RECLAMATION OF PHOSPHOGYPSUM IN FLORIDA: EFFECTS OF AN OVERBURDEN CAP [1]

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Abstract: Phosphogypsum is a byproduct of phosphate fertilizer production, and more than 600 million metric tons have accumulated on 2,000 plus ha in Florida. Field research was initiated in late 1990 to compare the benefits of capping phosphogypsum with overburden (up to 15 cm in depth) from mined sites versus treatment of the phosphogypsum with minimal amendments. After two growing seasons, vegetation cover and production were equally good on plots either with or without an overburden cap as long as adequate N, K and Mg were supplied. However, more species became established with an overburden cap. Fluoride uptake by bermudagrass (*Cynodon dactylon*) was high when grown directly on phosphogypsum (895 mg/kg in leaf tissue) and was reduced slightly by a 15 cm overburden cap (670 mg/kg). Fluoride uptake was less in bahiagrass (*Paspalam notatum*) (215 mg/kg) and bushy beardgrass (*Andropogon glomeratus*) (460 mg/kg) than in bermudagrass (847 mg/kg) at another overburden-capped site. Unexpectedly, radium uptake in bermudagrass grown directly on phosphogypsum (0.6 pCi/g) was less than when grown on the overburden cap (1.8 pCi/g). The presence of grass cut the radon efflux from phosphogypsum in half (from 24 pCi/m^2-s to 11 pCi/m^2-s), while 15 cm of overburden, in addition to grass cover, halved it again (down to 5 pCi/m^2-s).

Additional Key Words: radium, radon, fluoride, bermudagrass, bahiagrass

Introduction

Phosphogypsum is a by-product of phosphoric acid production. For each kg of P_2O_5 produced, approximately five kg of phosphogypsum must be stockpiled or disposed. To date, more than 600 million metric tons have accumulated in Florida on 2000 plus ha, and phosphogypsum is continuing to accumulate at the rate of about 30 million metric tons per year. After phosphate rock has been reacted with sulfuric acid to produce phosphoric acid, the precipitated gypsum is removed on filters and is pumped in slurry form to an impoundment where it is allowed to settle. As the gypsum accumulates, a small dragline removes some of the gypsum for raising the height of the dikes. By this process the gypsum settling impoundment, or "stack" as it is often called, increases in elevation. As a stack grows in height (up to 60 m) the area of the settling impoundment decreases, until a point is reached where the pond capacity becomes too small and the pumping height requires too much energy. When phosphogypsum stacks reach the end of their useful lives, they must be closed and reclaimed. Reclamation will include a cover of vegetation to improve aesthetic qualities, to reduce erosion and improve the quality of surface runoff water, and to allow beneficial use of the land such as for wildlife habitat.

There are several problems associated with establishing vegetative cover on phosphogypsum, including (1) the residual acidity, (2) nutrient deficiencies and low nutrient-holding capacity, and (3) the tendency for caking and crust formation. In addition, there are other potential environmental problems. Phosphogypsum has elevated levels of fluoride and radionuclides, such as ^{226}Ra.

The primary problem for vegetation establishment is the acidity of the phosphogypsum. May and Sweeney (1980) observed pH values usually in the range of 2 to 3 in numerous samples, although samples from older, more weathered stacks had slightly higher pH values near 4. Bromwell and Carrier, Inc. (1989) reported a pH of 5.1 in

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a sample of phosphogypsum from an older, inactive stack. Phosphogypsum is comprised primarily of the slightly soluble neutral salt, calcium sulfate dihydrate. The acidity is due mainly to residual phosphoric and sulfuric acids, although hydrofluoric and fluosilicic acids are also formed during processing (Smith and Wrench 1984, Wrench 1987).

Laboratory, greenhouse and field studies, plus field observations, have indicated that plants could grow on phosphogypsum if the pH was raised to 4.0 or greater and if N, K, and Mg nutrients were supplied (Richardson 1993). Dolomitic limestone (also an Mg source) and phosphatic clay (also a K and Mg source) were effective neutralizing agents, while leaching with water was also an effective mechanism for reducing acidity. Leaching with rainwater is probably responsible for the higher pH values (4.7 to 5.3) found at the surface of older, inactive phosphogypsum stacks compared to pH values near 2 or 3 at active, acid-laced phosphogypsum stacks.

Fluoride concentrations in phosphogypsum produced from Florida phosphate rock often range from 4 to 7 g/kg (Rechcigl et al. 1992, Carter and Scheiner 1992, Oates and Caldwell 1985). Radium-226 commonly ranges from 20 to 30 pCi/g in central Florida phosphogypsum and from 9 to 15 in northern Florida phosphogypsum (Roessler et al. 1979, Mays and Mortvedt 1986, May and Sweeney 1980). The concern with fluoride is the possible development of fluorosis (a bone and tooth disorder) in grazing animals from consuming plants with high concentrations of fluoride. Radium-226 may also be absorbed by plants and be ingested by animals. In addition, ^{226}Ra gives rise to ^{222}Rn gas, which may diffuse out of the phosphogypsum into the atmosphere. There is also concern about the quality of surface runoff waters and leachate from phosphogypsum stacks.

This study is part of a research program with the primary objective of developing effective, but low cost, methods of establishing vegetation on phosphogypsum stacks when they are closed. One approach to coping with the chemical and physical properties of phosphogypsum is to cover it with overburden or soil. However, the question then arises as to how deep the soil or overburden cover must be to support an adequate vegetative cover. The deeper the soil cover, the more costly are the earthmoving operations and the greater are the impacts on soil borrow areas. This paper compares vegetation establishment (1) directly on phosphogypsum and (2) with modest depths (5 to 15 cm) of overburden cover. It also examines the effects of overburden capping on plant uptake of fluoride and ^{226}Ra and on the efflux of ^{222}Rn gas from phosphogypsum.

Methods

The effects of depth of overburden cover on vegetation establishment on phosphogypsum stacks were studied at two sites. The first site was on a nearly level (1% to 2% slope) area on top of the Estech Silver City stack, which had been inactive for about 25 years. The second site was on a 3:1 (horizontal:vertical) slope on the eastern side of the active IMC New Wales stack. Surface pH values of phosphogypsum at the Estech site were near 4.8, while surface pH values at the IMC site, which was underlain by a toe drain, were near 4.5.

Estech

On September 17, 1990, overburden cover was applied at the Estech site at depths of approximately 0, 5, 10 and 15 cm with the aid of a scraper, a dozer and a grader. To facilitate use of the scraper, the various overburden depths were applied in adjacent 6 m wide strips running east and west, with the shallowest depth strip to the north and progressively deeper covered strips to the south. Two treatments were superimposed: (1) one st dolomite per acre and (2) no dolomite. All plots were rototilled and disked. Individual plots were 3.6 m x 6 m, and the treatments were replicated four times. Fertilizer was broadcast at the per ha rates of 54 kg N, 13 kg P_20_5, 27 kg K_20, 5.6 kg Fe, 0.37 kg Mn, 0.34 kg Zn, 0.13 kg Cu, and 0.13 kg B on October 4, 1990. No Mg was applied in 1990 except as dolomite. Seed was broadcast on October 4, 1990 at the per ha rates of 11 kg weeping lovegrass (*Eragrostis curvula*), 22 kg hulled common bermudagrass, 22 kg Pensacola bahiagrass, 22 kg ryegrass (*Lolium perenne*), and 22 kg browntop millet (*Brachiaria ramosa*). Bahiagrass hay mulch was blown on the site at the rate of 4 Mg/ha, and the mulch was crimped-in with a cultipacker roller. On July 18, 1991, the plots were fertilized at the per ha rates of 54 kg N, 13 kg P_2O_5, 27 kg K_2O, 4 kg Mg, 4 kg Fe, 1.5 kg Mn, 0.3 kg Cu, 0.27 kg Zn, and 0.1 kg B. It became apparent later in 1991 that the Mg rate was insufficient for good plant growth on phosphogypsum without dolomite or overburden (Richardson 1993). Therefore all plots were fertilized with 56 kg N, 28 kg K_2O and 14 kg Mg per ha in June 1992.

Percent cover was determined by the line-point method on the overburden depth plots at the Estech site on December 6, 1991, and September 21, 1992. Plant tissue of bermudagrass, bahiagrass and bushy beardgrass (a natural invader) were sampled from plots without overburden cover and with 15 cm of overburden cover in 1992 and analyzed for fluoride. Samples of overburden from the 15 cm depth plots, phosphogypsum from the plots without overburden, and phosphogypsum from a barren, untreated area were analyzed for pH, electrical conductivity, Mg, K, P, Mn, and Zn. Overburden and phosphogypsum samples with and without 2.2 metric tons/ha of dolomitic limestone amendment were also compared.

IMC

A study was designed to compare the effects of 0, 7.5 and 15 cm of overburden cover on vegetation establishment on a 3:1 slope at the IMC New Wales phosphogypsum stack. The three overburden depths were replicated three times on plots measuring 30 m downslope and 7.6 m along the contour. A site was cleared on June 20, 1991, on the east side of the IMC New Wales phosphogypsum stack. An existing bench, located immediately above the experimental site was widened to allow truck access and sloped to intercept surface runoff and route it away from the study plots. Dolomitic limestone was applied at the rate of 1.5 Mg/ha on plots that did not receive any overburden cover ("0" overburden depth) and the site was disked. Overburden application began June 24 and was completed on June 25, 1991. Overburden from a mined site south of the gypsum stack (site of the new stack expansion) was trucked and dumped on the bench and upper slope of the appropriate study plots. A D-3 dozer spread the overburden down-slope over the phosphogypsum, guided by a series of survey stakes marked with the proper depths (0, 7.5 or 15 cm). On the afternoon of June 25, 1991, the site was lightly scarified with a disk harrow and the overburden depth study plots were broadcast seeded with 29 kg common bermudagrass and 58 kg browntop millet per ha. Fertilizer was broadcast at the per ha rates of 78 kg N, 20 kg P_20_5, 39 kg K_20, 10 kg Mg, 2.4 kg Fe, 1.5 kg Mn, 0.5 kg Zn, 0.25 kg Cu, and 0.15 kg B. Bahiagrass hay mulch was blown on the overburden depth plots at 4 Mg/ha, and the hay was crimped in with a cultipacker roller and the dozer tracks. The plots were fertilized again on June 5, 1992 with 56 kg N, 28 kg K_20 and 14 kg Mg per ha.

Percent plant cover was determined on the overburden depth plots at the IMC site by the line-point method on December 5, 1991 and September 23, 1992. Samples of bermudagrass tissue were collected from the overburden depth plots at the IMC site on October 24, 1991, and were analyzed for ^{226}Ra activity, and for F concentration. Overburden from the 15 cm depth treatment, phosphogypsum from the plots without overburden, and phosphogypsum from a barren, untreated area were analyzed for pH, electrical conductivity, Mg, K, P, Mn, and Zn.

Radon-222 fluxes from the ground surface were measured in February, March and May 1992, with the aid of large area activated charcoal canisters placed for 24 hours on the grass-covered overburden depth plots and a barren (no vegetation or overburden cover) phosphogypsum "control" plot. In February the charcoal canisters on the grass-covered plots were simply pressed and twisted into the ground to achieve good contact with the ground, but the grass was not clipped. In an attempt to assure a better canister to soil seal in March and May, the grass was clipped to a height of approximately 4 cm, a canister was placed on the ground, and bermudagrass stolons (runners) and "soil" were cut with a knife around the perimeter of the canister. The canister was then pressed downward and twisted to attain good ground contact. On all sampling dates, canisters were pressed onto the surface of the barren phosphogypsum control plot, but because the ground surface was both hard and uneven, phosphogypsum was packed around the outside perimeter of the canisters to create a better seal. Additionally, in March and May a knife was used to scratch the ground surface around the perimeter of each canister to aid our efforts to press them into the ground on the barren plots. The ground surface beneath the charcoal-laden portion of each canister was not disturbed. Following the 24-h period in the field, charcoal from each canister was removed, placed in a sealed container, and sent to the Florida Health and Rehabilitative Services laboratory in Orlando for radon flux determination.

Results

Tables 1 and 2 show the chemical analyses of phosphogypsum and overburden used as capping material at the Estech and IMC sites. At Estech the overburden was higher in pH, lower in electrical conductivity, and higher in Mg, K, P and Mn than was the phosphogypsum. Application of dolomitic limestone raised the pH of the overburden by 0.2 unit and of the phosphogypsum by 0.3 unit. Available Mg was also increased by dolomite application. At the IMC site the overburden was higher in pH, Mg, K, Mn, and Zn than the bare phosphogypsum, but the dolomite amended phosphogypsum was higher in pH and Mg than the overburden. Phosphogypsum at both sites was chemically similar, except the pH was a little lower at IMC. The pH of the IMC overburden was lower and its electrical conductivity was higher than that of the Estech overburden. The overburden caps at both the Estech and IMC sites were loamy sands (Estech: 84% sand, 4% silt, and 12% clay. IMC: 85% sand, 4% silt and 11% clay).

Vegetation

Estech. During the winter and early spring of 1990-91, an excellent cover of ryegrass became established on all the overburden-covered plots, but the phosphogypsum without overburden cover remained nearly bare. This is in contrast to a fertilizer study in which ryegrass did become established on phosphogypsum without overburden cover (Richardson 1992). In late spring the annual ryegrass died back and the warm season perennial grasses began to grow. In June, 1991, green grass (mainly bermudagrass) and weed cover appeared greater on the phosphogypsum without overburden cover than with overburden cover. By mid-July 1991, green grass cover on the dolomite-treated plots was fairly similar, regardless of overburden depth. On the plots without dolomite, grass cover and vigor appeared poorer on those without overburden. This was shown to be due to a magnesium deficiency in an experiment at another site (Richardson 1993). Because of the apparent Mg deficiency in the non-overburden covered plots without dolomite, cover data was only collected from the dolomite treated plots in December 1991. Total living plant cover ranged from 82% to 89% and was not statistically different (0.05 level) with or without overburden cover, and their were no statistically significant differences in litter cover. However, bare ground was statistically greater (0.05 level) without overburden (11%) than with overburden (4% to 5%).

A greater rate of Mg was applied in June 1992 to overcome the Mg deficiency observed in 1991 on phosphogypsum without dolomite. In September 1992, no differences were found between the dolomite or nondolomite treatments, so these data were pooled when analyzing the effects of overburden depth. Table 3 shows that ground covered by plants was slightly, but significantly, less without overburden cover than with overburden cover, but bare ground was only 3% without overburden cover. Even without overburden, plant cover was excellent and exceeded 90 percent. The most striking effect of overburden cover was on plant species diversity. The establishment of weeping lovegrass and bahiagrass was enhanced by overburden cover, and some species such as the invading annual legume, hairy indigo (*Indigofera hirsuta*), failed to grow on phosphogypsum without overburden cover. Bushy beardgrass, another invader, was actually more abundant without overburden cover.

Plant dry weights were measured in October 1992, but neither overburden depth nor dolomitic limestone application had any significant effects on plant yields (data not shown). Apparently, as long as adequate nitrogen, potassium and magnesium nutrients are supplied, and pH exceeds 4.5, excellent vegetation cover and production can be achieved directly on phosphogypsum without an overburden cap (see also Richardson 1993).

IMC. Only bermudagrass and browntop millet were planted at the IMC site. By mid-July, 1991, the height and vigor of browntop millet was clearly better on the overburden-covered than on the non-covered phosphogypsum plots

Table 1. Chemical analysis of overburden and phosphogypsum at the Estech site.[1]

			Mineral analyses (mg/kg)				
	pH	EC [2]	Mg	K	P	Mn	Zn
Overburden (grassed)							
Without dolomite	5.43	0.27	76.2	49.9	2185	3.37	1.72
With dolomite [3]	5.63	0.35	113.0	52.6	2197	3.69	1.37
Phosphogypsum (grassed)							
Without dolomite	4.77	2.35	16.3	14.7	196	0.34	1.57
With dolomite [3]	5.11	2.36	50.8	16.5	252	0.31	1.03
Bare phosphogypsum	4.81	2.36	7.1	10.5	212	0.25	1.16

[1] Mean values of four replicates
[2] Electrical conductivity, dS/m
[3] 2.2 metric tons/ha of dolomitic limestone applied

Table 2. Chemical analyses of overburden and phosphogypsum at the IMC site.[1]

			Mineral analyses (mg/kg)				
	pH	EC [2]	Mg	K	P	Mn	Zn
Overburden (grassed)	5.02	2.01	45.9	32.8	2193	2.43	2.37
Phosphogypsum (grassed) [3]	5.30	2.36	97.5	7.3	NA	0.33	0.64
Phosphogypsum (bare)	4.53	2.35	4.0	4.8	NA	0.15	0.89

[1] Mean values of three replicates
[2] Electrical conductivity, dS/m
[3] Dolomitic limestone applied at rate of 1.5 metric tons/ha
NA Not available

Table 3. Percent cover as affected by overburden depth at the Estech phosphogypsum stack in late September, 1992.[1]

	Overburden depth (cm)			
	0	5	10	15
Bermudagrass	91.0 a	86.6 a	78.0 b	89.4 a
Bahiagrass	9.7 b	28.8 a	33.1 a	32.7 a
Weeping lovegrass	0.0 b	5.1 b	18.2 a	4.0 b
Bushy beardgrass	13.9 a	3.5 b	2.4 b	2.6 b
Other grasses	0.0 c	0.9 c	2.6 b	5.8 a
Hairy indigo	0.0 c	0.0 c	9.7 a	5.2 b
Other broadleaves	0.0 a	0.2 a	0.0 a	0.2 a
Ground covered by plants	93.4 b	97.2 a	97.2 a	98.2 a
Litter	3.3 a	2.1 a	2.1 a	1.8 a
Bare ground	3.3 a	0.7 b	0.7 b	0.0 b

[1] Mean values of 8 replicates. Values within rows followed by the same letter are not significantly different at the 0.05 level. Because of plant overlap, sums of cover values within columns may exceed 100 %.

at IMC. However, plant cover was good on the phosphogypsum without overburden cover, and bermudagrass was actually doing better directly on phosphogypsum where competition from browntop millet was less. The purpose of the browntop millet was to provide a quick cover for erosion control. As expected, the browntop millet, which is an annual, died back in the fall. By December, 1991, bermudagrass cover was greater on the plots with zero or 7.5 cm of overburden than on the plots with 15 cm overburden. Bare ground ranged from 0 to 8 percent, but there were no statistically significant (0.05 level) differences.

In September 1992, ground covered by plants ranged between 96 and 100 percent and did not differ significantly regardless of overburden depth (Table 4). Bare ground was one percent or less. The primary effect of overburden was increased invasion of weeds, such as hairy indigo. The overburden cap had little or no effect on two other invaders, dog fennel (*Eupatorium capillifolium*) and saltbush (*Baccharis halimifolia*).

Plant yields were not significantly affected by overburden depth (data not shown).

Fluoride Analyses

At the Estech site, the fluoride content of bermudagrass was very high (Table 5). The 15 cm overburden cap only reduced the F content of bermudagrass by about one-third. The F concentrations in bushy beardgrass and bahiagrass were somewhat lower, but the 15 cm overburden cap had no significant effect on F concentrations in these two species. The F concentration in bahiagrass grown on phosphogypsum was many times greater than reported for bahiagrass grown on a native sandy soil (Rechcigl et al. 1992). Fluoride concentrations in bermudagrass at the
IMC site were also high, with mean values of 895 mg/kg on phosphogypsum and 670 mg/kg on the 15 cm thick overburden capped phosphogypsum (difference significant at 0.05 level).

Table 4. Percent cover as affected by overburden depth at the IMC phosphogypsum stack in late September, 1992.[1]

	Overburden depth (cm)		
	0	7.5	15
Bermudagrass	96.5 a	99.3 a	99.7 a
Other grasses	0.0 a	0.7 a	1.1 a
Hairy indigo	0.0 c	17.7 b	30.9 a
Dog fennel	8.3 a	9.4 a	10.1 a
Saltbush	1.0 a	0.0 a	2.1 a
Other broadleaves	0.0 a	0.4 a	3.8 a
Ground covered by plants	96.5 a	99.3 a	100.0 a
Litter	2.4 a	0.7 a	0.0 a
Bare ground	1.0 a	0.0 a	0.0 a

[1] Mean Values of three replicates. Values within rows followed by the same letter are not significantly different at the 0.05 level. Because of plant overlap, sums of cover values within columns may exceed 100%.

Table 5. Fluoride concentration (mg/kg) in leaves of bermudagrass, bushy beardgrass, and bahiagrass growing on phosphogypsum with or without a 15 cm overburden cap at the Estech site.[1]

	Overburden Depth (cm)	
	0	15
Bermudagrass	1256 a	847 a*
Bushy Beardgrass	505 b	460 b
Bahiagrass	255 c	215 c

[1] Mean values of three replicates. Values within columns followed by different letters are significantly different at the 0.05 level. An asterix (*) indicates a significant difference within a row at the 0.05 level.

Radionuclides

The activity of Ra-226 in bermudagrass tissue actually increased with increasing depth of overburden cover over phosphogypsum (Table 6), and linear regression analysis produced an r^2 value of 0.92. Apparently, Ra-226 uptake by bermudagrass is not necessarily closely correlated with Ra-226 levels in the growth medium, because Ra-226 concentrations are expected to be much higher in phosphogypsum than in overburden. It may be that the Ra-226 in the overburden is in a more soluble form.

The presence of bermudagrass drastically reduced the radon flux from phosphogypsum, based on the charcoal canister technique employed in this study (Table 6). Radon flux appeared to be reduced about in half by bermudagrass, while 15 cm of overburden cover appeared to reduce it in half again. Although the mean values of radon flux with the various depths of overburden cover differred significantly only in May, there did appear to be a trend for reduced radon flux with increasing overburden depth. The correlation coefficients (r) for radon flux versus overburden depth were -0.74 in February (r^2 = 0.54), -0.66 in March (r^2 = 0.44) and -0.82 in May (r^2 = 0.66). The correlations were significant at the 0.05 level in February and May, and nearly significant (0.052 level) in March.

Table 6. Radium levels in bermudagrass tissue and radon flux from the ground surface at the IMC phosphogypsum stack as affected by overburden cover and by plant cover.[1]

	Control (no plants)	Overburden Depth (cm) (with plant cover) 0	7.5	15
^{226}Ra in plant tissue (pCi/g)	--	0.6 c	1.1 b	1.8 a
^{222}Rn flux (pCi/m_2-s)				
Feb. 1992	18.3 a	5.6 b	3.5 b	1.1 b
Mar. 1992	32.4 a	15.1 b	12.7 b	8.3 b
May 1992	22.8 a	18.5 b	8.1 bc	6.9 c
Average	24.5	11.4	8.1	5.4

[1] Mean values of three replicates. Values within rows followed by the same letter are not significantly different at the 0.05 level.

Discussion

An overburden cap of up to 15 cm in depth was not necessary for the establishment of excellent plant cover on phosphogypsum when the pH was 4.8 to 5.3, when adequate nitrogen, potassium and magnesium were supplied, and when adapted plant species such as bermudagrass were planted. However, the overburden did enhance the establishment of plant species such as weeping lovegrass and bahiagrass, and thus may improve species diversity. The overburden also appears to be a source of nutrients such as magnesium, potassium, phosphorus, manganese and zinc.

Fluoride uptake was high in bermudagrass grown directly on phosphogypsum or on the six inch overburden cap, although the overburden cap did somewhat reduce the fluoride concentration of bermudagrass. Fluoride concentrations were much less in bahiagrass leaf tissue, but they were still nearly ten times the levels considered safe for grazing animals (Rechcigl et al. 1992, Church 1979). The simplest solution to this potential problem may be to prevent animals from consuming a large proportion of their diets from plants grown on phosphogypsum. Alternatives are to provide a thicker cap of low fluoride soil material and to use plant species that are less prone to accumulate fluoride. This study shows that plants may differ in their uptake of fluoride. It may also be possible to reduce the solubility of fluoride by lime application.

Although ^{226}Ra in phosphogypsum or overburden was not measured at the IMC study site, typically phosphate overburden in central Florida has much lower ^{226}Ra levels (average about 5 pCi/g) than phosphogypsum (average about 26 pCi/g) (Roessler et al. 1979 and 1980). Therefore it was surprising that the levels of ^{226}Ra in bermudagrass increased, rather than decreased, with increasing thickness of the overburden cap. It is possible that the ^{226}Ra in the overburden may have been in a more soluble form. Soil pH, soil calcium, and the chemical form of the radium compounds in the soil may all affect plant uptake of radium (Simon and Ibrahim 1988, Mortvedt 1992). The radium levels in bermudagrass grown on phosphogypsum in this study are similar to the radium levels in stargrass (*Cynodon nlemfuensis*), a relative of bermudagrass, grown in central Florida on waste phosphatic clay containing 22 pCi/g of ^{226}Ra (Mislevy et al. 1990). Bahiagrass grown on phosphatic clay contained less than one-third the radium level of the stargrass. This suggests that bahiagrass might take up less ^{226}Ra than bermudagrass when planted on overburden-capped phosphogypsum (bahiagrass establishment was poor on uncapped phosphogypsum at the Estech site).

Plants growing in Ra-containing materials may have an effect on the release of radon to the atmosphere. Lewis and MacDonell (1990), for example, provided evidence that ^{222}Rn dissolved in soil water may be absorbed by plants and released to the atmosphere via cuticular transpiration. This mechanism of ^{222}Rn release would be most significant when a Ra-containing material was covered by a low radioactivity soil cap and plant roots came into contact with the buried material. The data presented here indicate that the presence of plants growing directly on phosphogypsum will reduce the efflux of radon, and a thin (e.g. 15 cm thick) soil or overburden cap will further reduce the radon efflux.

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