	0.415 (1)	0.391 (2)	0.4030	
15-2	P45	0.325 (1)	0.303 (2)	0.3140	H45	0.382 (2)	0.386 (1)	0.3840	0.307
	P46	0.270 (2)	0.253 (1)	0.2615	H46	0.412 (1)	0.368 (2)	0.3900	
15-3	P47	0.278 (1)	0.290 (2)	0.2840	H47	0.372 (2)	0.354 (1)	0.3630	0.300
	P48	0.298 (2)	0.300 (1)	0.2990	H48	0.447 (1)	0.408 (2)	0.4275	
	1st Ct Avg	0.3177	0.2713	0.2945	1st Ct Avg	0.4247	0.3687	0.3967	
	2nd Ct Avg	0.2783	0.3163	0.2973	2nd Ct Avg	0.3780	0.3890	0.3835	
	2-Ct Avg	0.2980	0.2938	0.2959	2-Ct Avg	0.4013	0.3788	0.3900	0.3173

Note: No.'s in ( ) indicate whether 1st or 2nd count (run) of the particular sample.