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INFLUENCE OF PHOSPHOGYPSUM ON FORAGE YIELD AND QUALITY AND ON THE ENVIRONMENT IN TYPICAL FLORIDA SPODOSOL SOILS

Volume I

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INFLUENCE OF PROSPHOGYPSUM ON FORAGE YIELD AND QUALITY AND ON THE ENVIRONMENT IN TYPICAL FLORIDA SPODOSOL SOILS

VOLUME I.

FORAGE YIELDS AND QUALITY OF BAHIAGRASS AND ANNUAL RYEGRASS PASTURES FERTILIZED WITH PHOSPHOGYPSUM AS A SOURCE OF SULFER AND CALCIUM

FINAL REPORT

FIPR Project 89-01-085

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July 1996

DISCLAIMER

PERSPECTIVE

When phosphate ore is treated with sulfuric acid to produce phosphoric acid, which is used primarily in the manufacture of phosphate fertilizers, a calcium sulfate byproduct is also produced, known as phosphogypsum. More than 800 million tons of phosphogypsum have accumulated in Florida, and about 30 million tons are added annually. A high priority research topic at the Florida Institute of Phosphate Research has been to investigate potential uses of this byproduct in agriculture and industry. This project is one of several funded by the Institute to examine the use of phosphogypsum as an agricultural soil amendment. The first volume of the report gives the results of the authors' research on the agronomic benefits of using phosphogypsum as a source of calcium and sulfur for enhancing bahiagrass and ryegrass forage production on native sandy soils in central peninsular Florida. The second volume contains research results addressing the potential environmental impacts of applying phosphogypsum to the land. The environmental work has been expanded in a subsequent project, "Impact of Phosphogypsum on Radon Emissions and on Radioactivity and Heavy Metals in the Soil, Groundwater and Bahiagrass Forage (FIPR Project # 92-03-038R), which is still in progress as this report goes to press.

The reader is also referred to additional FIPR reports on the subject:

Miller, W.P. 1989. Use of Gypsum to Improve Physical Properties and Water Relations in Southeastern Soils. FIPR Publ. No. 01-20-082. 42p.

Mullins, G.L. and C.C. Mitchell, Jr. 1990. Use of Phosphogypsum to Increase Yield and Quality of Annual Forages. FIPR Publ. No. 01-048-084. 56p.

Sumner, M.E., et al. 1990. Gypsum as an Ameliorant for the Subsoil Acidity Syndrome. FIPR Publ. No. 01-024-090. 56p.

Sumner, M.E. 1995. Literature Review on Gypsum as a Calcium and Sulfur Source for Crops and Soils In the Southeastern United States. FIPR Publ. No. 01-118-118. 89p.

An additional related topic is the reclamation of phosphogypsum piles, or "stacks" as they are commonly known in the phosphate industry. The following FIPR publication addresses this topic:

Richardson, S.G. 1995. Establishing Vegetation Cover on Phosphogypsum in Florida. FIPR Publ. 01-086-l16. 60p.

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EXECUTIVE SUMMARY

Phosphogypsum (PG), a by-product of the wet-process manufacture of phosphoric acid from phosphate rock, is primarily calcium sulfate or gypsum ($CaSO^4 \cdot 2H_2O$) and, thus, is a potential source of sulfur (S) and calcium (Ca) for crops.

The agronomic objective of this project was to determine the effects of PG on bahiagrass (Paspalum notatum Flugge) and annual ryegrass (Lolium multiflorum Lam.) in terms of forage yield and quality. The environmental objective was to assess the environmental impacts of PG, at agronomic rates, on forage, soil, groundwater, and the immediate ambient atmosphere. The project was carried out by the University of Florida, Institute of Food and Agricultural Sciences (IFAS) at the Range Cattle Research and Education Center (RCREC) at Ona, Florida. The field experiments were conducted on a long-established bahiagrass pasture and on tilled land cropped to annual ryegrass from 1990 to 1993. The soils were typical Florida Spodosol soils.

In the agronomic experiments, the amendments used were PG alone, PG+limestone, PG+dolomitic limestone, elemental sulfur, and limestone. The PG rates in treatments containing PG were 0.2, 0.4, and 1.0 MT PG ha^{-1} (MT or metric ton = l06 grams = megagrams or Mg) applied annually for three years, and 2.0 and 4.0 MT PG ha^{-1} applied once at the start of the experiments.

In the environmental experiments, PG alone was applied annually at 0.4 MT ha^{-1} for 3 years and one time at the start of the experiments at 2.0 and 4.0 MT PG ha^{-1}.

This report (Volume I) deals with the agronomic results of the agronomic and the environmental experiments. Volume II deals with the radiological and the agro-environmental results.

A. Phosphoqypsum on Established Bahiagrass Pasture

1. Effect on Forage Yield and Quality

Forage yield. Based on the significant linear regression equations, the 3-year average results of the agronomic study showed that PG alone applied annually increased forage dry matter (DM) yield by 0.23 MT DM per MT PG ha^{-1}. The one-time rates also increased forage yield by 0.56 MT DM at the highest rate of 4.0 MT PG ha^{-1}. Also based on the linear regression equations, S applied annually at the highest rate of 65 kg S ha^{-1} could reduce forage yield by 0.17 MT DM ha^{-1}. Limestone applied one-time up to 2.0 MT ha^{-1} could also reduce forage yield by 0.24 MT DM ha^{-1} at the highest application rate. Based on the actual yields for the individual rates, the agronomic study showed that PG alone applied annually at 0.4 MT PG ha^{-1} increased forage DM yield over the control by 17% in the first year (1990) and 23% in the second year (1991). The 1992 yield at 0.4 MT PG ha^{-1} was also 8% higher than the control, but the difference did not attain a significant level. In the environmental study, PG applied annually at 0.4 MT ha^{-1} increased forage yield by 46% over a 3-year period. Thus, the results from the two studies indicate that it is reasonable to expect increases in forage yield with PG by 15 to 20%. These increases in forage yield with PG applied at 0.4 MT ha^{-1} annually are a good basis for evaluating the economics of PG use in bahiagrass pastures in Central Florida.

Nutrient content of forage. The 3-year mean S contents in bahiagrass forage from both the agronomic and the environmental studies increased by 0.02 to 0.08% per 0.4 MT PG ha^{-1} applied annually. Calcium increased only by 0.01% at the same annual rate in both studies. The results indicate that as a Ca source, PG rates higher than 0.4 MT ha^{-1} are needed to make a difference.

The N content of forage harvested monthly (regrowth) was not affected by the treatments in either experiment. The environmental study, however, showed apparent and consistently higher N contents in PG-fertilized hay forage (mature forage harvested once a year) than in the control forage. The 3-year mean crude protein (CP = %N x 6.25) contents in hay fertilized with PG were 7.7 to 9.8% higher than those of the control. The effects of the treatments were significant at $P<0.10$.

Both studies showed that PG alone had no effect on %P in bahiagrass forage, but PG may enhance %K in forage. The agronomic study indicated that limestone, PG+limestone, and PG+dolomitic limestone, but not PG alone, may reduce %P in the forage particularly during the first year. In both studies, the one-time application of 4.0 MT PG ha^{-1} reduced %Mg in bahiagrass forage, probably due to the loss of Mg from the main root zone, but the effect was significant only during the first year.

The application of PG reduced the N:S ratio in forage in all three years in both studies. The 3-year mean N:S ratio in PG-fertilized forage ranged from 6.7:1 to 7.6:1 in the environmental study. The control forage showed a N:S ratio of 10.2:1. Similar values were noted in the agronomic study. In both studies, the N:S ratios in the PG-fertilized and the control forages were well outside the ideal N:S ratio range of 12:1 to 15:1 for cattle. This should be remedied using higher rates of N application. Some of the PG-fertilized regrowth harvests in the environmental study had higher *in* vitro organic matter digestibility (IVOMD) than the control.

From both studies, the Ca:P ratios in PG-fertilized forage ranged from 1.6:1 to 2.6:1. The Ca:P ratio in the control forage ranged from 1.47 to 2.3:1. Feeds with Ca:P ratios below 1:1 or over 7:1 had been shown to decrease feed efficiency and reduce growth. To keep the Ca:P ratio in heavily P-fertilized pastures from dropping below 1:1, PG fertilization is highly recommended.

MT PG ha^{-1} brought the N:S ratios in ryegrass forage within the ideal range. However, PG as applied in the environmental study was relatively ineffective compared to the application of PG at seeding in the agronomic study. Except for the 4.0 MT PG ha^{-1} rate in 1990-91 with 12:1 N:S ratio, the rest of the ratios ranged from 17:1 to 24:1 with the control having the highest. In both studies, the annual or the 3-year mean %IVOMD showed no significant effects of PG on regrowth forage digestibility.

The 3-year mean Ca:P ratios in PG-fertilized ryegrass forage in the environmental study ranged from 1.1:1 to 1.3:1. The control showed a Ca:P ratio of 1.1:1. Similar values of Ca:P ratio (1.5:1) with PG rates applied annually were obtained in the agronomic study. Thus, as with bahiagrass, PG fertilization is highly recommended for ryegrass pastures that are heavily fertilized with P to keep the Ca:P ratio from dropping below 1:1.

The F content of ryegrass forage was unaffected by the PG treatments. The 3-year mean F contents ranged from 8.4 mg kg^{-1} for the control to 10.5 mg kg^{-1} for the 4.0 MT PG ha^{-1} rate. As in the case of bahiagrass, this is an important finding on the use of PG on ryegrass pastures.

2. Effects on Soil.

The environmental study showed no significant effects of PG on soil pH, Ca, P, Mg, K, Cu, Fe, Mn, Na, Zn, and Cl. However, there were strong indications that soil K and Mg were reduced in the top 15 cm at the highest level of PG application. The agronomic study showed that soil Mg in the top 15 cm was significantly reduced with PG rates. Although not significant, the reduction in soil K with PG was also very apparent.

C. Conclusions

The two field studies on an established pasture and the two on tilled land have demonstrated that PG can serve as an effective source of S and/or Ca for pastures and for tilled crops. Because of its high solubility and its SO_4-form of S, PG supplies S to crops at a much faster rate than elemental S. Phosphogypsum also supplies Ca to crops at a much faster rate than limestone, primarily because PG is much more soluble than limestone. Thus, when either S or Ca or both are limiting the yield potentials of forage crops, PG application should increase forage yield and improve forage quality as well. Unlike elemental S, PG up to 4.0 Mg PG ha^{-1} has shown no significant acidifying effect on the soil, nor does PG have the liming effect of limestone. Hence, the fertilizer value of the S and/or the Ca in PG should make PG a valuable resource for agriculture, in general, and for Florida agriculture in particular.

INTRODUCTION

Phosphogypsum (PG), a by-product of the wet-process manufacture of phosphoric acid from phosphate rock, 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) ameliorants for Al toxicity and subsoil acidity and infertility, (3) ameliorants for sodic and non-sodic dispersive soils, (4) conditioners for hard-setting clay soils and hardpans, (5) bulk carriers for micronutrients or fillers in low analysis fertilizers, (6) additives to modify cation-to-Ca ratios such as Mg:Ca ratio of soils, and (7) absorbents for NH_3-N in urea and other volatiles in manures (Shainberg et al., 1989; Alcordo and Rechcigl, 1993; and Alcordo and Rechcigl, 1995).

Sulfur (S) is essential to plant nutrition. In general, plants contain as much S as phosphorus (P), ranging in concentration from 0.2 to 0.5% on a dry-weight basis. Sulfur ranks in importance with nitrogen (N) as a constituent of the amino acids cysteine, cystine, and methionine in proteins that account for 90% of S in plants. It is also involved in the formation of oil in crops such as peanut (*Arachis hypogaea* L.), soybean (*Glycine max* (L.) Merr.), flax (*Linum usitissimum*), and rapeseed (*Brassica campestri*) (Tisdale et al., 1985)

Prior to 1950, S deficiencies were not a common occurrence in U.S. soils. Since then the number of states that has reported soil S deficiencies has progressively increased from 13 in 1962 to 36 in 1986 and 48 in 1991 (Blevins, 1991). Some of the reasons for the observed S-deficiencies in soils are the increasing use of S-free fertilizers (Morris, 1986), the declining use of S in pesticides and, possibly, the reduction in the amounts of S released into the atmosphere from fossil-fueled power plants as a result of the implementation of the Clean Air Act of 1970. This Act sets the annual arithmetic mean limit on SO_2 at 0.08 mg m^{-3} or 0.03 mg kg^{-1} (Louis and Buonicore, 1988). One of the goals of the Act as amended in 1990 is to further reduce SO_2 emission by 10 million Mg (megagrams = 10^6 grams) by year 2000, relative to 1980 levels (Stebbins, 1992). When the other countries of the world move to adopt flue gas desulfurization technology to clean their immediate ambient atmospheres (Alcordo and Rechcigl, 1995), S deficiencies in U.S. soils and worldwide could become severe in the near future. Already, crops grown in deep sandy soils with low nutrient-holding capacity such as those found in the coastal plain region of the southeastern U.S., including Florida, have shown positive responses to S fertilization (Jordan, 1964; Rabuffetti and Kamprath, 1977; Reneau and Hawkins, 1980; Mitchell and Blue, 1989; Rechcigl, 1989; Sumner, 1990). Consequently, the need for an inexpensive S-source has become more apparent. Phosphogypsum may just be the material to meet that need, both at present and long into the future.

In ruminant nutrition, Thomas et al., (1951) demonstrated conclusively that S deficiency limits nonprotein N utilization in purified diets, and that SO_4-S as the sole source of S can correct the deficiency. Hume and Bird (1970) showed that an intake of 1.9 g S per day by sheep produced the maximum protein production in the rumen, and that inorganic SO_4-S was used as efficiently as that from cystine for synthesis of protein by rumen microorganisms. Bray and Helmsley (1969) showed that S supplement to the diet increased both crude fiber digestion and S and N retention by sheep. Moir et al. (1967-1968) demonstrated that narrowing the mean dietary N:S ratio of a basal ration for sheep from 12:1 to 9.5:1 increased the mean N retention from 28.8 to 36.0%. Dietary N:S ratios from 12:1 to 15:1 have been considered excellent for cattle (McDowell et al., 1993). Rees et al. (1982) found that sheep ate substantially more S-fertilized digitgrass (Digitaria pentzii Stent) forage than one not fertilized with S. Akin and Hogan (1983) indicated that S fertilization did not affect plant anatomy of digitgrass but enhanced the fiber-digesting capability of the microbial rumen population.

Sulfur fertilization of forage crops reduces N:S ratio of plant tissue. Lancaster et al. (1971) reported that applications of S at 40 mg kg^{-1} soil reduced the N:S ratios of orchardgrass (Dactylis glomerata L.) from 32 to 9 ; sudangrass (Sorghum vulgare var Sudanese L.) from 45 to 19 and 72 to 14 for the first and the second cutting, respectively; and annual ryegrass (Lolium multiflorum Lam.) from 36 to 5. Rechcigl (1989), using ammonium sulfate as the source of S applied at the rate of 86 kg S ha^{-1} to bahiagrass (Paspalum notatum Flugge) reported increased dry matter yield by 25%, crude protein by 1.2 percentage unit, digestibility by 3 to 4 percentage units, and S content by 100% 30 days after application. Woodhouse (1969) showed that excessive amounts of N applied to bermudagrass (Cynodon dactylis (L.) Pers), despite S fertilization, increased N:S ratio in excess of 60:1.

Calcium, at concentrations ranging from 0.2 to 1.0% in plant tissues, is also essential to plants. Calcium deficiency manifests itself in the failure of terminal buds and apical tips of roots to develop. Also, lack of Ca results in general breakdown of membrane structures, with resultant loss in retention of cellular diffusible compounds (Tisdale et al., 1985). While Ca may be readily supplied by lime materials such as calcium carbonate or dolomite, lime application in large amounts in certain soils can be detrimental to plant growth. Kamprath (1971) reported that lime application that raised the soil pH to 7 resulted in reduced rates of water infiltration, reduced availability of P, B, Mn, and Zn, and reduced growth of sudangrass, corn (Zea mays L.), and soybean. Therefore, for certain soils that require large amounts of Ca to support commercially viable crop yields, or for crops such as peanut that need large amounts of readily available Ca (Colwell and Brady, 1945; Hallock and Garren, 1968; Cox et al., 1976; Alva et al., 1989), a Ca source other than lime is necessary. Phosphogypsum as a Ca source can meet this need.

While PG is an ideal source of S and Ca for crops, there are some drawbacks. The radionuclide impurities in PG such as radium-226 (^{226}Ra), lead-210 (^{210}Pb), and polonium-210 (^{210}Po) have raised an environmental concern in using PG for agriculture. Other concerns are the eight heavy metals (As, Ba, Cd, Cr, Pb, Hg, Se, and Ag) that the United States Environmental Protection Agency (USEPA) uses to determine whether a solid waste is hazardous under its "toxicity characteristic" category (USEPA, 1992). Although probably of minor concern, fluorides (F) in PG, PG's acidic pH, and the effect of the high solubility of PG on electrical conductivity (E,) and on total dissolved solids (TDS) have raised the issue of PG's possible impacts on surficial groundwater quality. Such a high solubility of 2.7 g PG L^{-1} (Alcordo and Rechcigl, 1992) relative to the solubilities of natural $CaCO_3$ minerals calcite (0.0145 g L^{-1}) and aragonite (0.0153 g L^{-1}) (Weast, 1981), may have a depleting effect on soil cationic and anionic plant nutrients when PG is applied in large quantities (Syed, O.S.R., 1987; O'Brien and Sumner, 1988). Hence, from the agronomic point of view, not only is there a need to determine the potential beneficial effects of PG on crop yields and quality but also the possible adverse effects on the other plant nutrients when used at such rates as to supply adequate amounts of S and Ca for crops.

The two general objectives of the project were to evaluate the effect of PG applied at agronomic rates as a source of S and Ca for agricultural crops and to assess the environmental impacts of the treatments. The specific objectives of the field experiments are given in Section A of the EXPERIMENTAL PLAN OF THE PROJECT in page 4.

Two agronomic-environmental and two solely agronomic field experiments involving the application of PG as a source of S and Ca to an established bahiagrass pasture and to annual ryegrass were conducted from 1990 to 1993 by the University of Florida, Institute of Food and Agricultural Sciences (IFAS), Range Cattle Research and Education Center at Ona, Florida.

Volume I of the report covers the agronomic aspects of the environmental experiments (PART ONE) and the solely agronomic experiments (PART TWO) with bahiagrass and annual ryegrass. Volume II covers the environmental results, radiological and non-radiological, of the environmental experiments with bahiagrass and annual ryegrass.

EXPERIMENTAL PLAN OF THE PROJECT

A. General and Specific Objectives of the Project

The general objectives of the project were to evaluate the effects of PG as a source of S and Ca on forage yield and quality (agronomic experiments) and to assess the environmental impacts (environmental experiments) of the agronomic rates used on a long-established bahiagrass pasture and on a tilled site which was then planted to annual ryegrass every year for three years.

Agronomic data from the environmental experiments were also collected.

The specific objectives of the agronomic aspects of the study were:

(a) to determine the effects of PG on forage yields and quality of bahiagrass and annual ryegrass at various PG rates and at two application frequencies;

(b) to compare the efficacy of PG, as a source of S and Ca, versus elemental S and $CaCO_3$ as S and Ca sources, respectively: and

(c) to determine the effects of PG and the other amendments on the various plant macronutrients in the forage and in the soil.

B. Experimental Treatments and Design

For the agronomic experiments, the PG application rates, on a dry-weight basis, were 0.0, 0.2, 0.4, 1.0, 2.0, and 4.0 Mg PG ha^{-1} which were applied by hand to the plots. The 0.2, 0.4, and 1.0 Mg PG ha^{-1} rates were applied annually for three years while the 2.0 and 4.0 Mg PG ha^{-1} rates were applied only at the beginning of the study or initially (Table 1). The environmental experiments had only the 0.4 Mg PG ha^{-1} for the annual rate (Table 1).

A randomized complete block design was used for both agronomic and environmental experiments. The agronomic experiments had four replicates using 3 m x 6 m plots. The environmental experiments had two replicates using large-area plots measuring 32 m x 32 m.

C. Experimental Sites and PG Material

Bahiagrass site. The bahiagrass experiments were conducted on long-established Pensacola bahiagrass pasture on an area with a Myakka fine sand soil (sandy, siliceous, hyperthermic Aeric Haplaquods). USDA Soil Conservation personnel used a ground penetrating radar (GPR) to establish the presence of a spodic horizon, characteristic of Spodosols. The spodic horizon was characterized as a continuous layer between 60 to 120 cm beneath the surface, and there was a broken argillic horizon just beneath the 120-cm depth.

Table 1. Group treatments and individual treatments (amendment rates) for the bahiagrass and the annual ryegrass experiments.

GT or Group Treatments		Amendment Rates (AR) (Individual Treatments)	Amendments
A. Agronomic Experiment:			
		---- Mg PG ha^{-1} -----	
GT1	(1,2,3,4,5)	0.2,0.4,1.0,2.0,4.0	PG (phosphogypsum)[1]
GT2	(6,7,8,9,10)	0.2,0.4,1.0,2.0,4.0	PG+1% dolomite[2]
GT3	(11,12,13,14,15)	0.2,0.4,1.0,2.0,4.0	PG+1% $CaCO_3$[3]
		---- Kg Ca ha^{-1} -----	
GT4	(16,17,18,19,20)	41, 82, 206, 412, 825	$CaCO_3$[4]
		---- Kg S ha^{-1} ------	
GT5	(21,22,23)	33, 66, 165	Elemental S[5]
GT6	(24)	0.0	Control
B. Environmental Experiment:			
		---- Mg PG ha^{-1} -----	
PG[6]		0.0, 0.4, 2.0, 4.0	

1 PG rates 0.2, 0.4, and 1.0 were applied annually (An); 2.0 and 4.0 were applied only at the start of the experiment or initially (In).
2 The same as GT1 but with 1% dolomite by weight added to PG to raise PG pH in water (1:1) to 5.5.
3 The same as GT1 but with 1% $CaCO_3$ by weight added to PG to raise PG pH in water (1:1) to 5.5.
4 Ca-equivalent in PG supplied in the form of $CaCO_3$ and applied as in GT1.
5 S-equivalent in PG supplied in the form of elemental S with 33 and 66 rates applied annually and 165 applied initially.
6 PG rates 0.4 applied annually and 2.0 and 4.0 initially.

Tables 2 and 3 show the chemical analyses of the topsoil and of the bahiagrass samples, respectively, taken from the experimental site prior to PG application.

Table 2. Pre-treatment surface soil (0-15 cm depth) chemical analyses[1] of the bahiagrass experimental site.

pH[3]	Plant nutrients[2]							
	P	K	Ca	Mg	Zn	Cu	Fe	Mn
	mg kg^{-1}							
5.5	4.6	33.9	778.0	93.0	0.61	0.11	6.44	0.66

[1]Mehlich 1 as extractant.
[2]Average of 4 samples.
[3]1:1 in water.

Table 3. Pre-treatment chemical analyses[1] of bahiagrass tissues collected from the bahiagrass experimental site.

Plant nutrients[2]									
N	P	K	S	Ca	Mg	Zn	Cu	Fe	Mn
%						mg kg^{-1}			
0.78	0.19	0.90	0.18	0.36	0.35	56.1	2.5	54.9	12.1

[1]0.3025 M HCl as solvent for the ashen tissue.
[2]Average of 8 samples.

Annual ryegrass site. A previously uncropped land that spanned across Pomona fine sand (sandy, siliceous, hyperthermic Ultic Haplaquods) and Myakka fine sand soils was used for the annual ryegrass experiments. Soil core sampling established the presence of a spodic horizon, characteristic of Spodosols, as a continuous layer between 60 to 120 cm beneath the surface, and a broken argillic horizon just beneath the 120 cm depth. The area, which was originally covered with saw palmetto, was plowed, harrowed, and leveled. Dolomite was then applied at the rate of 8 Mg ha^{-1} in July 1990. The experimental plots were seeded with annual ryegrass (Gulf variety) each year for three years at the rate of 40 kg ha^{-1}.

Table 4 shows the chemical analyses of the topsoil samples taken from the ryegrass experimental site after land preparation and dolomite application.

Table 4. Pre-treatment surface soil (0-15 cm depth) chemical analyses[1] of the annual ryegrass experimental site.

pH[3]	Plant nutrients[2]							
	P	K	Ca	Mg	Zn	Cu	Fe	Mn
	$mg\ kg^{-1}$							
5.9	15.7	24.2	995.0	81.1	0.82	0.89	0.05	8.50

[1]Mehlich 1 as extractant.
[2]Average of 4 samples.
[3]1:1 in water.

Chemical analysis of PG used in the study. The PG used contained 25% Ca and 19% S on a dry-weight basis (Table 5). The small quantities of the other plant nutrients such as P, K, Mg, and some essential micronutrients present in PG as impurities are not large enough to meet the needs of crops.

Table 5 shows F and Al as major impurities. The Al concentration in PG, however, is much less than the usual range in soil which is from 14,000 to 40,000 mg kg^{-1} (Baker and Chesnin, 1975). The analysis of F in forage may have to be done since large concentrations of F in animal feed may lead to fluorosis in cattle.

D. Cultural Practices, Sample Collection, and Analytical Methods

In the first year, the bahiagrass experiments ran from August (first application of PG) to December, 1990 (last harvestable regrowth). The succeeding crop years (1991 and 1992) ran from March or April to December.

For annual ryegrass the growing season in the locality runs from November-December (seeding) to the following February-March (last regrowth harvest). In the first year, the PG treatments for the environmental study were applied in September, 1990, and the plots then seeded and fertilized on December 19-20, 1990. In the subsequent years, the annual PG treatment and the fertilizers were applied during seeding. In the agronomic experiment all the treatments and the fertilizers were applied during seeding in all years.

Table 5. Total chemical analyses of phosphogypsum (PG) used in the study and of other PG samples from Florida PG stacks.

Elements	Concentration (Unit)		
	U.S. Agri. Chem. Corp.[a]	Pembroke Laboratory[a]	Average in Florida PG[a,1]
<u>Major Nutrient:</u>		Percent	
Calcium (Ca)	24.5	25.6	26.2
Sulfur (S)	19.8	–[b]	19.5
Phosphorus (P)	–[b]	0.3	0.7
<u>Minor:</u>		$mg\ kg^{-1}$	
Iron (Fe)	690.0	460.0	860-1,000±300-600
Sodium (Na)	260.0	260.0	520±79
Potassium (K)	38.0	110.0	200-230±83-94
Molybdenum (Mo)	–[b]	17.0	2.2-11±1.4-2.2
Magnesium (Mg)	16.0	13.0	<940±<27
Boron (B)	–[b]	<10.0	<3.0
Zinc (Zn)	6.0	6.2	<340±21
Copper (Cu)	0.6	2.1	<82±<9.6
Manganese (Mn)	–[b]	1.9	25±14
Chloride (Cl)	–[b]	–[b]	<150±<4.7
Nickel (Ni)	–[b]	–[b]	<2.0
<u>Phytotoxic:</u>			
Fluoride (F)	4,300	–[b]	5,000
Aluminum (Al)	–[b]	1,100	2,000±540

[a]Moisture-free basis: [1]May and Sweeney (1983); [b]Not determined in the analysis.

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 to all experiments at the rate of 180, 45, 67.5 and 28.0 kg ha^{-1}, respectively, at the start of the growing season each year.

Sampling and measurements for both bahiagrass and ryegrass experiments included:

<u>Soil sampling</u>. Soil samples were collected at the end of the growing season each year to a depth of 90 cm at 15-cm intervals. The samples were air-dried and pulverized to pass a 2-mm sieve.

Forage sampling. For regrowth forage, a portion of each plot was first cut 30 to 35 days after fertilizer application and at similar intervals thereafter. For hay (mature) forage samples, a portion of each plot was left uncut-and sampled only near the end of the growing period (November-December for bahiagrass and February-March for ryegrass) each year for three years. Regrowth and hay samples were cut down to an inch from the ground using a garden mower or forage harvester. The samples were oven-dried at 60°C and ground to pass a 0.84-mm sieve.

Chemical analyses. The soil nutrients were extracted using Mehlich 1 solution (0.025 M HCl + 0.0125 M H_2SO_4). The plant tissue samples were first ashen in a Thermolyne Type 30400 furnace and the ashes dissolved in 0.3025 M HCl. The soil and the plant elements were analyzed using inductively coupled plasma (ICP) methods at the UF-IFAS Analytical Research Laboratory (ARL). Tissue S was analyzed by the combustion method using a LECO sulfur analysis apparatus at the Florida Institute of Phosphate Research (FIPR). Soil pH was determined using 1:1 soil/water slurries. Nitrogen contents and the in vitro organic matter digestibility (IVOMD) of the forage were analyzed by the IFAS Forage Evaluation Support Laboratory (FESL).

E. Statistical Analysis and Data Presentation

All statistical analyses were done by the UF-IFAS Department of Statistics. The data were analyzed by individual collection or harvest, by crop year (annual), and, when appropriate, averaged over all collections or harvests over the 3-year period of the study (3-year analysis).

For the environmental experiments, treatment mean comparisons for significance were determined using Duncan's Multiple Range test (DMRT) (Gomez and Gomez, 1984). The tests for linear (P{linear}) and quadratic (P{quadratic}) effects for the first year data (1990) were done using all four PG applications rates. Similar tests in the subsequent years data (1991 and 1992) were done using the three treatments of 0.0, 2.0, and 4.0 Mg PG ha^{-1}.

For the agronomic experiments, the statistical analysis employed could most easily be described as an ANOVA model with Multiple Regression. Tests for quadratic trends were also done to test for the validity of this approach. Comparisons between amendments (ex. PG vs elemental S) and between application frequencies (Annual vs Initial) for each amendment were done using the estimates of slopes in the ANOVA to test for differences in the rate effects or slopes. The effects of rates, annually or initially applied, for each amendment were determined using tests for linear effects (P{linear}).

For the first year, PG rates used for Multiple Regression analysis and estimates of slopes were 0.0, 0.2, 0.4, 1.0, 2.0, and 4.0. For the second and the third years, PG rates used were

0.0, 0.2, 0.4, and 1.0 for annual (An) application and 0.0, 2.0, and 4.0 Mg PG ha^{-1} for the one-time or initial (In) application. For the equivalent rates of S and Ca using elemental S and $CaCO_3$, respectively, refer to Table 1. To make a fair comparison between the two amendment application frequencies - annual versus initial - after the first year, the second and the third year analyses used twice and three times the rates used annually in 1990, which cut the annual slope estimates by one-half and one-third, respectively.

The tests (P-values) associated with AR*GT (Table 1, AR = amendment rates; GT = group treatments), AR*GT*FREQUENCY, and AR*GT*FREQUENCY*YEAR are tests relating to the magnitudes of the sources of variability due to the different slopes. A P>0.05 for AR*GT for year 1 implies that there is insufficient evidence to conclude that the true slopes of PG, PG+$CaCO_3$, PG+dolomite, S, and $CaCO_3$ are different. In other words, there is insufficient evidence to conclude that the treatments (rates or amendments) differ in their effects for year 1. A P>0.05 for AR*GT*FREQUENCY implies that there is insufficient evidence to conclude that the true slopes of PG annual (An), PG initial (In), PG+$CaCO_3$ An, PG+$CaCO_3$ In, PG+dolomite An, PG+dolomite In, S An, S In, and $CaCO_3$ An, and $CaCO_3$ In are different. In other words, there is insufficient evidence to conclude that the, treatments (rates, amendments, or application frequencies) differ in their effects for year 2 and 3. A similar interpretation applies for a P>0.05 for AR*GT*FREQUENCY*YEAR for the 3-year mean.

Consequently, the statistics tested the following null hypotheses using the various experimental data, such as forage yields, etc., expressed in terms of rate effects or slopes:

(a) PG Versus Other Amendments: there is no difference between the effect of PG rates (slope) and that of elemental S, as sources of S, at their corresponding or equivalent rates; there is no difference between the effect of PG rates (slope) and that of $CaCO_3$, as sources of Ca, at their corresponding rates; there is no difference between the effect of PG rates (slope) and that of PG+1% $CaCO_3$; and there is no difference between effect of PG rates (slope) and that of PG+1% dolomite:

(b) Annual Versus Initial Application: there is no difference between the effect of rates (slope) of any given amendment applied annually and the effect of rates of the same amendment applied initially at their corresponding or equivalent rates at a particular span of years;

(c) PG_{all} Averall Annual Versus PG_{all} Average Initial: there is no difference between the average effect of rates (average slope) of all treatments containing PG applied annually (PG_{all} annual) and the average effect of rates (average slope) of all treatments containing PG applied initially (PG_{all} initial) at their corresponding or equivalent rates at a particular span of years;

(d) Effect of Amendment Rates Applied Annually: the effects of rates (slopes) of PG, or PG+$CaCO_3$, or PG+dolomite, or elemental S, or $CaCO_3$ applied annually is zero;

(e) Effect of Amendment Rates Applied Initially: the effects of rates (slopes) of PG, or PG+$CaCO_3$, or PG+dolomite, or elemental S, or $CaCO_3$ applied initially is zero; and

(f) PG_{all} Average Annual; PG_{all} Average Initial: the average effect (average slope) of all treatments containing PG applied annually (PG_{all} An) is zero; the average effect (average slope) of all treatments containing PG applied initially (PG_{all} In) is zero.

In both environmental and agronomic experiments, P>0.05 but P<0.10 are given as P<0.10 for reference, and referred to as "slightly" significant.

RESULTS AND DISCUSSION

PART ONE: ENVIRONMENTAL EXPERIMENTS

A. BAHIAGRASS EXPERIMENT

A.1. Effects of PG on Forage Yields, Percent Dry Matter (DM), Nutrient Contents, and on Other Forage Quality Measures

This part of the report covers the agronomic data from the environmental experiment with bahiagrass. For the Duncan's Multiple Range Test (DMRT), treatments 0.0, 0.4, 2.0, and 4.0 Mg PG ha^{-1} were used in all years. For the linear and the quadratic tests, treatment 0.4 Mg PG ha^{-1} applied annually was included only in 1990 but not in 1991 and 1992. All the rates were again used in the 3-year mean DMR test and in the linear and the quadratic tests.

A.1.1. Forage Dry Matter (DM) Yields

The total annual and the 3-year average regrowth DM yields from plots fertilized annually with 0.4 Mg PG ha^{-1} were consistently higher relative to the yields from the control plots and, to a lesser degree, to the yields from the plots that received one-time applications of 2.0 and 4.0 Mg PG ha^{-1}. The total regrowth DM yields in 1991 (5 harvests) and 1992 (6 harvests) from plots fertilized with 0.4 Mg PG ha^{-1} annually were significantly different and higher than those from the control plots by 51% and 48%, respectively (Table 6). The 3-year mean yield from plots that received annual application of 0.4 Mg PG ha^{-1} was 46% higher than the mean yield from the control plots.

The trends in regrowth yields with PG rates for each harvest during the 3-year period are given in Figure 1. Treatments with the same letter(s) are not significantly different.

The analysis for hay forage yields for 1990 showed the yields in the order of 0.4 greater than 2.0 and 2.0 greater than C (or simply 0.4>2.0>C); the order in 1991 was 2.0>4.0, C; 0.4>C. The 1992 analysis indicated no treatment differences, but the data showed that all PG-fertilized plots showed consistently high yields relative to that of the control.

The 3-year mean analysis also showed that the average hay DM yields from plots fertilized with 0.4 Mg PG ha^{-1} annually and with 2.0 and 4.0 Mg PG ha^{-1} once initially during the 3-year period were different from and were higher by 22.6, 17.4, and 17.6% than the 3-year average yield from the control plots, respectively (Table 6).

Table 6. Total regrowth and hay forage dry matter yields of bahiagrass from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year 1990	1991	1992	Mean
A. Regrowth:[1]	----------- Mg DM ha^{-1}		----------------	
Mg PG ha^{-1}				
0.0(C)	2.04a[2]	9.58b	8.48c	6.70b
0.4	2.40a	14.48a[3]	12.55a[3]	9.81a
2.0	1.57a	13.46ab	11.47abc	8.83a
4.0	1.77a	10.48ab	11.78ab	8.01a
Tests:[4]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:[5]	----------- Mg DM ha^{-1}		----------------	
Mg PG ha^{-1}				
0.0(C)	5.91b	7.28c	8.92a	7.66b
0.4	8.05a	9.20ab[3]	10.25a[3]	9.39a
2.0	6.09b	9.43a	10.00a	8.99a
4.0	6.52ab	7.67bc	11.61a	9.01a
Tests:				
P(linear)	ns	ns	ns	0.0398
P(quadratic)	ns	0.0216	ns	ns

[1]With 3, 5, and 6 regrowth harvests in 1990, 1991, in 1992, respectively.
[2]means with the same letter(s) are not different (DMRT).
[3]Excluded in the tests for linear or quadratic trends.
[4]ns=not significant (P>0.05).
[5]One harvest of mature forage from the uncut area in each plot.

The environmental experiment, with two replicates using large-area plots, gave strong indications that 0.4 Mg PG ha^{-1} applied annually to bahiagrass growing on a Florida Spodosol soil would most likely increase bahiagrass yields with adequate N-P-K fertilization.

A.1.2. Percent Dry Matter (%DM)

Table 7 shows that PG had no effect on the DM content of regrowth and hay forages of bahiagrass in all years. The 3-year mean %DM was 31% for both the control and the PG-fertilized regrowth forages. For hay forage, the 3-year mean %DM were 49.1 for the control and 45.5 to 49.2% for the PG-fertilized forages.

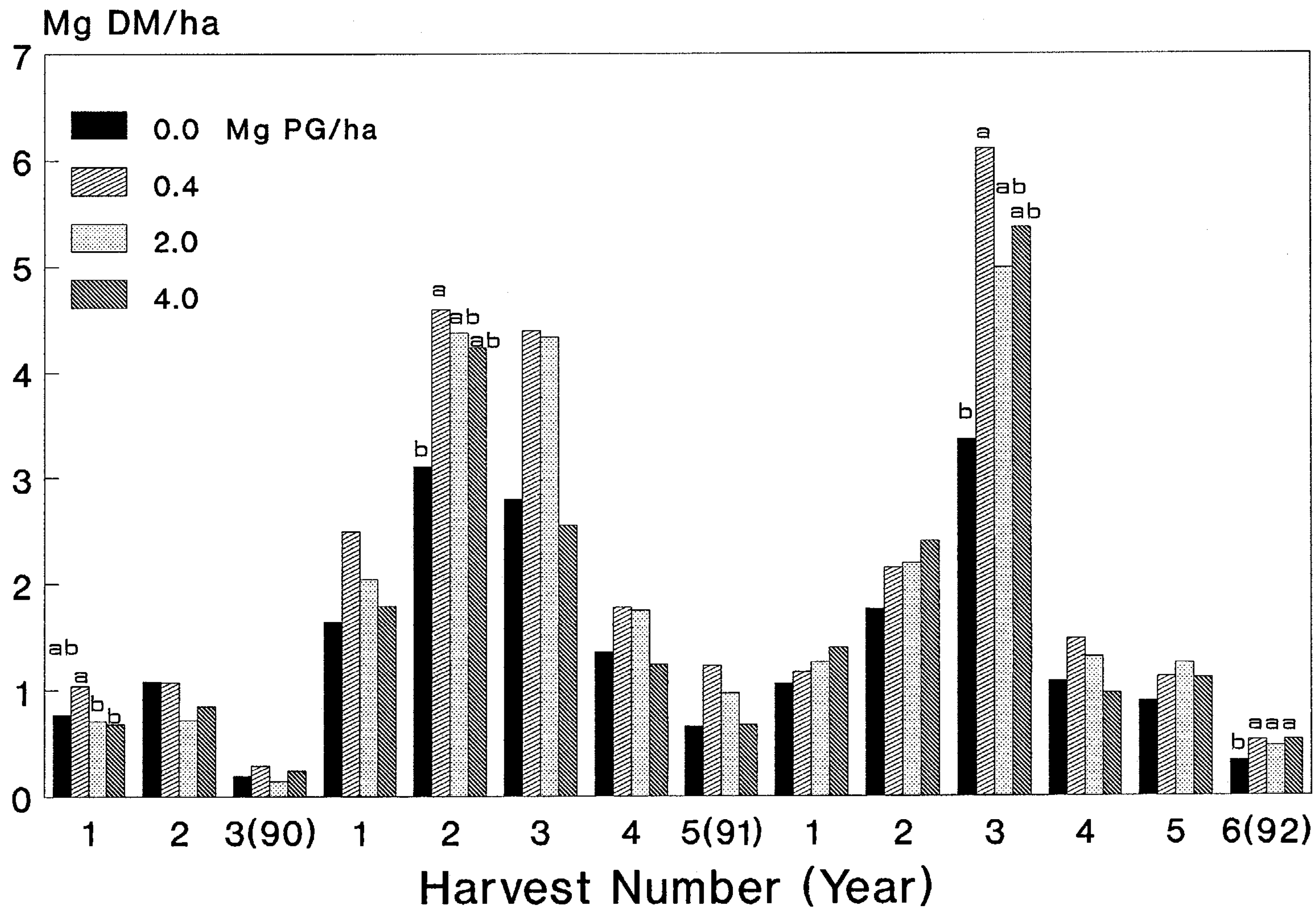


Figure 1. Regrowth forage dry matter yieldsof bahiagrass from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

Table 7. Percent dry matter (%DM) of regrowth and hay forages of bahiagrass from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year			
	1990	1991	1992	Mean
<u>A. Regrowth:</u>	----------- %DM -----------			
Mg PG ha^{-1}				
0.0(C)	30.9a[1]	31.7a	30.0a	30.8a
0.4	32.1a	30.9a[2]	29.5a[2]	30.6a
2.0	30.5a	31.4a	30.0a	30.6a
4.0	32.2a	31.3a	29.7a	30.8a
<u>Tests:</u>[3]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
<u>B. Hay:</u>	----------- %DM -----------			
Mg PG ha^{-1}				
0.0(C)	39.9a	55.0a	47.8a	49.1a
0.4	40.5a	49.0a[2]	47.7a[2]	46.8a
2.0	36.6a	57.4a	47.3a	49.2a
4.0	37.3a	46.7a	48.3a	45.5a
<u>Tests:</u>				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different (DMRT).
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

Figure 2 shows no consistent trends in %DM in the individual regrowth harvests with PG rates during the 3-year period.

A.1.3. Nutrients in Forage

Sulfur content. Sulfur content is an important measure of forage quality. The S-amino acids methionine, cystein, and cystine, though they are small components of proteins, are also essential to animal life. Likewise, S is a part of the vitamins thiamin and biotin and of polysaccharides, including chondroitin. The latter is a key component of cartilage, bone, and tendons (McDowell et al., 1993).

Sulfur requirements of ruminants are not well defined but are estimated to range from 0.10 to 0.32% S in forage for grazing ruminants (McDowell, et al., 1993). Maximum tolerable level of

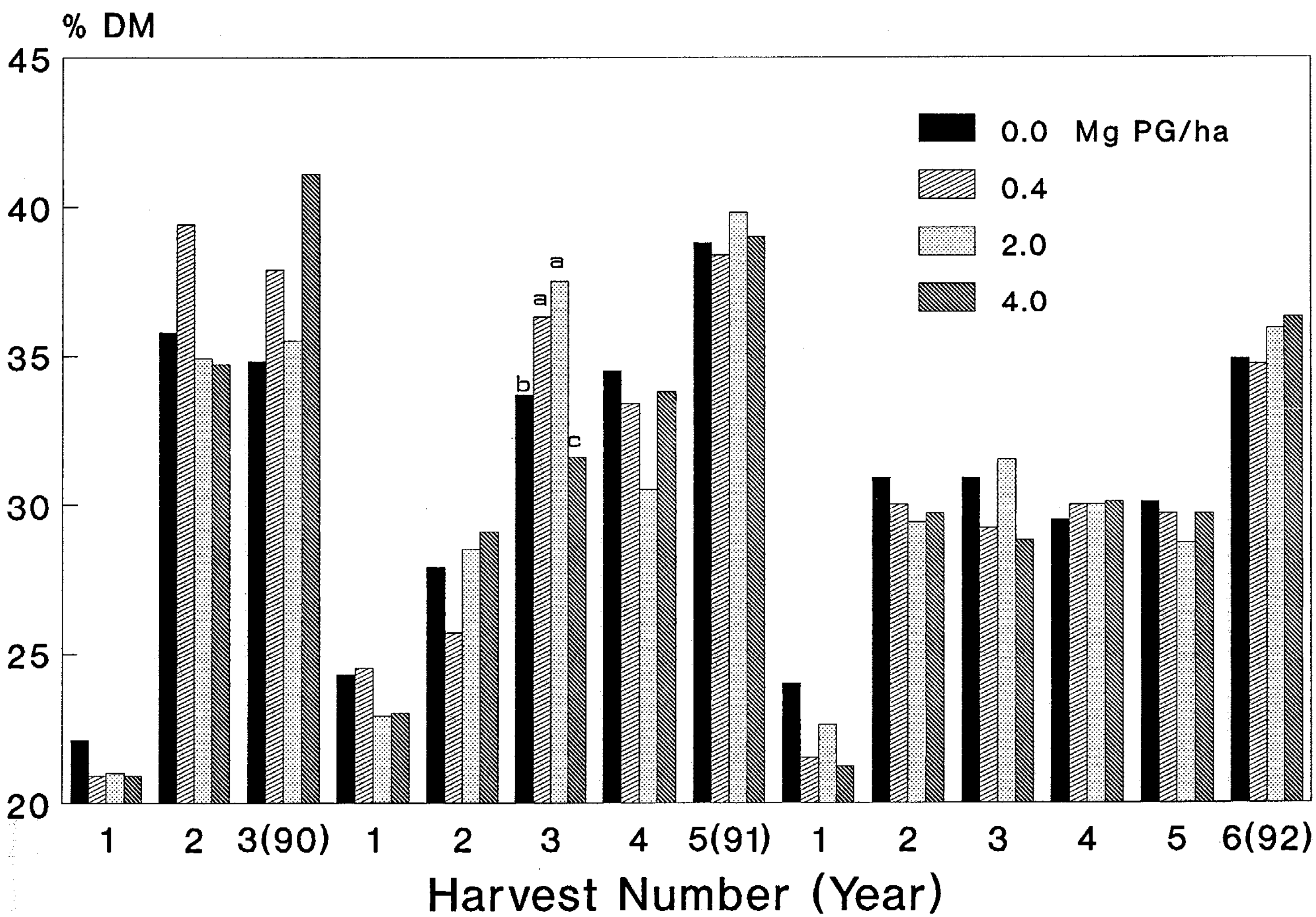


Figure 2. Percent dry matter (%DM) of bahiagrass regrowth forage from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

S is reported to be 0.40% (NRC, 1980) but is less defined than the maximum requirement. Ruminants can tolerate more S from natural feed ingredients than from added SO_4-S (McDowell, et al., 1993), but excessive dietary S levels may lead to acute toxicity. Clinical signs of toxicity include abdominal pain, muscle twitching, diarrhea, severe dehydration, strong odor of sulfide on the breath, congested lungs, and acute enteritis (Miller, 1979).

Rees et al. (1982) found that sheep ate substantially more S-fertilized digitgrass forage than forage not S-fertilized. In the case with cattle, studies in Ireland (Murphy et al., 1983) showed that cattle that grazed on S-fertilized pastures gained up to 29% more weight than those grazed on S-deficient fields. Also, for any given daily weight gain, S-treated pastures had 21 and 19% greater stock-carrying capacity during the first and second year, respectively, than the untreated pastures. Other studies point to the need for S fertilization of forage crops to increase yields as well as to achieve desirable S levels in forages to meet animal nutrition requirements and attain the proper N:S ratios for the rumen microorganisms.

Two major sources of S for agriculture are elemental S and gypsum ($CaSO_4 \cdot 2H_2O$) (Anderson, 1991). In PG, $CaSO_4 . 2H_2O$ content may range from 83-94%. The S in elemental S needs to be oxidized to SO_4-S to be usable by crops. For sources with SO_4-S, such as mined gypsum and PG, S availability is determined primarily by the solubility (weight dissolved per unit volume of solvent) and solubility rate (weight dissolved per unit volume of solvent per unit time) of the S carriers. While both PG and mined gypsum have similar solubility constants (2.1 to 2.6 g L^{-1}), studies by Keren and Shainberg (1981) and Bolan et al. (1991) indicated that the solubility rate of PG may be three to ten times that of mined gypsum .

The order of the treatment effects on %S in regrowth forages in 1990 was 4.0>0.4,C; 2.0>C; and in 1992 the order was 0.4>2.0,4.0>C (Table 8). The 3-year means indicated the effects of the treatments in the order of 4.0>0.4>C; 2.0>C.

The annual rate effects ranged from slightly significantly linear (1991) to significantly linear (1990 and 1992) as shown in Table 8. Measured over the 3-year period, the rate effect was significantly quadratic (P{quadratic =0.0159}), with 0.17, 0.26, 0.27% S for the PG rates of 0.0, 2.0, and 4.0, respectively (Table 8).

In 1991, only the 4.0 Mg PG ha^{-1} rate gave a %S in hay that was higher than the control and the other PG rates. In 1992 all PG applications showed higher %S than the control. Based on the 3-year mean DMRT, the order of the treatment effects on %S in hay forage was 4.0>0.4, C; 2.0>C with the corresponding actual values of 0.29>0.23, 0.17; 0.25>0.17% S (Table 8).

The effects of PG rates were significantly linear in 1990 and 1991 but quadratic in 1992. When averaged over the 3-year period, the effect of PG rates was shown to be significantly linear, with 0.17, 0.25, and 0.29% S for treatments 0.0, 2.0, and 4.0 Mg PG ha^{-1}, respectively.

In managing PG application to bahiagrass pastures, it is important to note that the one-time applications of 2.0 and 4.0 Mg PG ha^{-1} raised %S in regrowth forage in 1990 from 0.19% (control) to slightly greater than 0.409, the tolerable S limit for ruminants (NRC, 1980). However, the S levels decreased to near 0.20% S in 1991 and 1992. This indicates that S from PG is indeed readily available for plant use, but it can also be lost from the soil quite fast.

Table 8. Sulfur concentrations in bahiagrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year			Mean
	1990	1991	1992	
A. Regrowth:	----------- %S -----------			
Mg PG ha^{-1}				
0.0(C)	0.19c[1]	0.18a	0.13c	0.17c
0.4	0.25bc	0.26a[2]	0.23a[2]	0.25b
2.0	0.41b	0.23a	0.19b	0.26ab
4.0	0.43a	0.25a	0.18b	0.27a
Tests:[3]				
P(linear)	0.0145	0.0584	0.0273	0.0011
P(quadratic)	ns	ns	ns	0.0159
B. Hay:	----------- %S -----------			
Mg PG ha^{-1}				
0.0(C)	0.27a	0.12b	0.19b	0.17c
0.4	0.31a	0.17b[2]	0.26a[2]	0.23b
2.0	0.44a	0.18b	0.28a	0.25ab
4.0	0.43a	0.25a	0.27a	0.29a
Tests:				
P(linear)	0.0245	0.0056	0.0190	0.0017
P(quadratic)	ns	ns	0.0480	0.0630

[1]Means with the same letter(s) are not different (DMRT).
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05), but P-values <0.10 are given for reference and referred to as "slightly" significant.

The %S values in the individual harvests are shown in Figure 3. Rates of 2.0 and 4.0 Mg PG ha^{-1} gave S contents in excess of the maximum tolerable level of 0.40% during the first year, especially in the second and third regrowth harvests. The annual rate of 0.4 Mg PG ha^{-1}, however, gave adequate levels of S in bahiagrass forage without coming close to the maximum tolerable level of 0.40% S. Thus, the individual harvests, the annual means, and the 3-year means treatment effects on regrowth forage point to a recommendation of 0.4 Mg PG ha^{-1} to be applied annually to keep %S in bahiagrass forages above that of the untreated forages yet not exceed 0.32% S in the dietary requirement range of 0.10 to 0.32% S for grazing ruminants.

Calcium content. Calcium has a vital function in almost all tissues in the animal body and must be made available to livestock in proper quantities and ratios relative to P. Together, Ca and P are the most abundant mineral, elements in the animal body, making up 70% of the total mineral elements with 99% of Ca and 80% of P in the entire body found in bones and teeth (McDowell, 1985).

The NRC (1984) Ca requirements for beef cattle indicate that 0.17 to 1.53% Ca are adequate for growing and fattening steers and heifers. McDowell (1985) gave a range of from 0.18 to 1.04% Ca. For lactating dairy cows, the NRC indicates a range of 0.43 to 0.77% Ca, while McDowell (1985) found 0.43 to 0.60% Ca to be adequate.

Two of the major sources of Ca for use in agriculture (Anderson, 1991) are $CaCO_3$ (natural aragonite or calcite), $CaMg(CO_3)_2$ (natural dolomite), and $CaSO_4.2H_2O$ (mined or by-product gypsum) with solubilities in water at room temperature of 0.014-0.015, 0.32, and 2.6 g L^{-1} (for the PG used in this study), respectively (Weast, 1980-81; Alcordo and Rechcigl, 1992). The effectiveness of PG as a source of Ca lies in its high solubility, PG being 170 and 8 times more soluble than $CaCO_3$ and dolomite, respectively.

The 1991 analysis showed the order of the treatment effects on %Ca in regrowth forage as 4.0>0.4, C; and in 1992 it was 0.4, 2.0, 4.0>C. The order for the 3-year mean was 4.0>0.4, C; 2.0>C. The 1991, 1992 and 3-year mean analysis showed the effect of PG rates to be linear, with 3-year mean values of 0.41, 0.48, and 0.52% Ca for treatments 0.0, 2.0, and 4.0 Mg PG ha^{-1}, respectively. The results indicated that PG rates greater than 0.4 Mg ha^{-1} applied annually are needed to boost %Ca in bahiagrass regrowth forage above that of the untreated forage.

The effects of PG on Ca content were less pronounced in hay than in the regrowth. Only the 1991 harvests showed significantly different treatment means in the order of 4.0>0.4,C. The effects of PG rates were linear in 1991 and when averaged over the 3-year period.

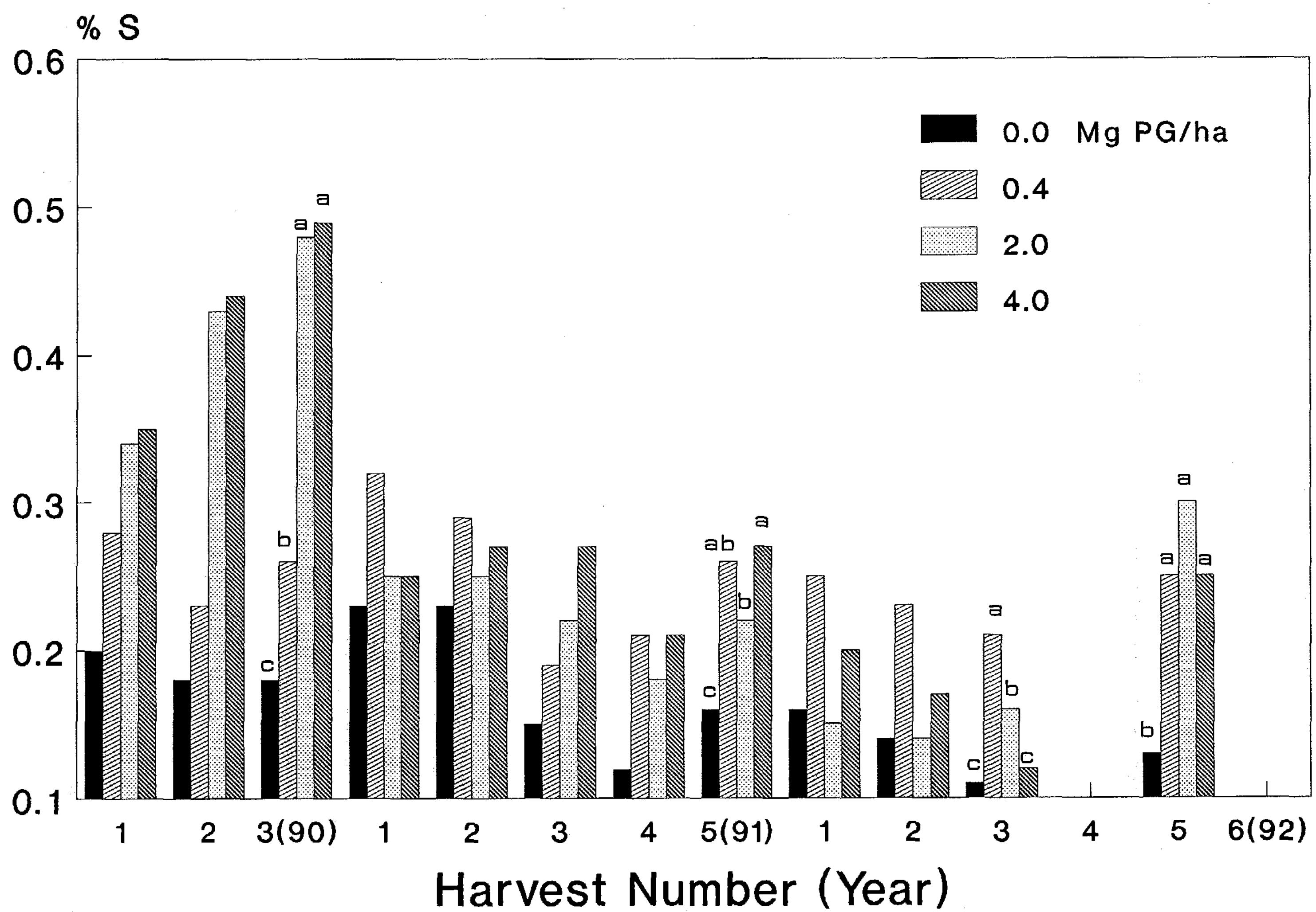


Figure 3. Sulfur concentrations in regrowth bahiagrass forage from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

The effects of PG rates on Ca content in the individual harvests are shown in Figure 4.

Table 9. Calcium concentrations in bahiagrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year			
	1990	1991	1992	Mean
A. Regrowth:	----------- %Ca -----------			
Mg PG ha^{-1}				
0.0(C)	0.44a[1]	0.45b	0.35b	0.41c
0.4	0.45a	0.49b[2]	0.39a[2]	0.45bc
2.0	0.57a	0.52ab	0.39a	0.48ab
4.0	0.58a	0.58a	0.40a	0.52a
Tests:[3]				
P(linear)	ns	0.0107	0.0177	0.0034
P(quadratic)	ns	ns	ns	ns
B. Hay:	----------- %Ca -----------			
Mg PG ha^{-1}				
0.0(C)	0.36a	0.49b	0.40a	0.44a
0.4	0.41a	0.51b[2]	0.45a[2]	0.47a
2.0	0.40a	0.58ab	0.42a	0.50a
4.0	0.42a	0.70a	0.41a	0.56a
Tests:				
P(linear)	ns	0.0178	ns	0.0259
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different (DMRT).
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant ($P>0.05$).

The Ca levels in the control and the treated forages were higher than the lower range of 0.17% Ca for what is considered to be adequate for growing and fattening steers and heifers. All values, however, were well below the upper level of 1.54% Ca. For lactating cows, the 3-year mean %Ca in the control forage fell short of the lower level of 0.43% Ca. The use of PG should help raise %Ca in bahiagrass forage. The 3-year mean analysis showed that it would be best to apply 2.0 Mg PG ha^{-1} once every 3 years to raise Ca concentrations in regrowth bahiagrass forage above that of the control, or annually at rates higher than 0.4 Mg PG ha^{-1} and probably 1.0 Mg ha^{-1}.

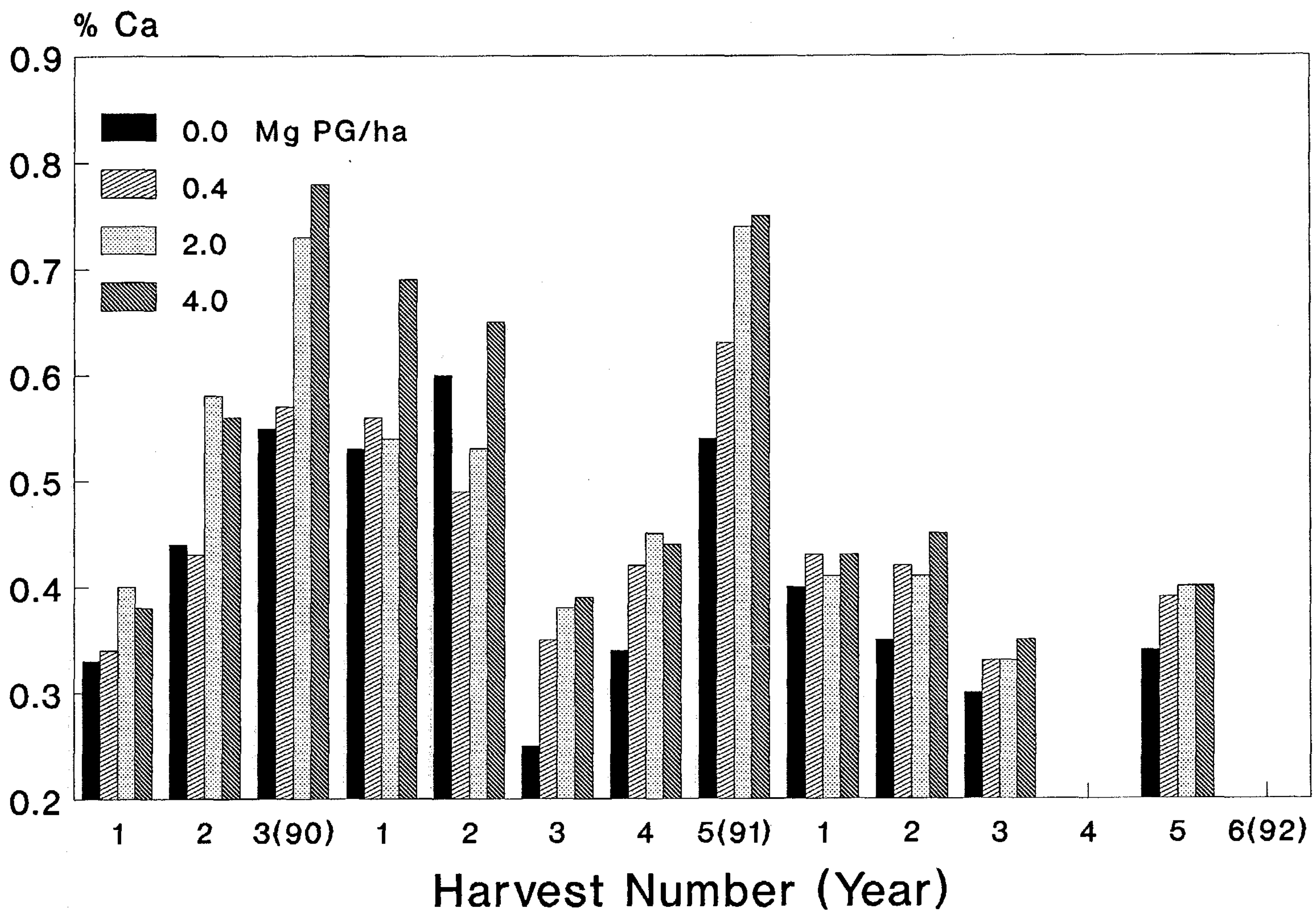


Figure 4. Calcium concentrations in regrowth bahiagrass forage from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

Nitrogen or crude protein (CP) content. The value of a forage as a source of amino acids can be determined by analyzing for total N. Forages contain N in many forms other than amino acids which may be converted to amino acids by the rumen microorganisms. All forms of N present in plants are included in the term crude protein (CP) which is obtained by multiplying total %N by 6.25. Protein contains 22 different amino acids and is necessary for the overall health and development of animal life. For ruminants, protein is needed for milk, muscle, wool, hair, and to replace protein lost during the maintenance of animal body weight (Minson, 1990).

The annual average N contents in the control regrowth forages ranged from 1.37% N (8.56% CP) to 1.79% N (11.19% CP). Those in PG-fertilized forages ranged from 1.35 (8.44% CP) to 1.84% N (11.50% CP). There was no evidence that PG application affected the levels of N based upon both the annual and the 3-year mean analyses and other tests.

The N contents in the individual regrowth harvests are given in Figure 5. There was no consistent trend in %N with PG rates.

The trend in N contents in hay showed consistently high values in PG-treated forages relative to those in the control forages for both annual and 3-year averages. The corresponding CP values for the N contents in hay were 5.69% for the control and 6.25, 6.19, and 6.13% for the 0.4, 2.0, and 4.0 Mg PG ha^{-1} treatments, respectively. The F test for the treatments (not shown in Table 10) gave a slightly significant (P=0.0830) effect of PG rates on %N, hence also on crude protein.

Thus, only in mature forages were there indications that PG may increase %N or crude protein contents in bahiagrass forage. With the increases in yields, however, PG could be said to have effectively enhanced the recovery of applied N. Based on a 6-year S fertilization study using gypsum conducted in Florida with bahiagrass, Mitchell and Blue (1989) showed that S fertilization enhanced the recovery of N applied at the rates of 200 and 400 kg N ha_{-1}. The present study used 180 kg N ha^{-1}.

Phosphorus content. Soil or applied PO_4-P may be adversely affected in the soil by large amounts of SO_4-S in PG applied to soils, both being multivalent anions. This, in turn, may adversely affect plant uptake of P.

The NRC (1984) P requirements for beef cattle indicate that 0.17-0.59% P are adequate for growing and fattening steers and heifers, 0.25 -0.48% P for lactating dairy cows, and 0.16 - 0.38% P for sheep (McDowell et al., 1993).

Table 11 shows that PG had little negative or positive effects on P uptake by bahiagrass. The 3-year average %P in regrowth forage was 0.24% for both the control and the PG treatments.

In hay, the P contents were 0.19% for the control and ranged from 0.19 to 0.21% for the PG treatments.

Table 10. Nitrogen concentrations in bahiagrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year			
	1990	1991	1992	Mean
A. Regrowth:	----------- %N -----------			
Mg PG ha^{-1}				
0.0(C)	1.64a[1]	1.37a	1.79a	1.58a
0.4	1.64a	1.37a[2]	1.77a[2]	1.57a
2.0	1.79a	1.35a	1.70a	1.59a
4.0	1.57a	1.40a	1.84a	1.59a
Tests:[3]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	----------- %N -----------			
Mg PG ha^{-1}				
0.0(C)	0.99a	0.81a	1.02a	0.91a
0.4	1.02a	0.93a[2]	1.11a[2]	1.00a
2.0	1.28a	0.85a	1.07a	0.99a
4.0	1.27a	0.84a	1.05a	0.98a
Tests:				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different (DMRT).
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant ($P>0.05$).

The P contents in the individual regrowth harvests are given in Figure 6 showing no consistent trends in the values. The PG treatments also had no positive nor negative effects on P contents in hay forage (Table 11).

The annual and the 3-year mean data and the statistical analysis showed no indications that PG affected, whether negatively or positively, P uptake by bahiagrass.

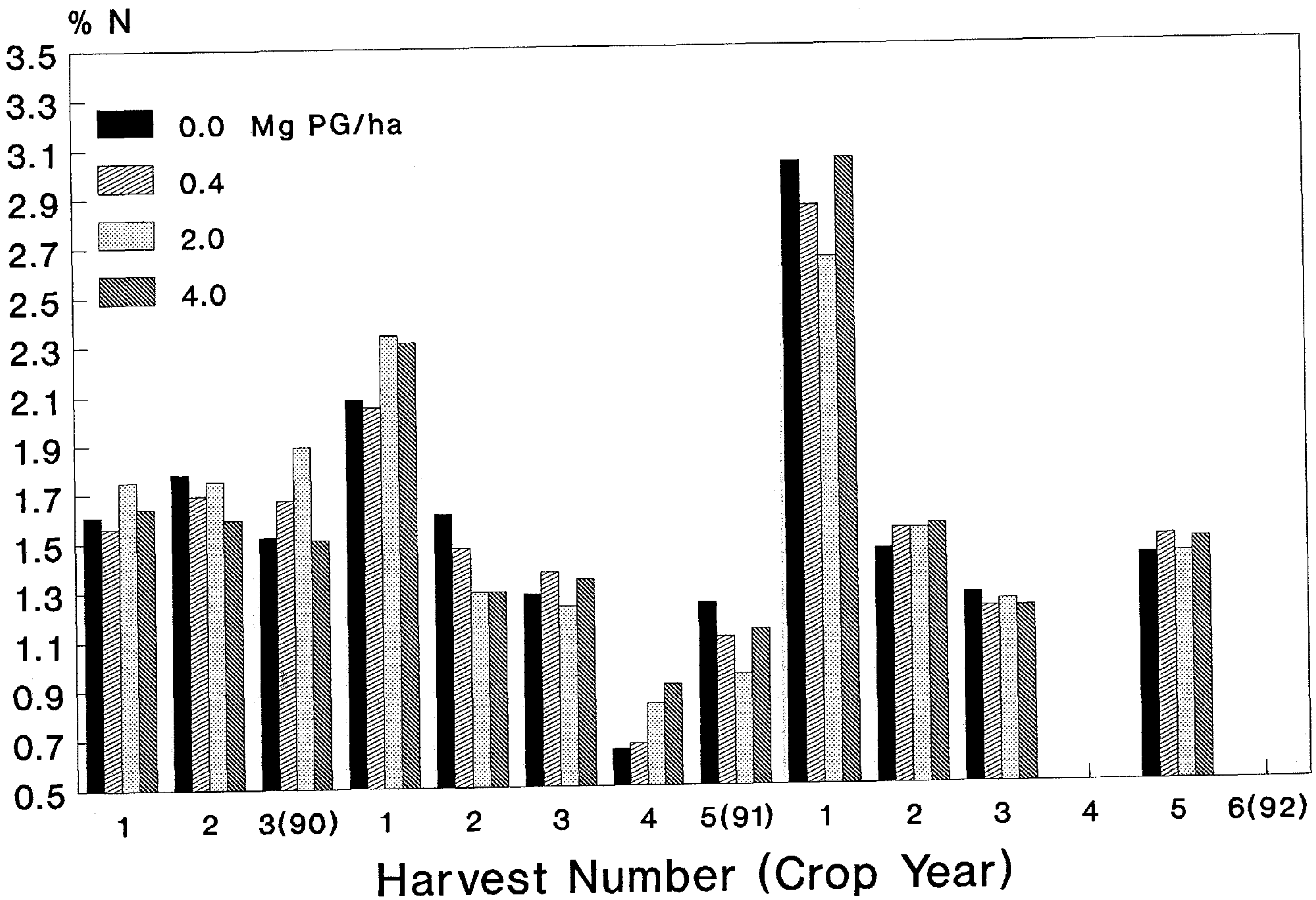


Figure 5. Nitrogen concentrations in regrowth bahiagrass forage from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter are not significantly different.

Table 11. Phosphorus concentrations in bahiagrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year 1990	1991	1992	Mean
A. Regrowth:	----------- %P			
Mg PG ha^{-1}				
0.0(C)	0.26a[1]	0.22b	0.24a	0.24a
0.4	0.25a	0.24a[2]	0.24a[2]	0.24a
2.0	0.22a	0.22b	0.22a	0.22a
4.0	0.22a	0.25a	0.23a	0.24a
Tests:[3]				
P(linear)	ns	0.0012	ns	ns
P(quadratic)	ns	0.0041	ns	ns
B. Hay:	----------- %P			
Mg PG ha^{-1}				
0.0 (C)	0.17a	0.19a	0.18a	0.18a
0.4	0.19a	0.23a[2]	0.18a[2]	0.21a
2.0	0.22a	0.20a	0.16a	0.19a
4.0	0.21a	0.22a	0.14a	0.19a
Tests:				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different (DMRT).
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant ($P>0.05$).

Potassium content. According to McDowell et al. (1993), K is the third most abundant mineral element in the animal body and is the principal cation of intercellular fluid. It is essential to animal life for a variety of body functions including osmotic balance, acid-base equilibrium, several enzyme systems, and water balance. An ionic balance exists between Ca, K, Mg, and Na.

For ruminant species, the requirement is estimated to be between 0.5 and 1.0% K in feed. The K requirement appears to be increased for livestock under stress (McDowell et al., 1993). Florida studies indicate that 0.8% K is not adequate under heat stress particularly with high-producing dairy cows (Beede et al., 1983). The K requirement for lactating cows under heat stress is reported to be 1.2% K (McDowell et al., 1993).

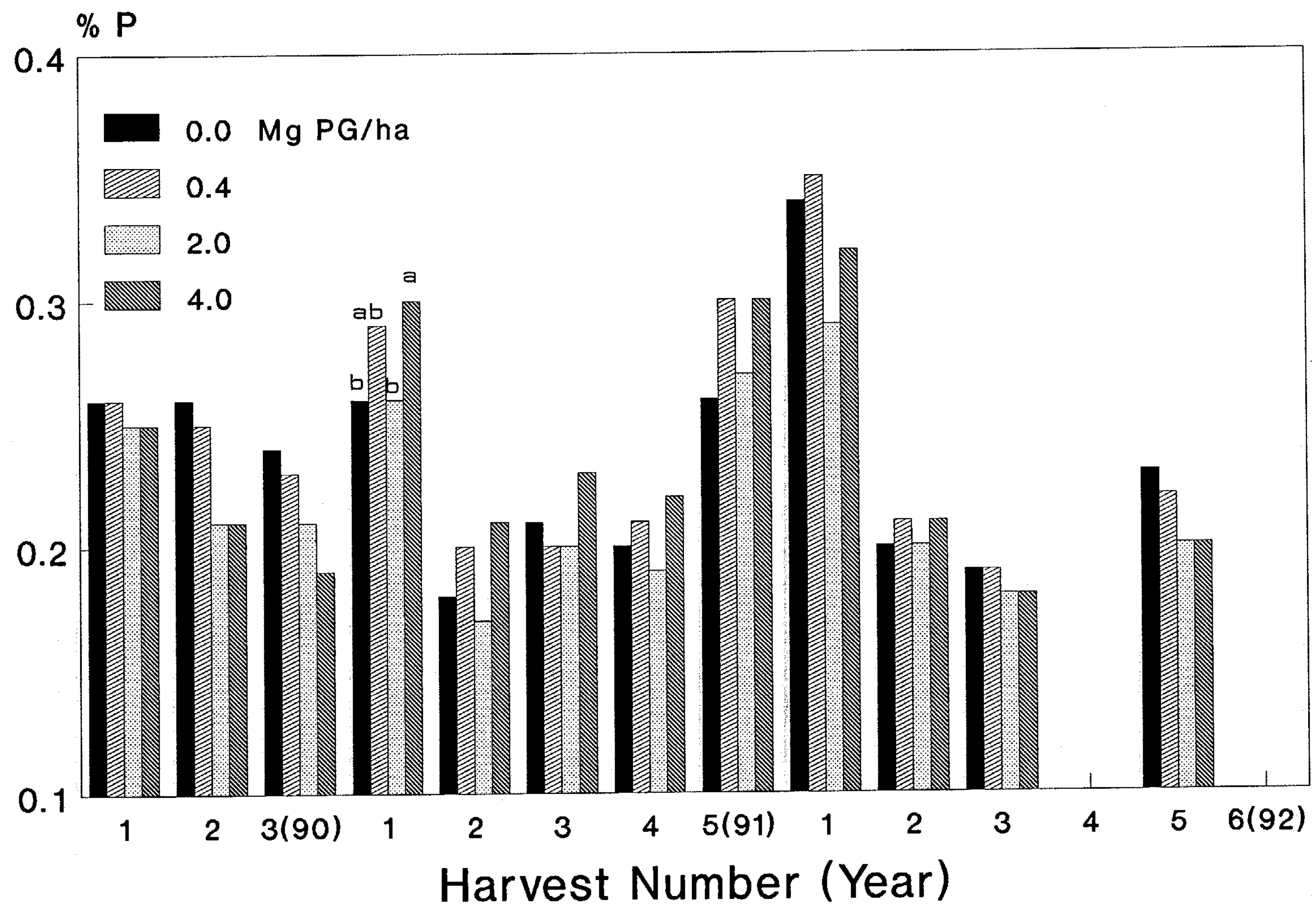


Figure 6. Phosphorus concentrations in regrowth bahiagrass forage from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

According to McDowell et al. (1993), it was believe until quite recently that there was little possibility of K deficiency in young forages. But mature winter pastures or hay forages exposed to rain and sun or which were overly mature when harvested can have K levels less than adequate for good nutrition.

Potassium is a cation like Ca. Relatively large quantities of PG applied to soils supply the soil with large quantities of highly active Ca cations in the soil solution. Thus, K may be displaced by Ca from the exchange complex in the soil and leached to deeper horizons beyond the reach of plant roots. O'Brien and Sumner (1988) showed a leaching effect of PG on K, but to a lesser degree than on Mg.

The %K in the 1990, 1991, 1992 control regrowth forages were 0.81, 0.44, 0.81% K, respectively, with a 3-year mean of 0.66% K. The annual averages for the PG-fertilized forages ranged from 0.68 to 1.09% K with a 3-year mean range of 0.83-0.87% K (Table 12). The 1990, 1991, and 3-year mean data clearly showed high %K in PG-treated regrowth forages compared with those in the control forages. The 1991 results showed a slightly significant linear increase in %K with PG rates. The 1992 analysis showed that regrowth forages from plots fertilized annually with 0.4 Mg PG ha^{-1} had higher K levels than forages from the control plots and from lots that received one-time applications of 2.0 and 4.0 Mg PG ha^{-1} (Table 12). The positive effect of the low annual rate of 0.4 Mg PG ha^{-1} on K uptake by bahiagrass was confirmed in the agronomic experiment.

Figure 7 shows most of the PG-fertilized regrowth forages with consistently high K contents relative to those in the control forages in all 1990 and 1991 harvests. The trend persisted into 1992 with forages fertilized annually at 0.4 Mg PG ha^{-1}. It may be that as Ca replaces K in the exchange complex, K becomes more readily available for plant use as it goes into the soil solution.

In hay, the annual averages for the PG-fertilized ranged from 0.39 to 1.03 with a 3-year mean range of 0.43 to 0.63% K (Table 12). The 1990 and 1991 data clearly showed high %K in PG-fertilized hay relative to those in the control forages. The 1991 analysis showed the treatment effects in the order of 4.0>2.0, C; 0.4>C. The 3-year mean analysis showed all PG-fertilized forages with significantly higher %K than the control hay forages (Table 12).

The tests on trends indicated a significantly increasing linear effect of PG rates on tissue K in 1991 and significantly quadratic in 1992. The 3-year mean results indicated a linear effect with 0.43, 0.56, and 0.63% K for treatments 0.0, 2.0, and 4.0, respectively.

Table 12. Potassium concentrations in bahiagrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year			Mean
	1990	1991	1992	
A. Regrowth:	%K			
Mg PG ha^{-1}				
0.0(C)	0.81a[1]	0.44a	0.81b	0.66a
0.4	0.91a	0.68a[2]	0.96a[2]	0.83a
2.0	1.09a	0.67a	0.79b	0.83a
4.0	1.00a	0.81a	0.84b	0.87a
Tests:[3]				
P(linear)	ns	0.0981	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	%K			
Mg PG ha^{-1}				
0.0(C)	0.61a	0.28c	0.55a	0.43b
0.4	0.76a	0.47ab[2]	0.60a[2]	0.56a
2.0	0.96a	0.39b	0.49a	0.56a
4.0	1.03a	0.59a	0.55a	0.63a
Tests:				
P(linear)	ns	0.0063	ns	0.0153
P(quadratic)	ns	ns	0.0280	ns

[1]Means with the same letter(s) are not different (DMRT).
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant ($P>0.05$).

Magnesium content. Magnesium is the second most plentiful cation (after K) of intercellular fluid. An ionic balance exists between Ca, K, Mg, and Na. Magnesium also has many diverse physiological functions in animals and plays important roles in many fundamental enzymatic reactions in intermediary metabolism, in the metabolism of carbohydrates and lipids, in protein synthesis, and in neuromuscular transmission and activities (McDowell et al., 1993).

Minimum needs of sheep and cattle for growth can generally be met by pastures containing 0.10% Mg. For lactating cows 0.18 to 0.20% Mg in diets is considered necessary. In order to meet lactation requirement, forages would need to contain between 0.16 to 0.19% Mg (McDowell, et al., 1993).

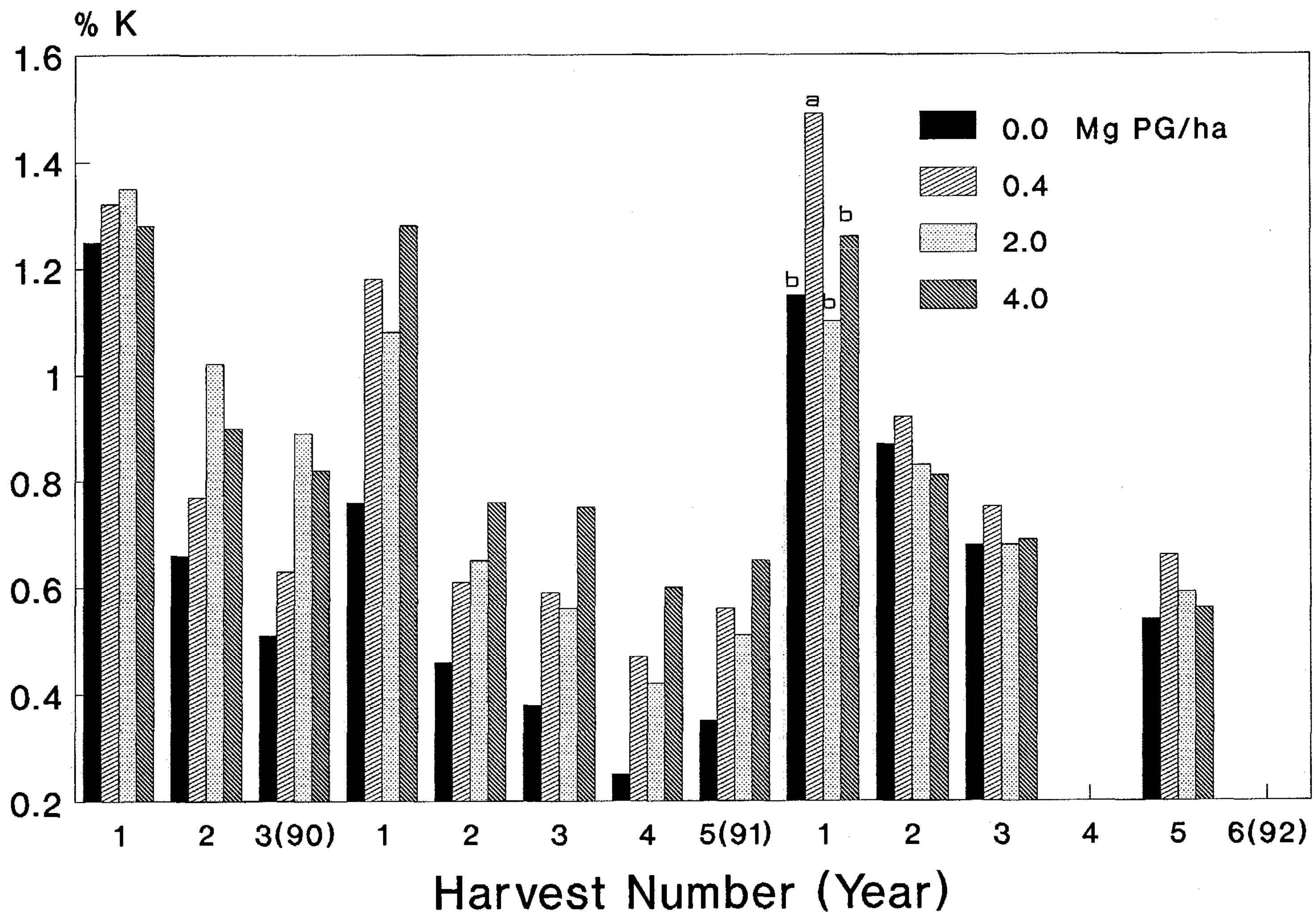


Figure 7. Potassium concentrations in regrowth bahiagrass forage from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

Magnesium is much more easily leached than K upon PG application (O'Brien and Sumner, 1988). A single pore volume of water applied at the rate of 1.5 mL per minute to 8 cm long soil cores on which PG was applied on the surface at the equivalent rate of 1.12 Mg PG ha^{-1} leached out as much as 60% of Mehlich 1 extractable Mg (Alva and Gascho, 1991). In the Philippines, PG has been used for years to leach out excess Mg in Mg-rich soils, especially in soils used for banana production. Hence, the need to examine the effects of PG application to pastures on Mg levels in forage in relation to ruminant nutrition.

In 1990, the analysis showed the effects of the treatments in the order of 4.0>0.4, C in reducing Mg content in regrowth forage. The tests for trends indicated a quadratically decreasing Mg content with increasing PG rates (Table 13).

Table 13. Magnesium concentrations in bahiagrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year			Mean
	1990	1991	1992	
A. Regrowth:	%Mg			
Mg PG ha^{-1}				
0.0(C)	0.35a[1]	0.32a	0.26a	0.31a
0.4	0.37a	0.35a[2]	0.29a[2]	0.33a
2.0	0.33ab	0.35a	0.29a	0.32a
4.0	0.28b	0.29a	0.27a	0.28a
Tests:[3]				
P(linear)	0.0145	ns	ns	ns
P(quadratic)	0.0474	ns	ns	ns
B. Hay:	%Mg			
Mg PG ha^{-1}				
0.0(C)	0.60a	0.40a	0.28a	0.39a
0.4	0.35a	0.40a[2]	0.31a[2]	0.36a
2.0	0.48a	0.37a	0.27a	0.36a
4.0	0.29a	0.29a	0.24a	0.27a
Tests:				
P(linear)	ns	0.0286	ns	0.0793
P(quadratic)	ns	0.0660	ns	ns

[1]Means with the same letter(s) are not different (DMRT).
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05), but P-values <0.10 are given for reference and referred to as "slightly" significant.

The %Mg in individual regrowth harvests during the 3-year period are given in Figure 8. The adverse effects of the one-time application of 4.0 Mg PG ha" on %Mg in regrowth bahiagrass forage, highlighted in Figure 8, lasted into the first harvests of 1992 or two years after application. Interestingly, the 0.4 Mg PG ha^{-1} applied annually showed no adverse effects on tissue Mg. The individual harvests in all three years showed %Mg in regrowth forages from plots that received 0.4 Mg PG ha^{-1} were, in most harvests, actually higher than the %Mg in the control forages. This indicates that reasonably low PG rates may enhance the availability of Mg in the soil and increase %Mg in bahiagrass forage.

In hay, the annual %Mg means were lowest in forages fertilized with 4.0 Mg PG ha^{-1}, ranging from 0.24 to 0.29% Mg compared with 0.28 to 0.60% for the control, 0.31 to 0.40% for the annual PG rate, and 0.27 to 0.48% for the 2.0 Mg PG ha^{-1} initial rate. The 1991 and the 3-year mean linear tests indicated significant (P{linear=0.0286}) and slightly significant (P{linear}=0.0793) linear trends, respectively, with %Mg decreasing with PG rates.

Thus, the adverse effects of high rates of PG on soil Mg reported in the literature may also have adverse effects on Mg uptake by crops.

A.1.4. Other Forage Quality Measures

Nitrogen:sulfur (N:S) ratio. Another measure of forage quality related to N and S is the N:S ratio. In plant protein, the N:S ratio is about 15:1 and remains fairly constant. If either S or N is limiting, protein synthesis is restricted, but the protein already synthesized will have a N:S ratio of 15:1. Excess N relative to S accumulates as NO_3 nitrogen, amides, and amino acids. Excess S leads to SO_4 accumulation (Stewart and Porter, 1969).

The **INTRODUCTION** part of this report gives a review of the literature on the effect of S fertilization on N:S ratios in various forage crops and on the ratio's significance in animal nutrition.

The 1990 analysis showed that PG reduced the N:S ratios in regrowth forages in the order of 2.0, 4.0>0.4>C with actual values of 4.57 and 3.87 less than 6.71 and 6.71 less than 9.29, respectively (or simply 4.57, 3.87<6.71<9.29). In 1991 the effect of treatments reduced N:S ratios in the order of 0.4, 4.0>C with actual values of 8.11, 10.26<13.24, respectively. The 3-year mean showed that all PG-treated forages had significantly lower N:S ratios than that of the control (Table 14).

The linear tests showed that PG reduced the N:S ratios in regrowth forage with PG rates in all three years and when averaged over the 3-year period (Table 14).

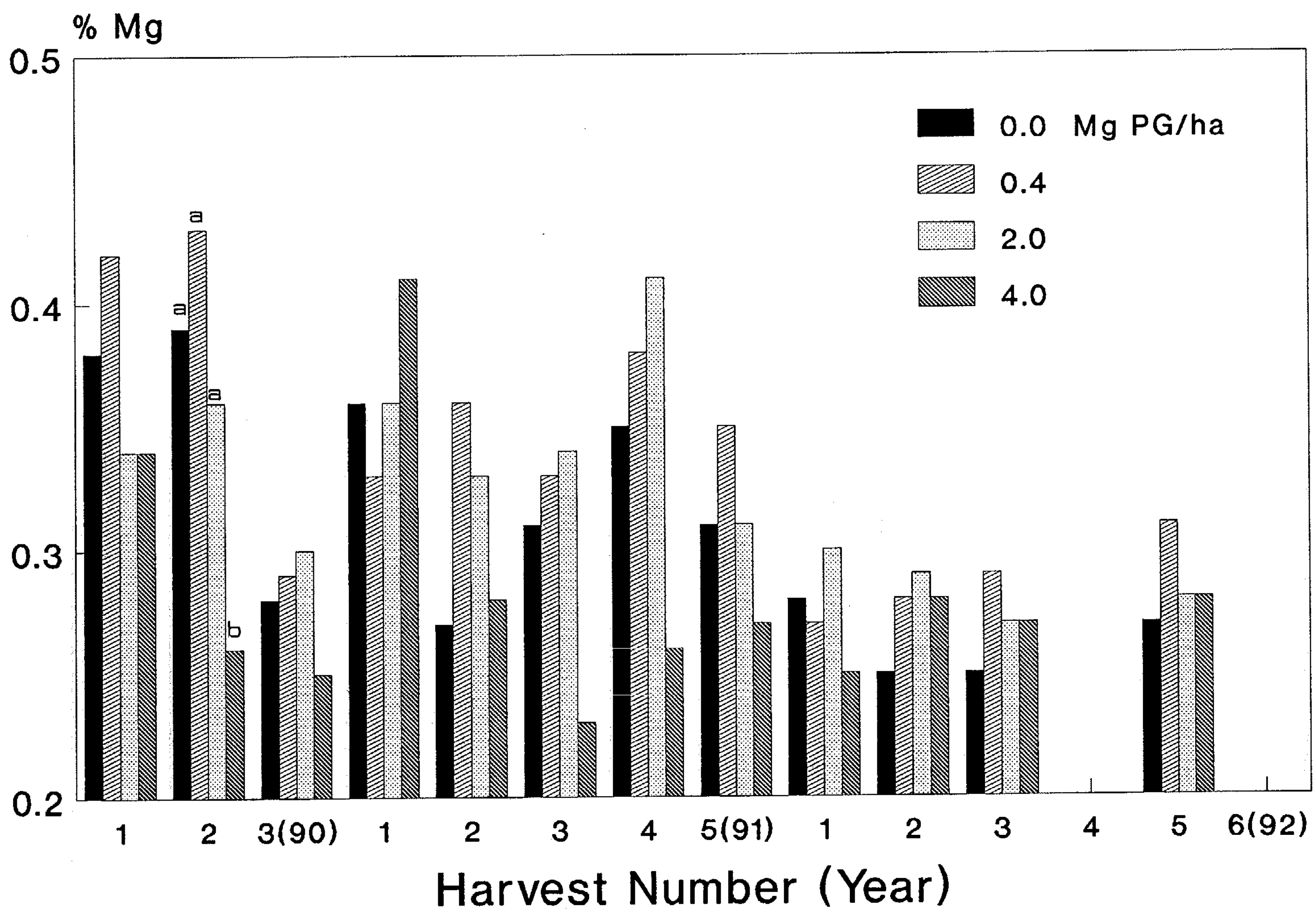


Figure 8. Magnesium concentrations in regrowth bahiagrass forage from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

The annual average N:S ratios for hay tended to decrease with increasing PG rates. The 3-year means analysis showed the N:S ratios in bahiagrass hay forage decreased linearly with PG rates in the order of 4.0<2.0, 0.4<C (Table 14).

The N:S ratios for the individual harvests are given in Figure 9. A few of the N:S ratios in bahiagrass reached or exceeded 10:1. Most N:S values were much less than 10:1. The very high N:S ratios in the first harvests of 1992 were very unusual and were due to the unusually high %N in these harvests as shown in Figure 5. Also from Figure 9, it would appear that at the rate of 180 kg N ha^{-1}, as was applied in the study, no S fertilization was needed. However, the first harvests in 1992 indicated that when conditions favorable to N uptake do occur, the N:S ratios could become unusually high when no S source is applied.

Table 14. N:S ratios in bahiagrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year			
	1990	1991	1992	Mean
A. Regrowth:	------------ N:S ------------			
Mg PG ha^{-1}				
0.0(C)	9.29a[1]	8.44a	13.24a	10.20a
0.4	6.71b	5.72a[2]	8.11b[2]	6.76b
2.0	4.57c	6.64a	10.42ab	7.55b
4.0	3.87c	5.72a	10.26b	6.74b
Tests:[3]				
P(linear)	0.0005	0.0493	0.0657	0.0034
P(quadratic)	0.0056	ns	ns	0.0446
B. Hay:	------------ N:S ------------			
Mg PG ha^{-1}				
0.0(C)	3.76a	7.02a	5.85a	6.08a
0.4	3.42a	5.42a[2]	4.31a[2]	4.66b
2.0	2.98a	4.95a	3.99a	4.30b
4.0	2.97a	3.53a	3.96a	3.58c
Tests:				
P(linear)	ns	0.0295	ns	0.0004
P(quadratic)	ns	ns	ns	0.0246

[1]Means with the same letter(s) are not different (DMRT).
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

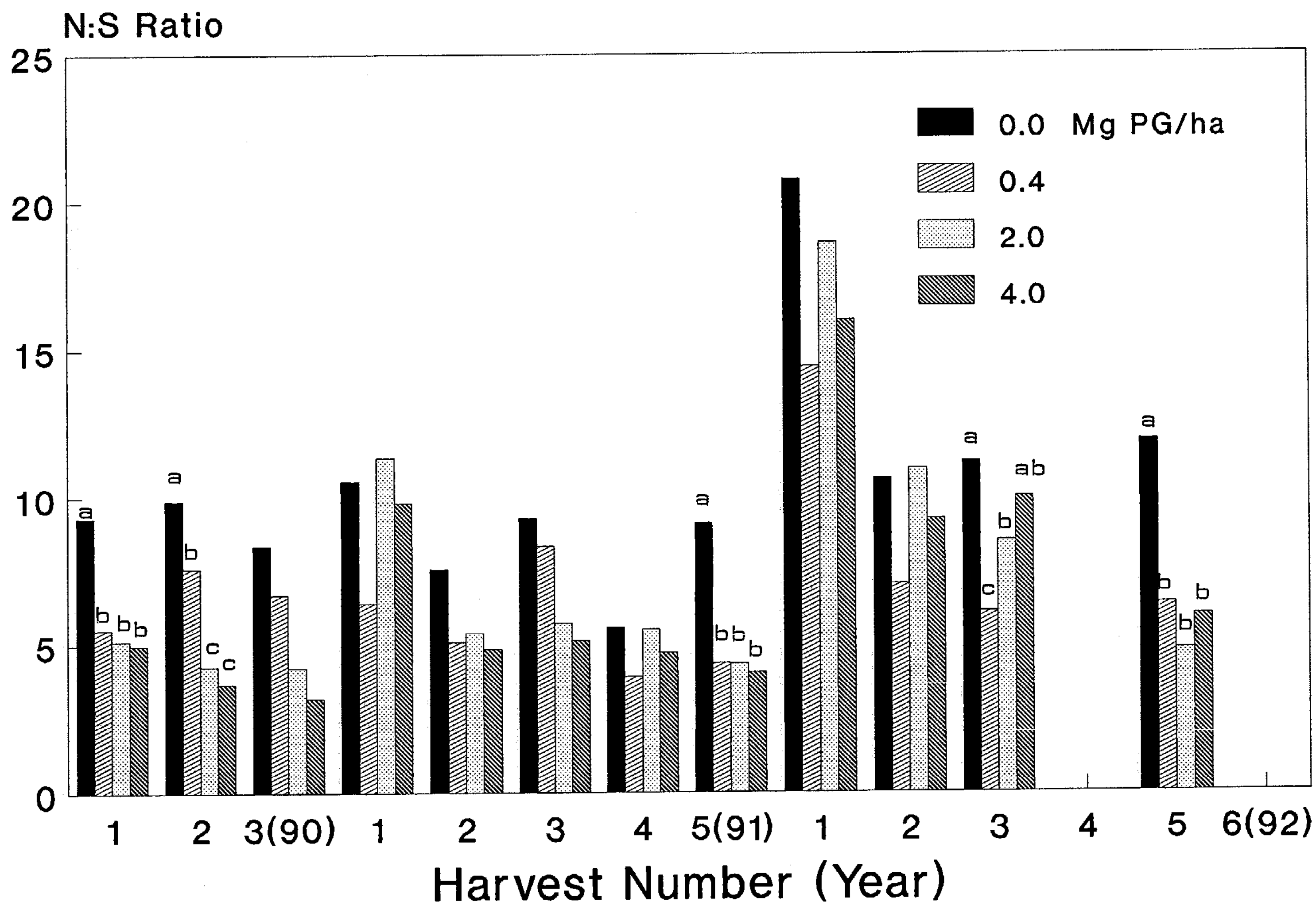


Figure 9. N:S ratios in regrowth bahiagrass forage from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

The %N and %S in bahiagrass before PG and N were 0.78% and 0.18%, respectively, with a N:S ratio of 4.33 (Table 3). Ruminants require a N:S ratio between 10:1 to 12:1 for optimum performance (Rendig and Weir, 1957; Allaway and Thompson, 1966; Moir et al., 1967-1968; Tisdale, 1977; and Murphy et al., 1983). Bahiagrass is a low-quality grass with low N contents and relatively adequate S levels supplied from atmospheric S resulting in low N:S ratios in the forage. Under such conditions, PG or S fertilization must be accompanied with relatively high N fertilization to improve forage quality in terms of N:S ratios.

Calcium:phosphorus (Ca:P) ratio. The Ca:P is another important dietary ratio since P and Ca need to be supplied to animals in a rather narrow ratio. It has been suggested that dietary Ca:P ratio should be kept between 1:1 to 2:1 since this range covers the range of ratios of the two minerals in bone (McDowell et al., 1993). Wise et al. (1963) found that of nine dietary Ca:P ratios ranging from 0.41:1 to 14.3:1, only the ratios below 1:1 or over 7:1 resulted in decreased growth and feed efficiency. There may be a need to monitor the Ca:P ratio in pastures since it can be affected by excessive application of cheap Ca sources, such as PG or $CaCO_3$, which could significantly drive up the Ca:P ratio without adequate P fertilization.

Table 15. Ca:P ratio in bahiagrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment[1]	Year			Mean
	1990	1991	1992	
A. Regrowth:	Ca:P			
Mg PG ha^{-1}				
0.0(C)	1.69	2.04	1.47	1.69
0.4	1.79	2.04	1.61	1.89
2.0	2.56	2.38	1.79	2.17
4.0	2.63	2.33	1.75	2.17
B. Hay:	Ca:P			
Mg PG ha^{-1}				
0.0(C)	2.13	2.56	2.22	2.44
0.4	2.17	2.22	2.50	2.22
2.0	1.82	2.94	2.63	2.63
4.0	2.00	3.22	2.94	2.94

[1]No statistical analysis was done with the data. It was more important to know the ratios in both regrowth and hay forages.

The annual mean Ca:P ratios ranged from 1.47 to 2.63 in regrowth and from 1.82 to 3.22 in hay which were near the ideal ratio range of from 1:1 to 2:1 (Table 15). The Ca:P ratios for the individual harvests with PG rates are given in Figure 10. The highest ratio obtained was about 4:1, with most of the ratios falling within the range of 1:1 to 3:1.

In vitro organic matter digestibility (IVOMD) Another measure of forage quality related to S and N is its digestibility. The apparent digestibility of forage is the proportional difference between the quantities consumed and those excreted in the feces (Minson, 1990). Digestibility is related to the energy value of forage. Most studies of the energy value have been limited to measuring the loss of forage dry matter in the feces, the results being expressed as dry matter digestibility (DMD) coefficient or organic matter digestibility (OMD) coefficient (Minson, 1990).

The digestibility measurements of forages may also be done in vitro with the results reported as percent in vitro organic matter digestibility (%IVOMD). This is the method used in this study to measure forage digestibility. Minson (1990) reported that there appears to be no consistent pattern on IVOMD as a response to N fertilization in both young and mature forage. The higher crude protein in N-fertilized forage is often offset by a reduction in the level of soluble carbohydrate (Alberda, 1965; Raymond and Spedding, 1965; Wilson and Mannetje, 1978 as cited by Minson, 1990). The effect of S fertilization, however, is different. Low levels or available S in soil have been shown to reduce DMD (Rees et al., 1974). Application of S fertilizer to S-deficient Digitaria decumbens increased DMD by 0.05 (Rees et al., 1974) and energy digestibility by 0.10-0.12 (Rees et al., 1980). McDowell et al. (1993) stated that the optimum S level for cellulose digestion in vitro has been reported to be 0.16 to 0.24% S of dry matter. Akin and Hogan (1983) concluded that this was due to enhanced fiber-digesting capability of the rumen microorganisms and not to any change in the anatomy of the forage (Akin and Hogan, 1983).

The annual and 3-year mean %IVOMD of bahiagrass fertilized with PG did not show any treatment effects in both regrowth and hay forages (Table 16).

The %IVOMD of the individual harvests are given in Figure 11. Some PG-fertilized individual harvests showed apparently high %IVOMD relative to those of the controls. The first harvest in 1990 showed significant treatment effects in the order of 2.0, 4.0, 0.4>C with actual values of 59.7, 59.2, 56.7>49.9% IVOMD, respectively. Harvest 4 in 1991 also gave significant treatment effects in the order of 2.0>0.4>4.0, C with values of 49.5, 48.3>44.3, 43.5, respectively. Harvest 5 in 1991 (Figure 11) showed the highest %IVOMD for 0.4 Mg PG ha^{-1} rate applied annually which was significantly different from the rest of the treatments.

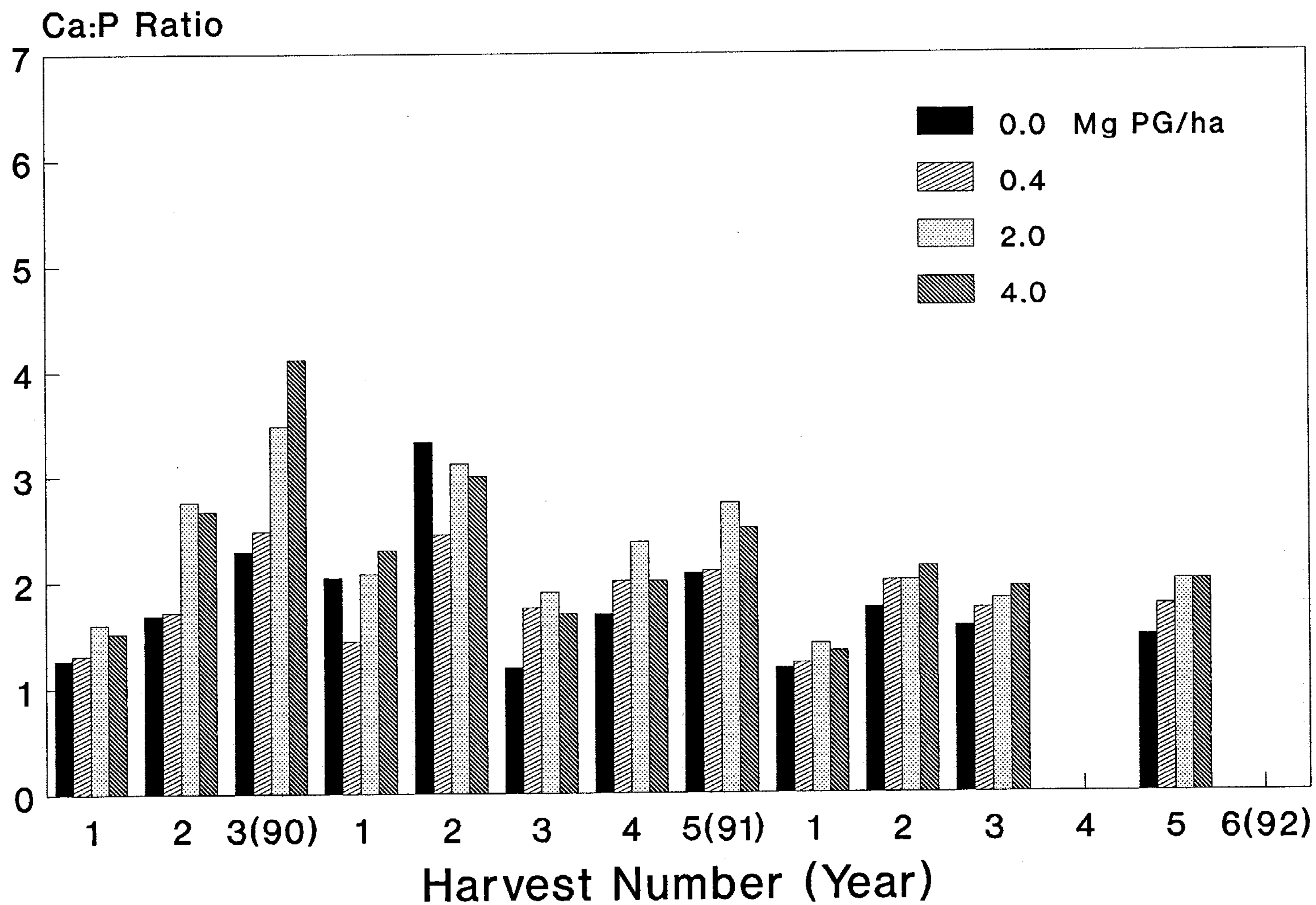


Figure 10. Ca:P ratios in regrowth bahiagrass forage from plots which were amended with PG, 1990-1992. No statistical analysis was done with the data.

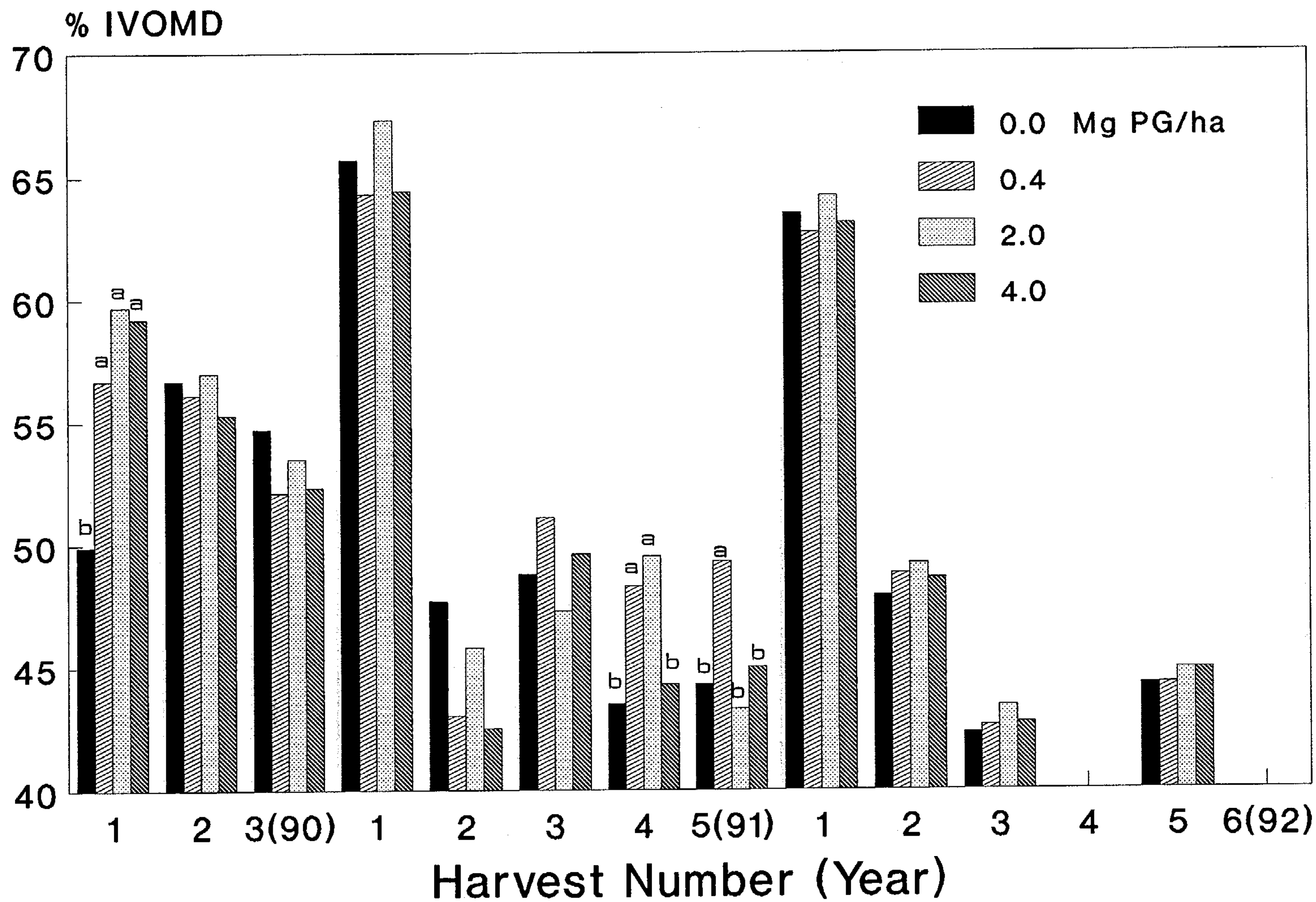


Figure 11. In vitro organic matter digestibility (IVOMD) of regrowth bahiagrass forage from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter or with the same letter(s)

Thus, PG may enhance the digestibility of bahiagrass in certain harvests, if not in all harvests, in a growing season.

A.1.5. Fluoride in Forage

Fluoride is a cumulative poison. Intake of small quantities of F over an extended period may lead to the accumulation of F in animals to toxic levels (Campbell and Lasley, 1969). Several investigators have found that adverse effects of chronic F toxicosis on bones and teeth can result in leg stiffness, lameness, reduced feed intake, a decline in general health, and greatly reduced animal productivity (Hobbs, et al., 1954; Allcroft, et al. 1965, and Suttie, J.W., 1977). Doses of F that cause acute toxicity have been found to cause gastroenteritis, muscular weakness, chronic convulsion, pulmonary congestion, and respiratory and cardiac failure (Suttie, 1977).

Table 16. In vitro organic matter digestibility (IVOMD) of bahiagrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year			Mean
	1990	1991	1992	
A. Regrowth:	------------ %IVOMD --------------------			
Mg PG ha^{-1}				
0.0(C)	54.1a[1]	50.0a	49.5a	50.8a
0.4	55.0a	51.2a[2]	49.6a[2]	51.6a
2.0	56.4a	50.6a	50.1a	51.7a
4.0	55.9a	49.1a	50.1a	51.1a
Tests:[3]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	------------ %IVOMD --------------------			
Mg PG ha^{-1}				
0.0(C)	39.7a	39.1a	25.1a	34.5a
0.4	38.0a	41.6a[2]	25.3a[2]	35.6a
2.0	46.8a	38.1a	27.4a	36.0a
4.0	41.7a	39.0a	26.6a	35.3a
Tests:				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different (DMRT).
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

Based on dietary tolerances developed by the National Research Council, dietary F should not exceed 40 mg kg^{-1} for beef and dairy cattle, 60 mg kg^{-1} for horses, and 60 and 150 mg kg^{-1} for breeding ewes and feeder lambs, respectively (NRC, 1974). Some data on bovines indicate that long-term feeding of diets containing more than 30 mg F kg^{-1} may lead to fluorosis within a period of 2 to 3 years (Church, 1979).

According to McDowell et al. (1993), ruminants are more susceptible to F toxicity than nonruminants. Chronic fluorosis is generally observed under conditions of continuous consumption of high F mineral supplements, continuous drinking water with 3-15 mg F L^{-1}, and grazing F contaminated forages from pastures adjacent to industrial plants that emit F fumes or dust.

Suttie (1977) reported that forages in areas free of F contamination will generally contain 5 to 10 mg F kg^{-1} dry matter. Forages subjected to atmospheric F pollution may show a ten-fold variation in F content from season to season, tending to be lower during the early part of summer and higher in the fall. It was suggested that forages to be razed for research studies should not exceed 15 to 20 mg F kg dry matter (IFAS, 1980).

The annual average F contents in regrowth forages ranged from 6.3 to 8.8 for the control and from 6.8 to 10.2 mg F kg^{-1} for the PG-fertilized forage. Those in hay ranged from 2.4 to 9.5 for the control and from 2.5 to 8.0 mg F kg^{-1} for the PG-fertilized forages.

The analysis for 1991 showed that regrowth forages from plots that received 4.0 Mg PG ha^{-1} had higher F contents than the control with actual values of 9.0 and 6.3 mg F kg^{-1}, respectively. The linear test also showed that tissue F increased linearly with PG rates in 1991. When averaged over the 3-year period, however, the analysis indicated no effects of PG on F in bahiagrass regrowth forage (Table 17).

The highest F content in individual harvests was about 14 mg F kg^{-1}, but most of the values were within the range of 4 to 10 mg F kg^{-1} (Figure 12). While there was not a single harvest that indicated significant treatment differences, Figure 12 does indicate the potential of increasing F contents in bahiagrass forage with PG applications. However, the application of PG at the rates and the frequency used resulted in F contents in bahiagrass forage which were much lower than the 30 mg F kg^{-1} forage which may be considered an upper limit for bovines (Church, 1979).

Table 17. Fluoride concentrations in bahiagrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-1992.

Treatment	Year			Mean
	1990	1991	1992	
A. Regrowth:	----------- mg F kg^{-1}	-----------------		
Mg PG ha^{-1}				
0.0(C)	8.8a[1]	6.3b	7.6a	7.2a
0.4	8.0a	6.8ab[2]	8.3a[2]	7.7a
2.0	10.2a	7.3ab	7.7a	7.9a
4.0	9.7a	9.0a	7.9a	8.6a
Tests:[3]				
P(linear)	ns	0.0393	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	----------- mg F kg^{-1}	-----------------		
Mg PG ha^{-1}				
0.0(C)	9.5a	7.4a	2.4a	5.8a
0.4	7.5a	6.9a[2]	2.6a[2]	5.3a
2.0	5.5a	7.6a	2.5a	5.2a
4.0	8.0a	7.0a	2.6a	5.4a
Tests:				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different (DMRT).
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

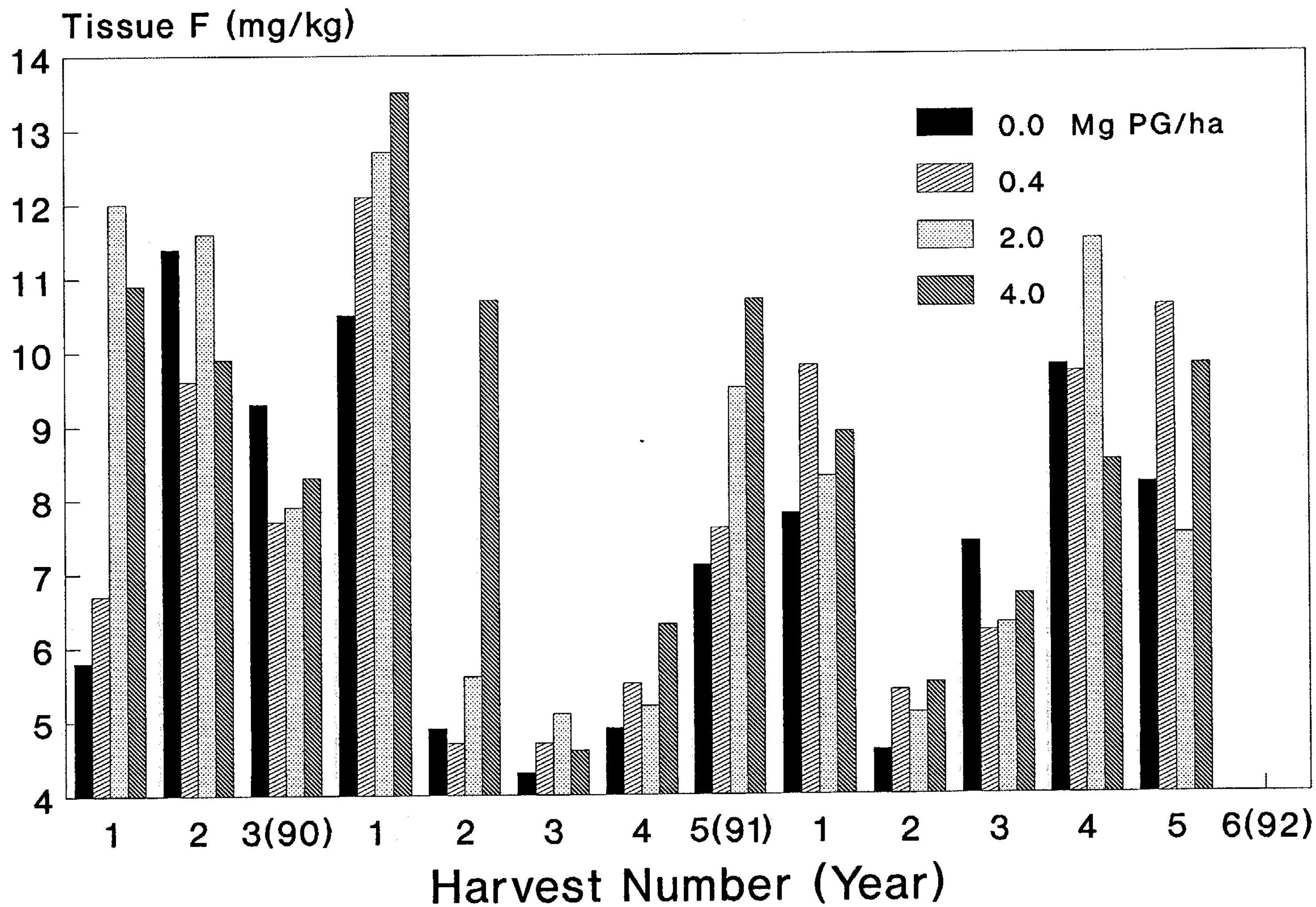


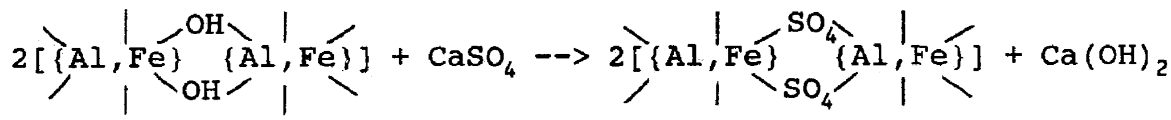
Figure 12. Fluoride concentrations in regrowth bahiagrass forage from plots which were amended with PG, 1990-1992. Treatments in each harvest without any letter are not significantly different.

A.2. Effects of PG on soil pH, Calcium, Phosphorus, Potassium, Magnesium, and on Certain Micronutrients

This section covers the fate and the influence of PG on the soil. Because it is more accurate to analyze for soil Ca than soil S, only Ca was used to evaluate the fate of PG and its effect on the other plant nutrients.

A.2.1. Soil pH

A "self-liming" mechanism had been proposed by Reeve and Sumner (1972) and Sumner (1990) to explain increases in pH and the reductions in exchangeable Al (or Fe) in acid soils upon gypsum or PG applications, according to the following reaction:



The $Ca(OH)_2$ not only would raise soil solution pH but may also neutralize active Al and Fe in the soil solution according to the following reactions:

$$3Ca(OH)_2 + 2Al^{3+} \text{---------------}> 2Al(OH)_3 + 3\ Ca^{2+};\ \text{and/or}$$

$$3Ca(OH)_2 + 2Fe^{3+} \text{---------------}> 2Fe(OH)_3 + 3Ca^{2+}.$$

Chang and Thomas (1968) proposed a more comprehensive mechanism to explain SO_4 sorption and the self-liming effect of SO_4-salts such as gypsum or PG in acid soils. Assuming a homoionic Al-saturated clay coated with hydrated oxides of Fe and Al (R), two opposing reactions may occur:

1. Al and/or Fe hydrolysis:

$$Clay\text{-}Al_x + yH_2O + yK^+ \text{-------}> Clay\text{-}Al_x(OH)^{yk}_y + yH^+$$

2. Ligand exchange:

$$Clay\text{-}R_x(OH)_y + SO_4^{2-} \text{-------}> Clay\text{-}R_x[(OH)_{y-z}(SO_4)_z] + zOH^-.$$

According to the above reactions, the hydrolysis of the exposed and/or adsorbed Al and/or Fe at the clay edges and/or surfaces, in the presence of salt (a K-salt for example), releases H^+ into the soil solutions causing Al-induced (or Fe-induced) acid conditions. In the case of a SO_4-salt, the more negatively charged SO_4 readily replaces OH^- in a ligand exchange, which then neutralizes the H^+ causing a so-called self-liming within the system.

It is by these two similar mechanisms that PG application to soils may be expected to affect soil pH.

The 3-year mean pH values across all depths, from 0-15 down to 75-90 cm, and across PG rates ranged from 4.9 to 5.5. The pre-PG pH at the 0-15 cm depth was 5.4 (Table 2). The 3-year pH means at 0-15 cm depth ranged from 5.1 in the control plot to 5.0-5.1 in the PG-treated plots. Across PG rates and at all depths, the control plots showed high pH values relative to those of the PG-treated plots. There was evidence at 30-45 cm depth that pH slightly significantly ($P_{linear}<0.10$) decreased with PG rate (Table 18).

The soil pH values by depth for the years 1990, 1991, and 1992 are graphically presented in Figure 13. In 1990 there was a clear trend showing reductions in pH with PG rates. At 30-45 cm and 45-60 cm depths, pH significantly ($P<0.05$) linearly decreased with PG rates. The analysis for 45-60 cm depth showed the order of the treatments as C, 0.4>4.0, 2.0 with actual values 4.8, 4.6>4.3, 4.1.

In 1991 and 1992 the pH values in PG-treated plots tended to equal those in the control plots at most depths (Figure 13).

It is concluded that the PG used in the study slightly reduced soil pH at certain depths, but the reductions in pH with PG rates were small and short-lived and may not be of any physiological significance to the plants.

A.2.2. Soil Macronutrients

Calcium. The 3-year mean Ca levels, by depth, were not significantly different at all depths at the various PG rates of applications. Soil Ca at the top 15 cm ranged from 442 mg Ca kg^{-1} in the control plots to 554 mg Ca kg^{-1} in plots that received 4.0 Mg PG ha^{-1} initially, respectively (Table 19). For reference, the mean pre-treatment Ca level at the top 15 cm was 778 mg kg^{-1} (Table 2).

The trends of the effects of PG rates on soil Ca levels were seen more clearly in the annual values (Figure 14). At the end of the 1990, soil Ca at 0-15, 30-45, and 45-60 cm depths tended to increased with PG rates. Below the 60 cm depth, soil Ca levels were apparently higher in all PG-treated plots than in the control indicating movements of Ca from PG into deeper horizons within a year's time. There were no clear trends in soil Ca in 1991. In 1992, Ca levels in plots that received 0.4 Mg PG ha^{-1} annually were apparently higher at the top 15 cm than in the control. Also at the top 15 cm, the plots that received one-time applications of PG in 1990 had apparently lower Ca than the control. Below 60 cm, Ca levels in all PG-treated plots were apparently higher than in the control (Figure 14). The plots treated with 0.4 Mg PG ha^{-1} annually started to show higher Ca levels than the control below the 45 cm depth. The movement and the accumulation of Ca from surface-applied PG into deeper soil horizons are important in the correction of subsoil acidity.

Table 18. Soil pH of a Florida Spodosol soil under bahiagrass which was amended with PG, averaged over a 3-year period, 1990-1992, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	pH					
0.0(C)	5.1a[1]	5.1a	5.4a	5.4a	5.3a	5.5a
0.4	5.1a	5.0a	5.0a	5.1a	5.1a	5.3a
2.0	5.0a	4.9a	5.1a	5.2a	5.2a	5.3a
4.0	5.0a	5.1a	5.1a	5.2a	5.2a	5.2a
Tests:[2]						
P(linear)	ns	ns	0.0632	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

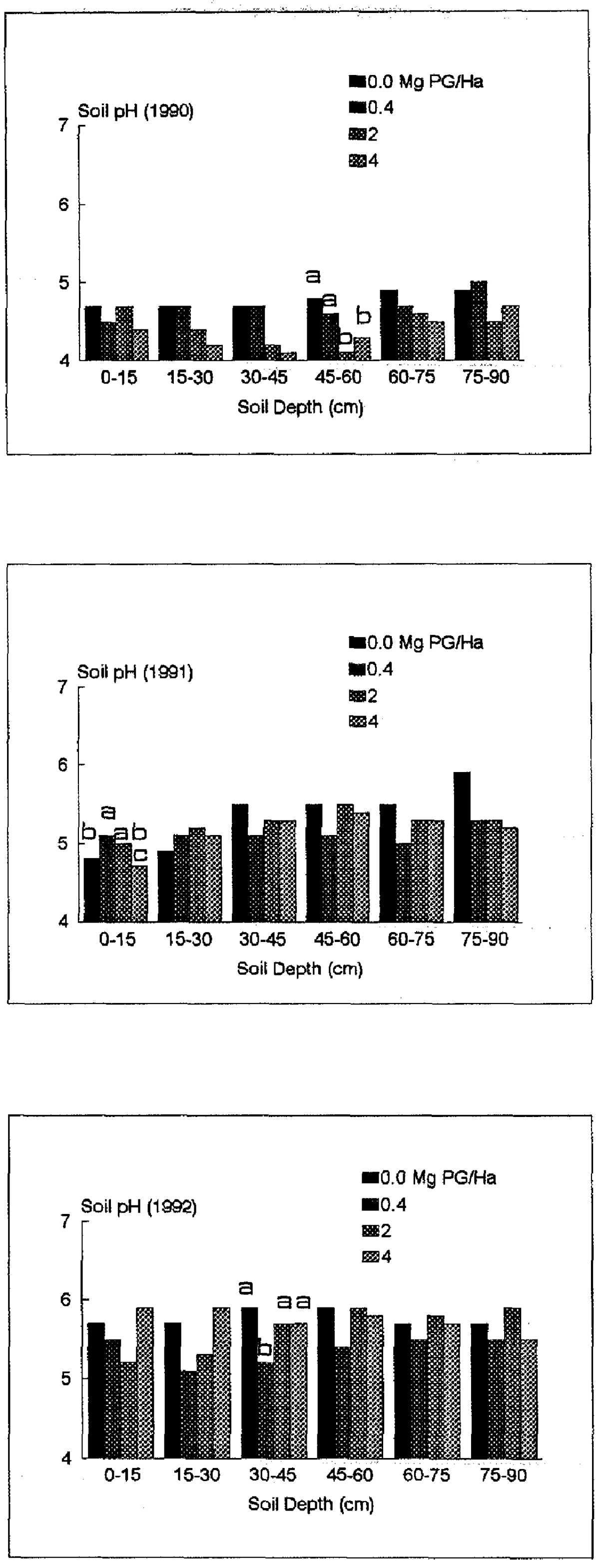


Figure 13. pH of a Florida Spodosol soil under bahiagrass which was amended with PG, 1990-1992, by depth. Treatments at each depth without any letter or with the same letter(s) are not significantly different.

Table 19. Calcium concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, averaged over a 3-year period, 1990-1992, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	mg Ca kg^{-1}					
0.0(C)	442.0a[1]	117.5a	41.2a	35.6a	32.7a	98.2a
0.4	440.0a	85.8a	34.3a	33.2a	56.1a	67.3a
2.0	464.0a	77.0a	42.1a	30.8a	38.0a	47.9a
4.0	554.0a	104.3a	53.5a	38.7a	52.8a	50.3a
Tests:[2]						
P(linear)	ns	ns	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

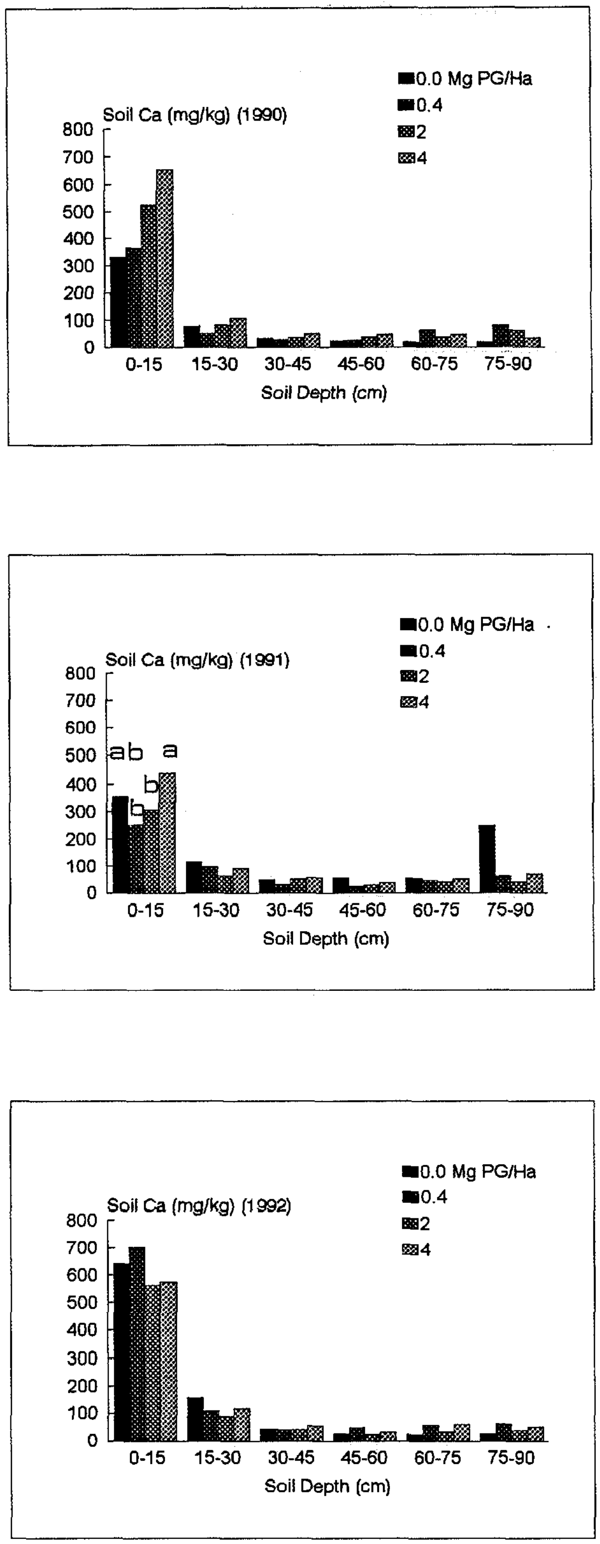


Figure 14. Calcium concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, 1990-1992, by depth. Treatments at each depth without any letter or with the same letter(s) are not significantly different.

The data on soil Ca levels and PG rates indicate the need to apply PG annually at 0.4 Mg PG ha^{-1} and preferably at 1.0 Mg PG ha^{-1}. Such rates should assure a supply of Ca at the top 15 cm beyond what the untreated or unlimed Spodosol soils can provide. Large one-time applications of PG every three years may not be effective to keep a high level of Ca within the feeding root zone as Ca in PG had been shown to move very fast, within a year's time after application, into deeper horizons.

Phosphorus. Statistically, the 3-year mean soil P levels did not differ within each depth at the various PG application rates (Table 20). However, the general trend showed that soil P values were lower in plots that received 2.0 and 4.0 Mg PG ha^{-1} beginning at 15-30 cm down to 60-75 cm relative to P levels in the control plots. Soil P increased at 60-75 cm and continued to increase at the 75-90 depth in these high PG plots. This trend indicates the leaching of soil P from the upper horizons and accumulating at 60-75 cm and below, particularly in plots treated with high rates of PG. This depletion at the upper depths and the accumulation of P at the lower depths over time is graphically illustrated in Figure 15. Figure 15 shows that the low annual PG application appeared to keep P levels at the top 15 cm within the soil P levels of the control.

Potassium. The 3-year mean soil K levels, by depth, were not different at all depths at the various PG rates of application (Table 21). The general trend in the values, however, showed that soil K levels in the control plots were higher than in the PG-treated plots at most depths. This would indicate that soil K were being displaced by Ca and leached into deeper horizons. After reaching the lowest K levels at 45-60 cm depth, K began to accumulate at the 60-75 cm depth and below in plots that received one-time rates of 2.0 and 4.0 Mg PG ha^{-1}.

The soil K concentrations with PG rates by depth and by year are given in Figure 16. The depleting effect of high PG rates on K levels was clearly indicated in 1992. However, Figure 16 also shows that the low annual PG application appeared to keep K levels at the top 15 cm within the soil K levels of the control. Once again, the data on soil K point to the need to apply PG at relatively small annual rates rather than at large rates applied once over several years.

Magnesium. The 3-year mean soil Mg levels, by depth, were not different within each depth with the various PG rates of application (Table 22). Soil Mg at the top 15 cm depth in the control plot and in plots that received 2.0 and 4.0 Mg PG ha^{-1} averaged 33.0, 28.5, and 27.8 mg kg^{-1}, respectively. Soil Mg levels across treatments and across depths were high at the top 15 cm depth, decreased sharply at 15-30 cm depth, reached the lowest concentrations at 30-60 cm, and then began to accumulate below the 60 cm depth.

Table 20. Phosphorus concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, averaged over a 3-year period, 1990-1992, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	mg P kg^{-1}					
0.0(C)	5.00a[1]	2.40a	1.65a	2.38a	2.17a	2.30a
0.4	4.90a	2.65a	1.83a	2.83a	4.10a	4.12a
2.0	5.22a	1.78a	1.00a	0.97a	1.88a	2.10a
4.0	6.28a	1.70a	1.35a	1.18a	2.02a	2.57a
Tests:[2]						
P(linear)	ns	0.0901	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05), but P-values <0.10 are given for reference and referred to as "slightly" significant.

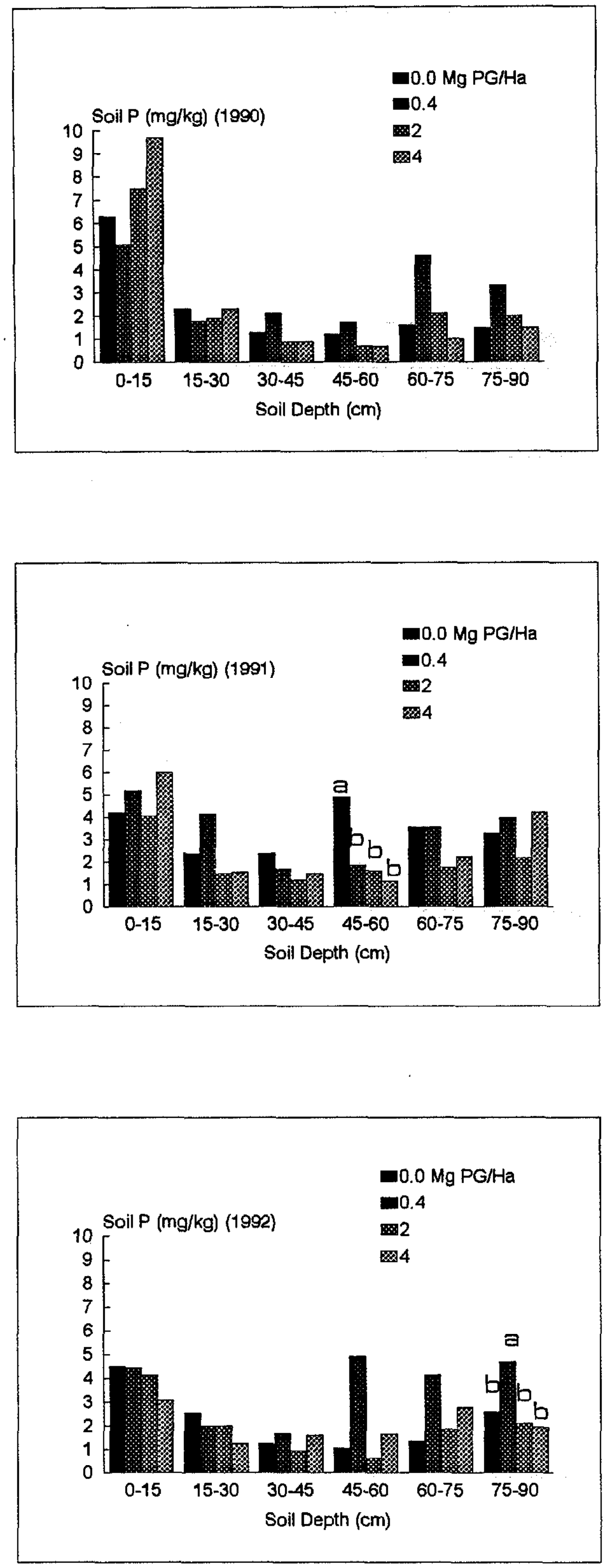


Figure 15. Phosphorus concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, 1990-1992, by depth. Treatments at each depth without any letter or with the same letter(s) are not significantly different.

Table 21. Potassium concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, averaged over a 3-year period, 1990-1992, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	mg K kg^{-1}					
0.0(C)	17.85a[1]	8.03a	4.82a	3.92a	3.88a	3.50a
0.4	20.95a	7.10a	3.32a	3.35a	3.42a	2.83a
2.0	14.15a	4.70a	3.12a	2.33a	2.80a	2.88a
4.0	16.32a	5.07a	3.20a	2.92a	3.07a	3.25a
Tests:[2]						
P(linear)	ns	ns	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

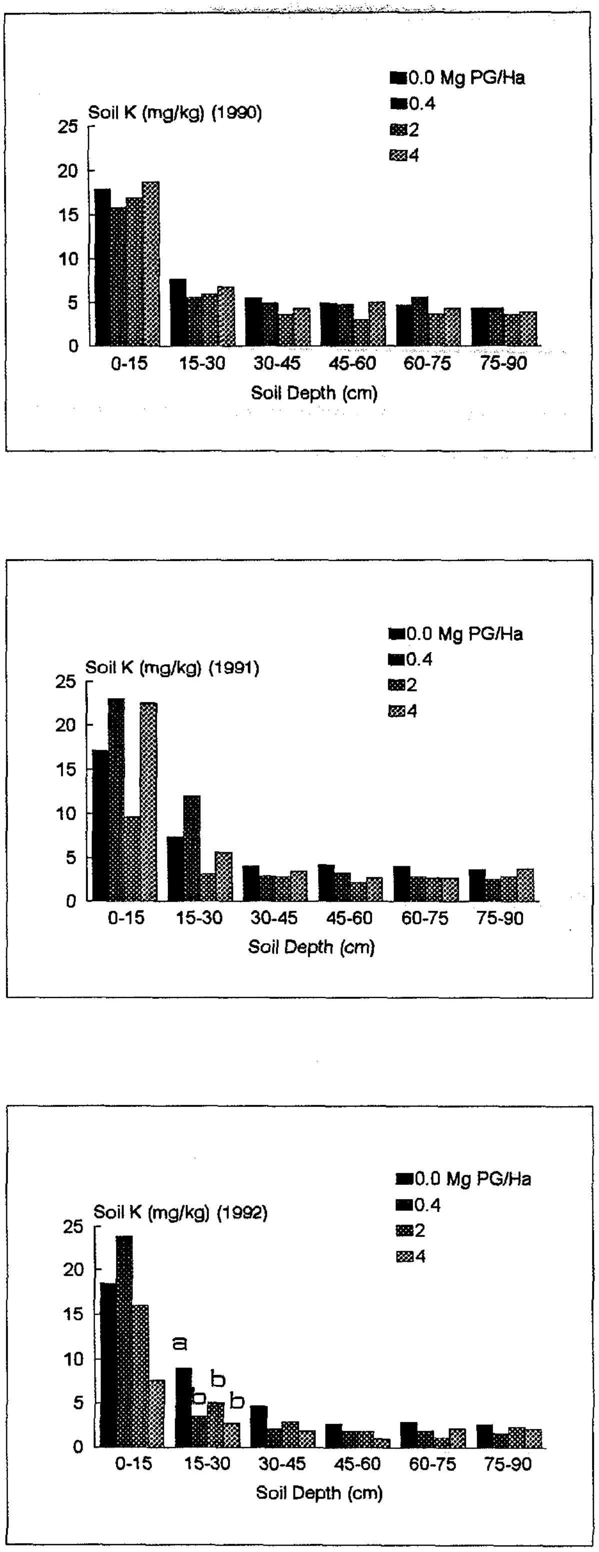


Figure 16. Potassium concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, 1990-1992, by depth. Treatments at each depth without any letter or with the same letter(s) are not significantly different.

Table 22. Magnesium concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, averaged over a 3-year period, 1990-1992, by depth.

Treatment	Depth(cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	mg Mg kg^{-1}					
0.0(C)	33.02a[1]	9.48a	3.98a	3.57a	3.60a	6.07a
0.4	35.45a	7.53a	3.77a	4.33a	7.08a	7.10a
2.0	28.47a	6.65a	4.33a	3.77a	4.45a	4.58a
4.0	27.77a	6.88a	4.35a	4.58a	5.42a	5.95a
Tests:[2]						
P(linear)	ns	ns	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

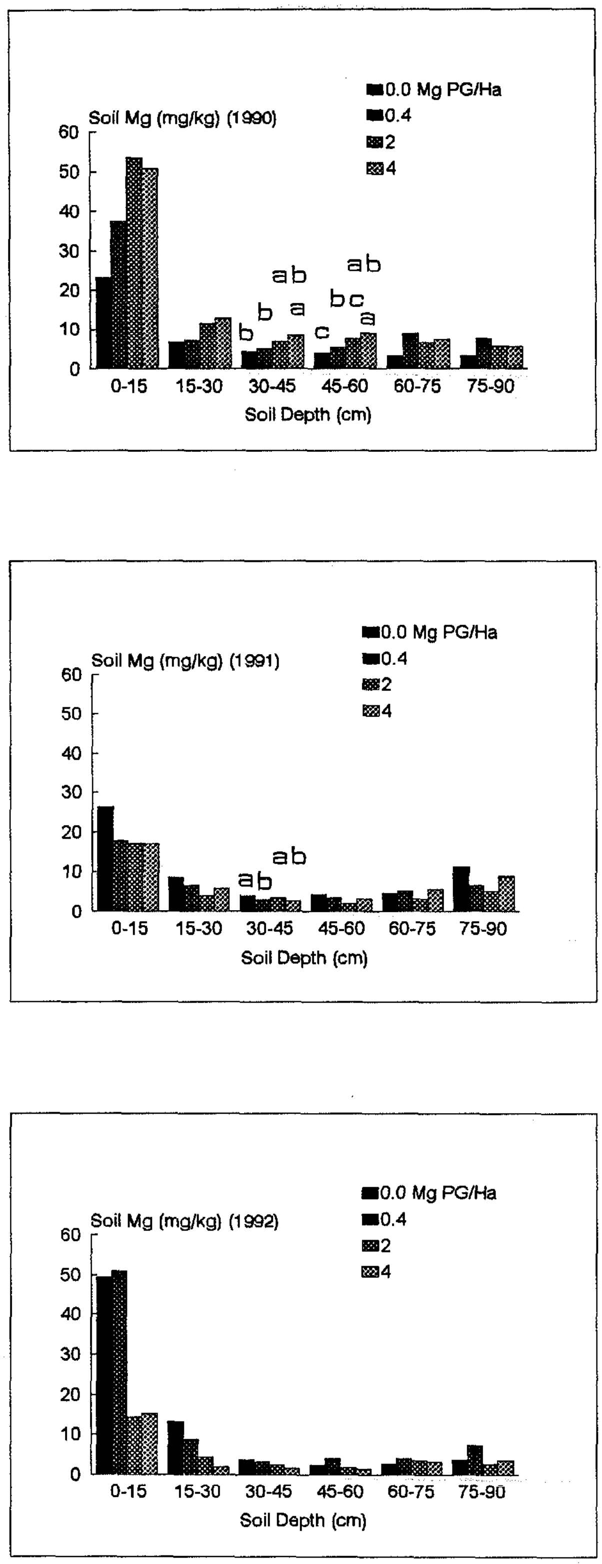


Figure 17. Magnesium concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, 1990-1992, by depth. Treatments at each depth without any letter or with the same letter(s) are not significantly different.

The annual trends for soil Mg levels at the various depths with the PG rates in Figure 17 shows that soil Mg began to accumulate at all depths below 15 cm within a year's time (1990) after application. The higher the PG rates the higher the Mg levels relative to those of the control at 15-30 cm, 30-45 cm and 45-60 cm depths. Also, PG appeared to have increased the Mehlich 1 extractable soil Mg at the top 15 cm.

Except at the top 15 cm, soil Mg levels in PG-treated plots were not very much different from those in the control plots in 1991. Strong indications of soil Mg depletion at the top 15 cm down to 60 cm depth were shown in 1992 with the one-time applications of 2.0 and 4.0 Mg PG ha^{-1} (Figure 17). Figure 17 also shows that the low annual PG application appeared to keep soil Mg levels at the top 15 cm within the soil Mg levels of the control.

The data on soil Mg again point to the need to apply PG at relatively small annual rates rather than at large rates applied once in three years.

A.2.3. Soil Micronutrients

The fertilization program in the experiments included micronutrients using a commercial micronutrient mix with 2.4% B, 2.4% Cu, 14.4% Fe, 6.0% Mn, 0.06% Mo, and 5.6% Zn applied at 28.0 kg ha^{-1} at the start of the growing season each year. At the rate of application, Cu, Fe, Mn, and Zn would have increased by 0.34, 2.02, 0.84, and 0.78 mg kg^{-1} at the top 15 cm, respectively.

The 3-year analyses showed no effects of PG rates on Cu (Table 23) and Zn (Table 23B) at all depths. The effects noted for Fe (Table 23) at 75-90 cm depth, Mn (Table 23A) at 0-15 and 15-30 cm depths, Na (Table 23A) at 15-30 cm depth, and Cl at 30-45 cm depths (Table 23B) either involved very small changes or appeared not to be related to PG rates.

Thus, it is concluded that PG at the rates used had little or no effects on the levels of soil Cu, Fe, Mn, Na, Cl, and Zinc.

Table 23. Copper (Cu) and iron (Fe) concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, averaged over a 3-year period, 1990-1992, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	mg Cu kg^{-1}[1]					
0.0(C)	0.06a	0.06a	0.07a	0.11a	0.07a	0.06a
0.4	0.12a	0.06a	0.09a	0.06a	0.07a	0.06a
2.0	0.07a	0.07a	0.07a	0.06a	0.08a	0.06a
4.0	0.09a	0.05a	0.05a	0.06a	0.07a	0.07a
Tests:[2]						
P(linear)	ns	ns	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns
Mg PG ha^{-1}	mg Fe kg^{-1}[1]					
0.0(C)	11.89a	6.92a	5.61a	9.99a	24.22a	24.94c
0.4	16.96a	11.36a	8.73a	10.23a	54.93a	44.21a
2.0	7.95a	4.90a	4.23a	3.89a	32.81a	27.55c
4.0	7.20a	5.82a	5.13a	6.68a	26.75a	31.61b
Tests:						
P(linear)	ns	ns	ns	ns	ns	0.0083
P(quadratic)	ns	ns	ns	ns	ns	0.0012

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

Table 23A. Manganese (Mn) and sodium (Na) concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, averaged over a 3-year period, 1990-1992, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	mg Mn kg^{-1}					
0.0(C)	0.19a[1]	0.09a	0.06a	0.06a	0.07a	0.07a
0.4	0.16a	0.08a	0.07a	0.07a	0.07a	0.07a
2.0	0.22a	0.07a	0.06a	0.05a	0.08a	0.07a
4.0	0.37a	0.06a	0.06a	0.05a	0.07a	0.07a
Tests:[2]						
P(linear)	0.0296	0.0513	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns
Mg PG ha^{-1}	mg Na kg^{-1}					
0.0(C)	7.15a	6.47a	6.17a	6.50a	7.75a	9.40a
0.4	8.40a	6.07a	5.98a	6.90a	9.00a	9.30a
2.0	7.73a	5.45a	5.55a	4.97a	7.82a	8.03a
4.0	7.18a	5.22a	5.20a	5.53a	6.23a	8.32a
Tests:						
P(Linear)	ns	0.0378	ns	ns	ns	ns
P(Quad.)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

Table 23B. Zinc (Zn) and chloride (Cl) concentrations in a Florida Spodosol soil under bahiagrass which was amended with PG, averaged over a 3-year period, 1990-1992, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	------------------ mg Zn kg^{-1} ------------------					
0.0(C)	0.98a[1]	1.25a	1.24a	1.24a	1.86a	1.59a
0.4	2.33a	1.28a	1.46a	1.17a	1.50a	1.88a
2.0	1.73a	1.07a	1.66a	1.40a	2.16a	2.15a
4.0	1.55a	0.49a	0.74a	0.63a	0.99a	1.15a
Tests:[2]						
P(Linear)	ns	ns	ns	ns	ns	ns
P(Quad.)	ns	ns	ns	ns	ns	ns
Mg PG ha^{-1}	------------------ mg Cl kg^{-1} ------------------					
0.0(C)	3.67a	4.00a	8.33a	4.67a	5.00a	9.00a
0.4	5.67a	7.67a	4.67a	6.33a	5.67a	8.33a
2.0	6.00a	3.67a	3.67a	3.67a	18.00a	5.67a
4.0	8.00a	13.00a	4.33a	2.00a	8.33a	4.33a
Tests:						
P(Linear)	ns	ns	ns	ns	ns	ns
P(Quad.)	ns	ns	ns	ns	0.0358	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

B. ANNUAL RYEGRASS EXPERIMENT

B.1. Effects of PG on Forage Yields, Percent Dry Matter (DM), Nutrient Contents, and on Other Forage Quality Measures

Unlike the bahiagrass, the ryegrass experiment was conducted on a land that was limed with dolomite, tilled every year, and the PG was mixed with the top soil to a depth of 15 cm. The first PG applications to the environmental experiment were made on September 27-28, 1990. The plots were seeded and fertilized on December 19, 1990. The treatments and the statistical analyses were the same as those in the bahiagrass environmental experiment.

B.1.1. Forage Dry Matter (DM) Yields

The total regrowth and hay forage dry matter yields are presented in Table 24 with the statistics.

The total annual and the 3-year average regrowth DM yields from plots fertilized annually with 0.4 Mg PG ha^{-1} were consistently high relative to the yields from the control plots and the plots that received one-time applications of 2.0 and 4.0 Mg PG ha^{-1}. The DMRT, however, showed that the differences did not attain any significant level (Table 24).

The non-significant but apparent differences from the control in the 3-year mean forage yields of 13.8, 7.8, and 4.8% for the 0.4, 2.0, and 4.0 Mg PG ha^{-1} treatments, respectively, indicate the potential of PG fertilization to increase annual ryegrass yield.

The trends in regrowth yields with PG rates for the individual harvests during the 3-year period are given in Figure 18. No harvest showed any significant effect of treatments.

The annual and 3-year analysis for hay or mature forage yield (Table 24) again showed no significant treatment effect. The trend in the values, however, showed the 2.0 Mg PG ha^{-1} application resulting in consistently high yields relative to that of the control, with the apparent difference in the 3-year mean yield of 10.9%.

Although no significant effects on forage yields were noted, the trend in the values indicate that annual application of 0.4 Mg PG ha^{-1} or 2.0 Mg PG ha^{-1} once every 3 years may be considered for annual ryegrass.

Table 24. Total regrowth and hay forage dry matter yields of annual ryegrass from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			
	1990-91	1991-92	1992-93	Mean
A. Regrowth:	------------ Mg DM ha^{-1} -------------------			
Mg PG ha^{-1}				
0.0(C)	3.58a[1]	3.78a	2.70a	3.34a
0.4	3.70a	4.44a[2]	3.24a[2]	3.80a
2.0	3.98a	3.80a	3.02a	3.60a
4.0	3.18a	4.24a	3.10a	3.50a
Tests:[3]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	------------ Mg DM ha^{-1} -------------------			
Mg PG ha^{-1}				
0.0(C)	4.23a	4.67a	5.38a	4.87a
0.4	4.47a	4.42a[2]	4.96a[2]	4.65a
2.0	5.22a	5.11a	5.79a	5.40a
4.0	4.51a	4.58a	4.63a	4.59a
Tests:				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant ($P>0.05$).

B.1.2. Percent Dry Matter (%DM)

Table 25 shows that PG had no effects on the DM content of regrowth of annual ryegrass in all years and when averaged over the 3-year period. There was an indication in the second harvest of 1990-91 that PG may have increased %DM (Figure 19), but this could be just a chance event.

In hay, PG again appeared to have increased %DM in 1990-91 season in the order of 4.0, 0.4>2.0, C, but not thereafter or when averaged over the 3-year period.

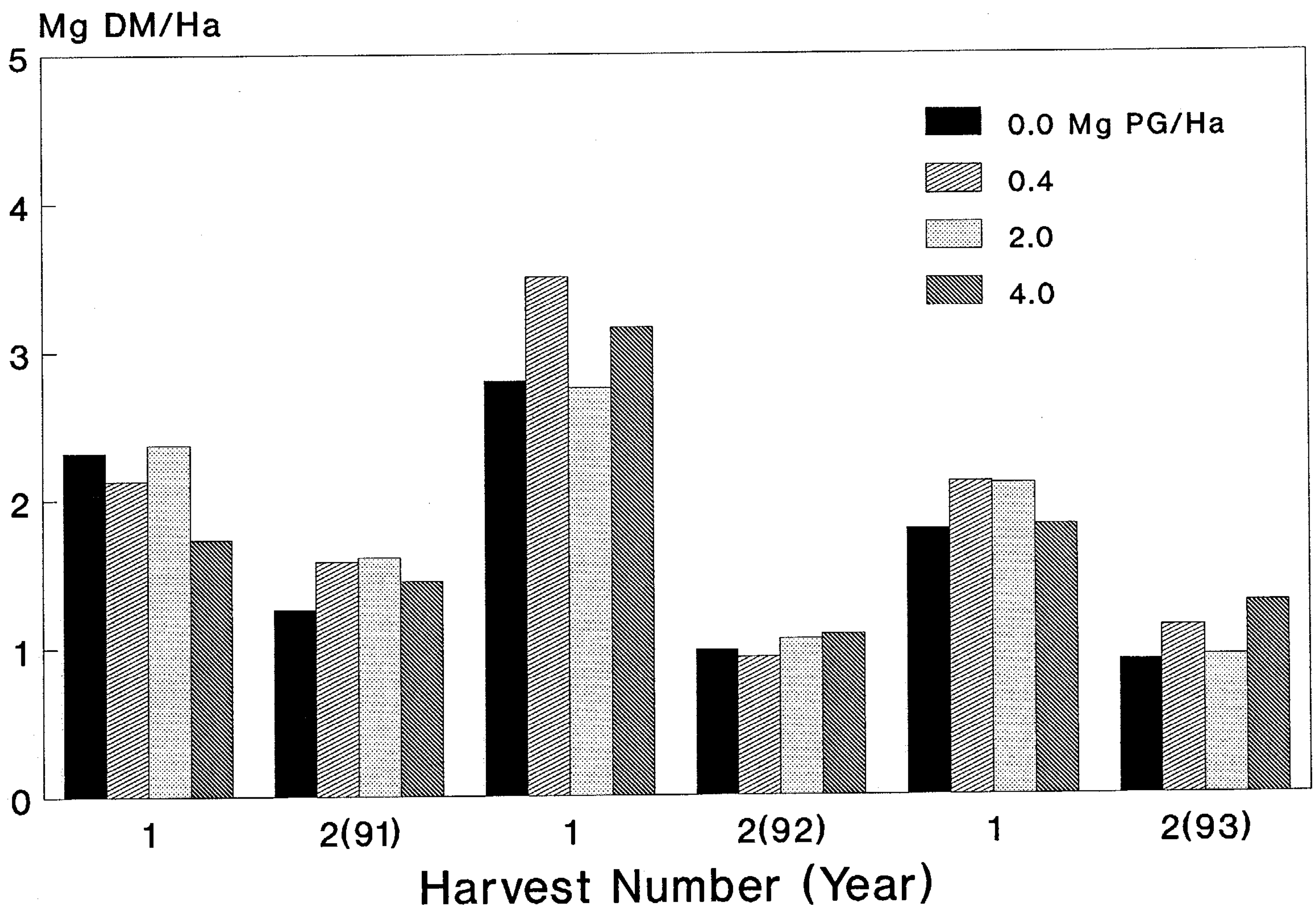


Figure 18. Regrowth forage dry matter yields of annual ryegrass from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter are not significantly different.

Table 25. Percent dry matter (%DM) of annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			
	1990-91	1991-92	1992-93	Mean
A. Regrowth:	------------ %DM ------------			
Mg PG ha^{-1}				
0.0 (C)	15.7a[1]	14.5a	14.3a	14.8a
0.4	16.6a	14.2a[2]	13.0a[2]	14.6a
2.0	17.4a	14.2a	12.6a	14.7a
4.0	18.4a	13.0a	14.7a	15.4a
Tests:[3]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	------------ %DM ------------			
Mg PG ha^{-1}				
0.0 (C)	23.9b	28.5a	27.9a	27.3a
0.4	26.3a	26.9a[2]	28.0a[2]	27.2a
2.0	24.4b	25.4a	28.6a	26.5a
4.0	26.4a	24.0a	30.6a	27.1a
Tests:				
P(linear)	0.0194	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

B.1.3. Nutrients in Forage

Sulfur content. Phosphogypsum fertilization at all rates effectively increased %S in ryegrass regrowth forage in 1990-91 and 1991-92 seasons but not in 1992-93. The annual analysis indicated the treatment effects in the order of 4.0>2.0, 0.4>C in 1990-91 and 4.0, 2.0, 0.4>C in 1991-92. The 3-year analysis gave the treatment effects in the order of 4.0>2.0, 0.4>C with values of 0.18>0.16, 0.15>0.13 (Table 26), which were well within the estimated requirements for grazing ruminants of 0.10 to 0.32% S.

The 1990-91 and 1991-92 tests for linear trends showed that %S in regrowth forage increased linearly with PG rates in both years and when averaged over the 3-year period (Table 26).

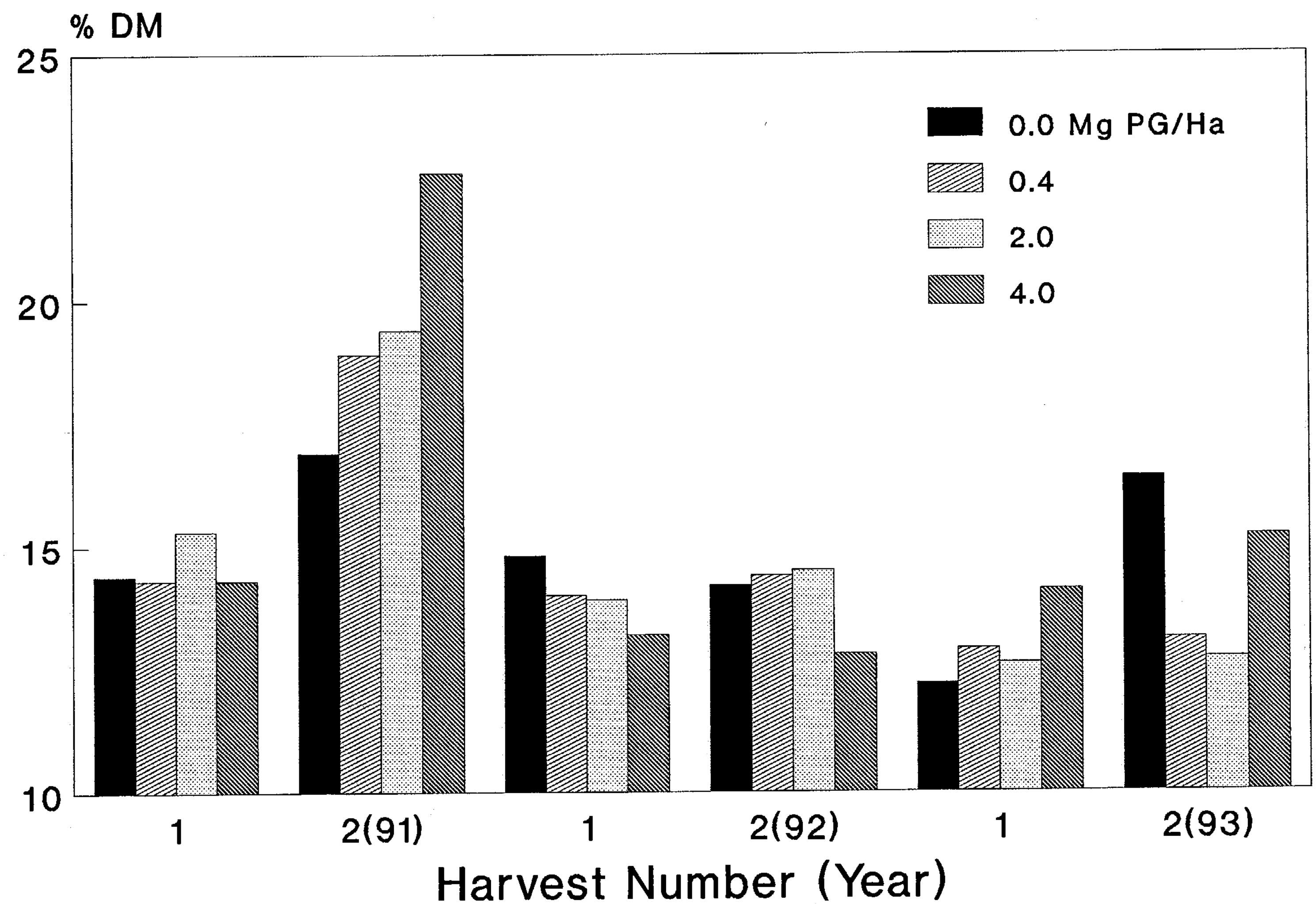


Figure 19. Percent dry matter (%DM) of annual ryegrass regrowth forage from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter are not significantly different.

Table 26. Sulfur concentrations in annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year 1990-91	1991-92	1992-93	Mean
A. Regrowth:	----------- %S	-------------------------		
Mg PG ha^{-1}				
0.0 (C)	0.15c[1]	0.11b	0.12a	0.13c
0.4	0.19b	0.15a[2]	0.12a[2]	0.15b
2.0	0.19b	0.16a	0.11a	0.16b
4.0	0.26a	0.18a	0.11a	0.18a
Tests:[3]				
P(linear)	0.0018	0.0105	ns	0.0041
P(quadratic)	0.0059	0.0363	ns	0.0160
B. Hay:	----------- %S	-------------------------		
Mg PG ha^{-1}				
0.0 (C)	0.14a	0.15a	0.11a	0.13b
0.4	0.16a	0.20a[2]	0.12a[2]	0.16a
2.0	0.19a	0.19a	0.11a	0.16a
4.0	0.20a	0.20a	0.11a	0.17a
Tests:				
P(linear)	ns	ns	ns	0.0056
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

The %S in the individual harvests are graphically presented in Figure 20. There was no treatment effects of PG by the third crop year.

In hay, despite the apparent differences in %S among the treatments in 1990-91 and 1991-92 (Table 26), the annual DMRT showed no treatment effects. The 3-year analysis, however, indicated that all PG treatments resulted in higher %S in PG-fertilized forages than in the control forage, with %S increasing linearly with PG rates,

Compared with the S contents in bahiagrass, %S in ryegrass were very low, ranging from 0.12 to 0.15% in regrowth in all harvests and from 0.11 to 0.15% in hay. Since the optimum S levels for cellulose digestion in vitro ranged from 0.16 to 0.24% S (McDowell et al., 1993), PG fertilization should improve the quality of both regrowth and hay ryegrass forage for ruminants.

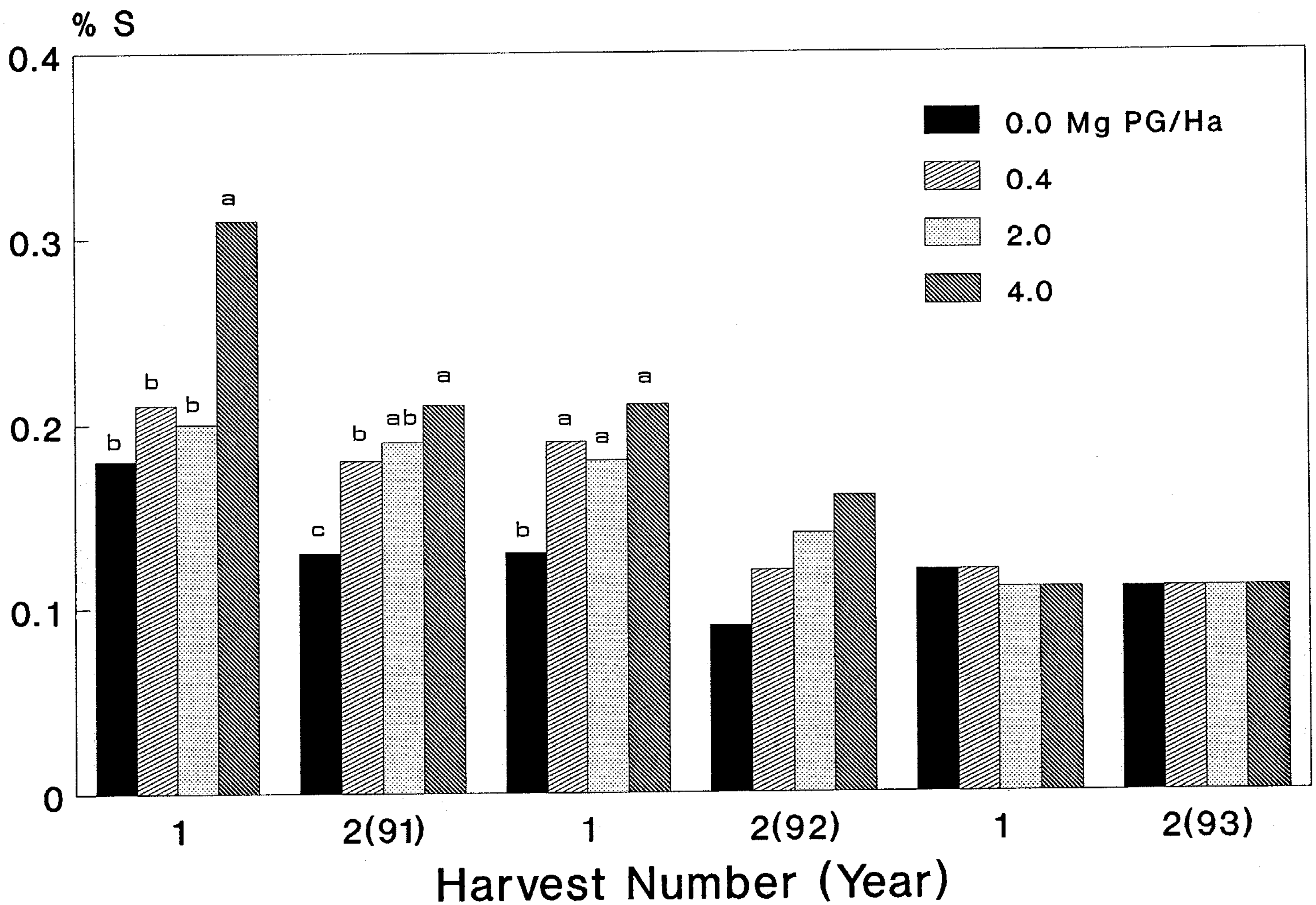


Figure 20. Sulfur concentrations in regrowth annual ryegrass forage from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

Table 26 showed a clear loss in the effectiveness of PG as an S-source as early as the second crop year. This may be due to the almost 3 months gap between PG application and seeding, especially for the one-time applications. Mixing the PG with the top 15 cm of the soil may also have increased the loss of S from the feeding root zone even for the low annual application.

Calcium content. Except for the 0.4 Mg PG ha^{-1} in 1990-91, PG-fertilized regrowth ryegrass forages showed high levels of Ca in most harvests relative to those in the control forages (Table 27). The annual and 3-year analysis, however, showed that the treatments were not significantly different. The effects of PG fertilization, however, became apparent when graphically presented in Figure 21, but the analysis showed treatment differences only in the first harvests of 1991-92.

Table 27. Calcium concentrations in annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			Mean
	1990-91	1991-92	1992-93	
A. Regrowth:	------------ %Ca		------------------------	
Mg PG ha^{-1}				
0.0(C)	0.39a[1]	0.45a	0.57a	0.47a
0.4	0.38a	0.51a[2]	0.63a[2]	0.50a
2.0	0.43a	0.59a	0.78a	0.60a
4.0	0.41a	0.59a	0.68a	0.56a
Tests:[3]				
P(linear)	ns	0.0603	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	------------ %Ca		------------------------	
Mg PG ha^{-1}				
0.0(C)	0.46a	0.52a	0.64a	0.56a
0.4	0.39b	0.55a[2]	0.67a[2]	0.57a
2.0	0.50a	0.61a	0.67a	0.61a
4.0	0.45ab	0.59a	0.63a	0.58a
Tests:				
P(linear)	0.0400	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

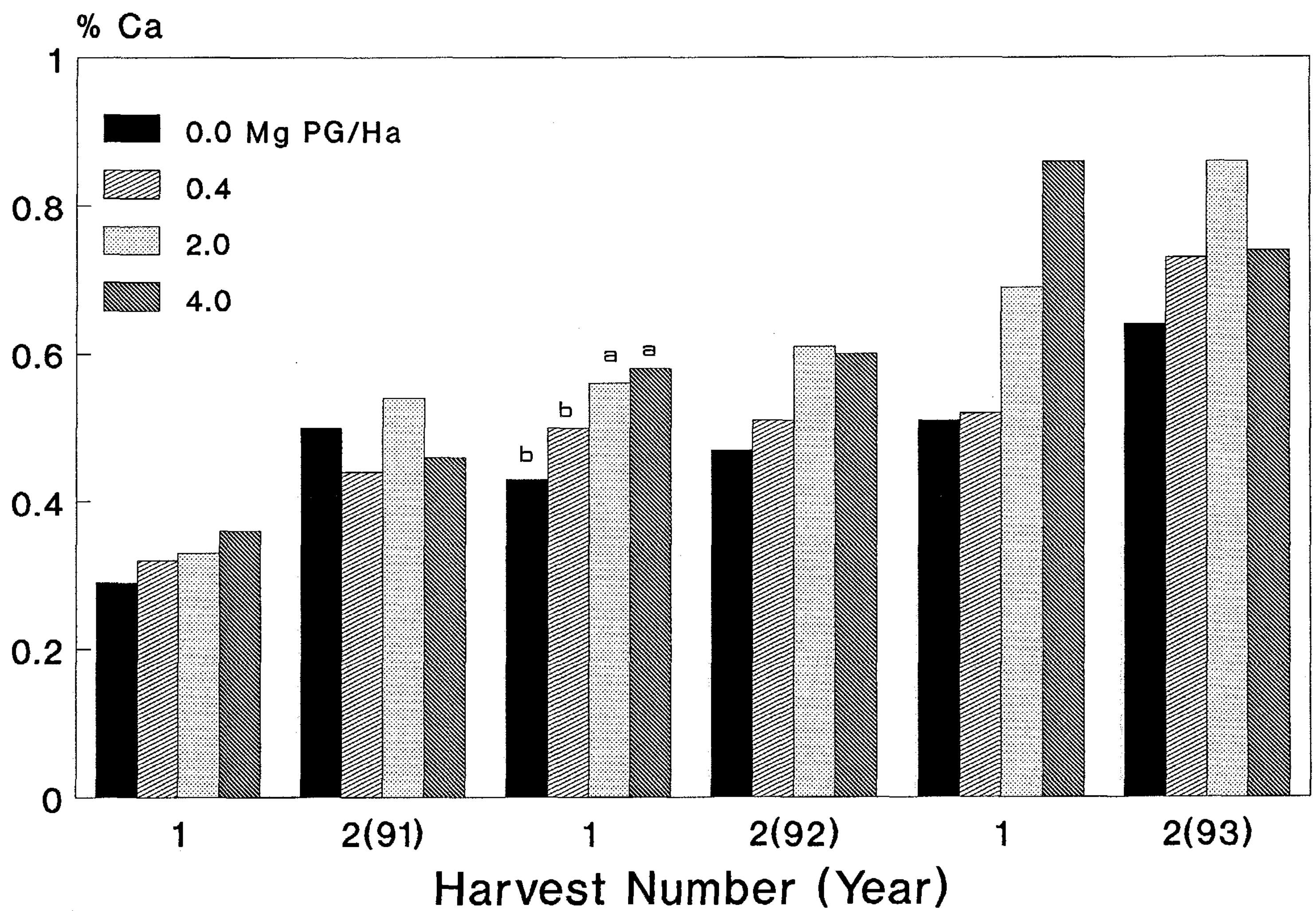


Figure 21. Calcium concentrations in regrowth annual ryegrass forage from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

The significant treatment differences in hay in 1990-91 were due more to the low %Ca in forage from the 0.4 Mg PG ha^{-1} plots than to PG fertilization (Table 27).

The absence of clear-cut effects of PG on %Ca in annual ryegrass forages may have been due to dolomite applied in August 1990 as well as to the loss of Ca from the feeding root zone due to the almost 3-month gap between PG application and seeding.

Nitrogen or crude protein (CP) content. The annual average N contents in the control regrowth forages ranged from 2.79% N (17.44% CP) to 4.37% N (27.31% CP). Those in PG-fertilized forages ranged from 3.10 (19.37% CP) to 4.29% N (26.81% CP) (Table 28). There was no evidence in regrowth harvests that PG application affected the levels of N based on both the annual and the 3-year DMRT and the other tests. There was also no consistent trend in N contents in hay (Table 28).

Table 28. Nitrogen concentrations in annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			Mean
	1990-91	1991-92	1992-93	
A. Regrowth:	------------ %N	------------	------------	------------
Mg PG ha^{-1}				
0.0(C)	3.48a[1]	2.79a	4.37a	3.55a
0.4	3.33a	3.10a[2]	4.38a[2]	3.61a
2.0	3.51a	3.10a	4.29a	3.63a
4.0	3.16a	3.08a	4.16a	3.47a
Tests:[3]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	------------ %N	------------	------------	------------
Mg PG ha^{-1}				
0.0(C)	3.25a	2.33a	1.37a	2.13a
0.4	3.21a	2.14a[2]	1.19a[2]	1.83a
2.0	2.83a	2.41a	1.07a	1.96a
4.0	2.79a	2.51a	1.36a	2.11a
Tests:				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]Excluded from the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

The %N in the individual harvests in Figure 22 showed no consistent trend for any particular PG rate. The DMRT indicated no treatment differences.

Under the conditions which the experiment was conducted, PG at the rates used showed no effects on N contents in annual ryegrass in both regrowth and hay forages.

Phosphorus content. Phosphogypsum showed no negative or positive effects on P uptake by ryegrass (Table 29). The 3-year average %P in regrowth forage was 0.44% for the control and 45-47% for the PG-fertilized forages.

Table 29. Phosphorus concentrations in annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			Mean
	1990-91	1991-92	1992-93	
A. Regrowth:	%P			
Mg PG ha^{-1}				
0.0 (C)	0.37a[1]	0.33a	0.62a	0.44a
0.4	0.41a	0.39a[2]	0.60a[2]	0.47a
2.0	0.37a	0.36a	0.62a	0.45a
4.0	0.37a	0.40a	0.59a	0.46a
Tests:[3]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	%P			
Mg PG ha^{-1}				
0.0 (C)	0.39a	0.37a	0.33a	0.36a
0.4	0.44a	0.36a[2]	0.31a[2]	0.35a
2.0	0.34a	0.34a	0.28a	0.32a
4.0	0.43a	0.37a	0.34a	0.37a
Tests:				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

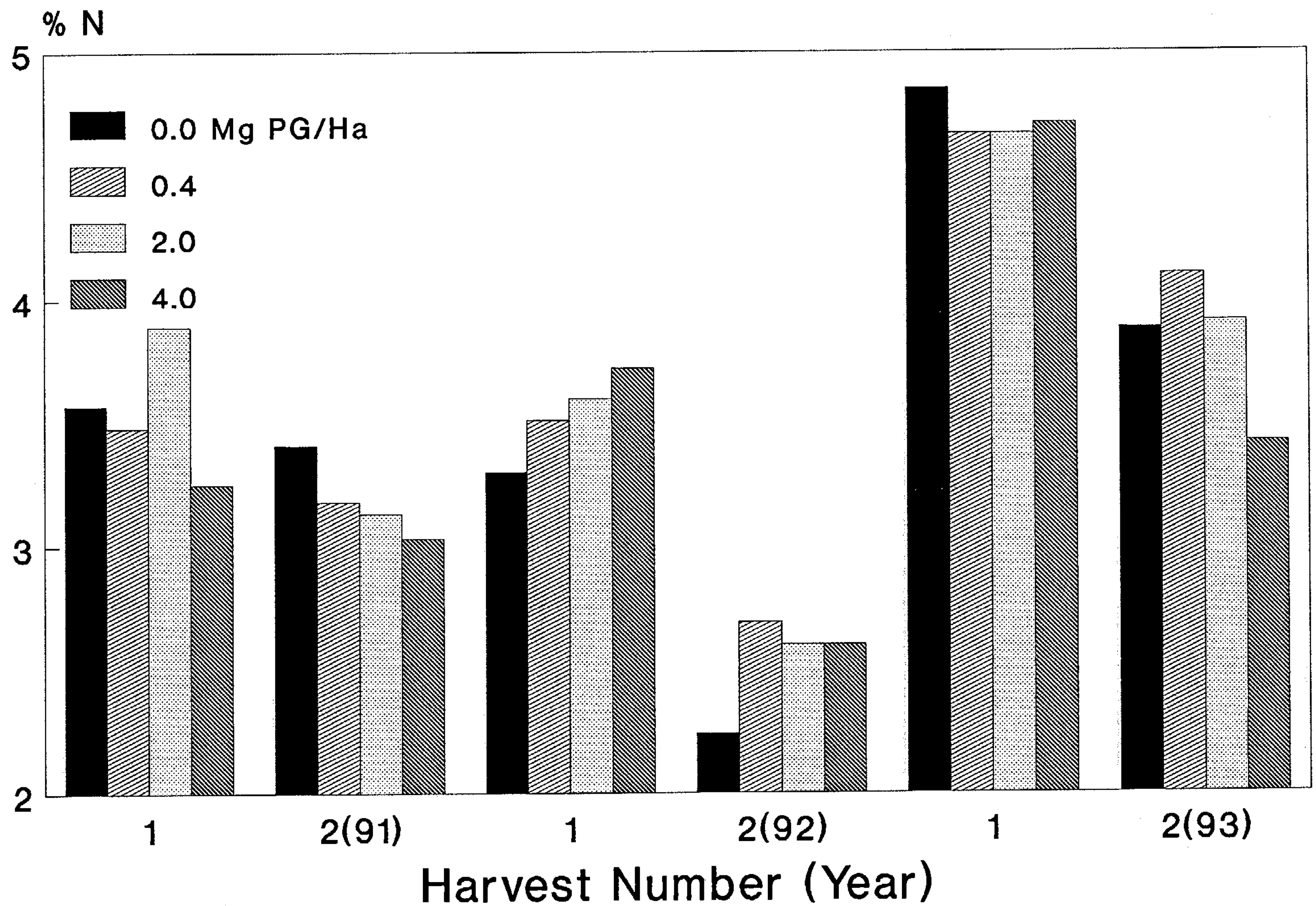


Figure 22. Nitrogen concentrations in regrowth annual ryegrass froage from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter are not significantly different.

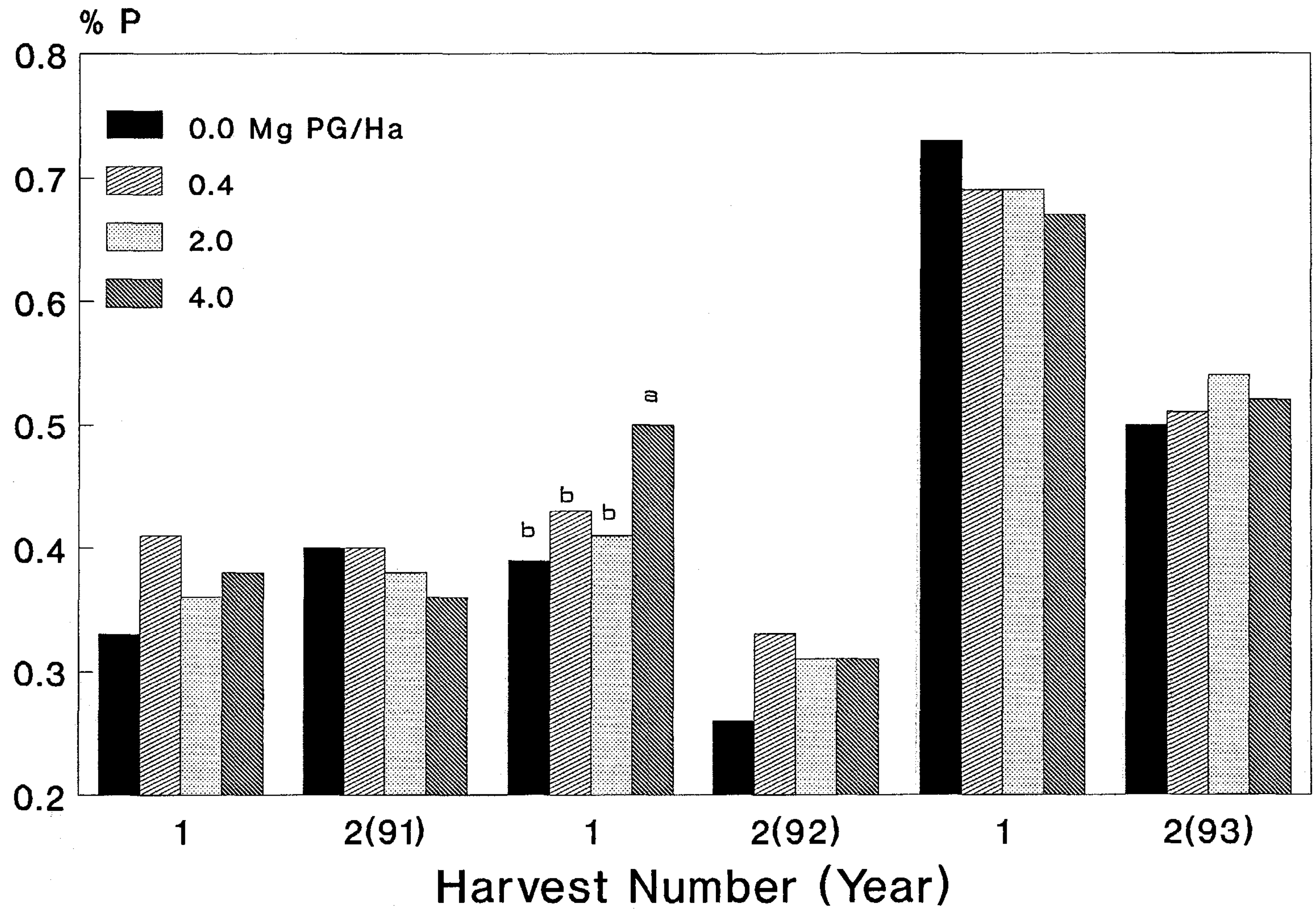


Figure 23. Phosphorus concentrations in regrowth annual ryegrass forage from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

There was no consistent trend in %P for any one PG rate in the individual regrowth harvests (Figure 23).

In hay, the 3-year P contents were 0.39% for the control and ranged from 0.32 to 0.37% for the PG treatments. There was no indication of any positive or negative effects of PG on P contents in hay forage (Table 29).

Potassium content. The 3-year mean %K in the control regrowth forage was 2.26% and %K in PG-fertilized forages ranged from 1.98 to 2.28% (Table 30). Both annual and 3-year analyses showed no treatment effects. The 3-year mean values showed the one-time application rates with low %K relative to those of the control and the annual PG rate. The increasing %K in regrowth with the years may be due to residual effect of the annual application of K fertilizer.

Table 30. Potassium concentrations in annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			Mean
	1990-91	1991-92	1992-93	
A. Regrowth:	------------ %K	------------	------------	------------
Mg PG ha^{-1}				
0.0(C)	1.54a[1]	2.25a	3.01a	2.26a
0.4	1.63a	2.26a[2]	2.95a[2]	2.28a
2.0	1.46a	1.94a	2.80a	2.07a
4.0	1.53a	2.15a	2.35a	1.98a
Tests:[3]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	------------ %K	------------	------------	------------
Mg PG ha^{-1}				
0.0(C)	1.88a	1.85a	2.46a	2.10a
0.4	1.58a	1.50a[2]	2.43a[2]	1.89a
2.0	1.85a	1.69a	1.97a	1.84a
4.0	1.61a	1.87a	2.27a	1.98a
Tests:				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]Exluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

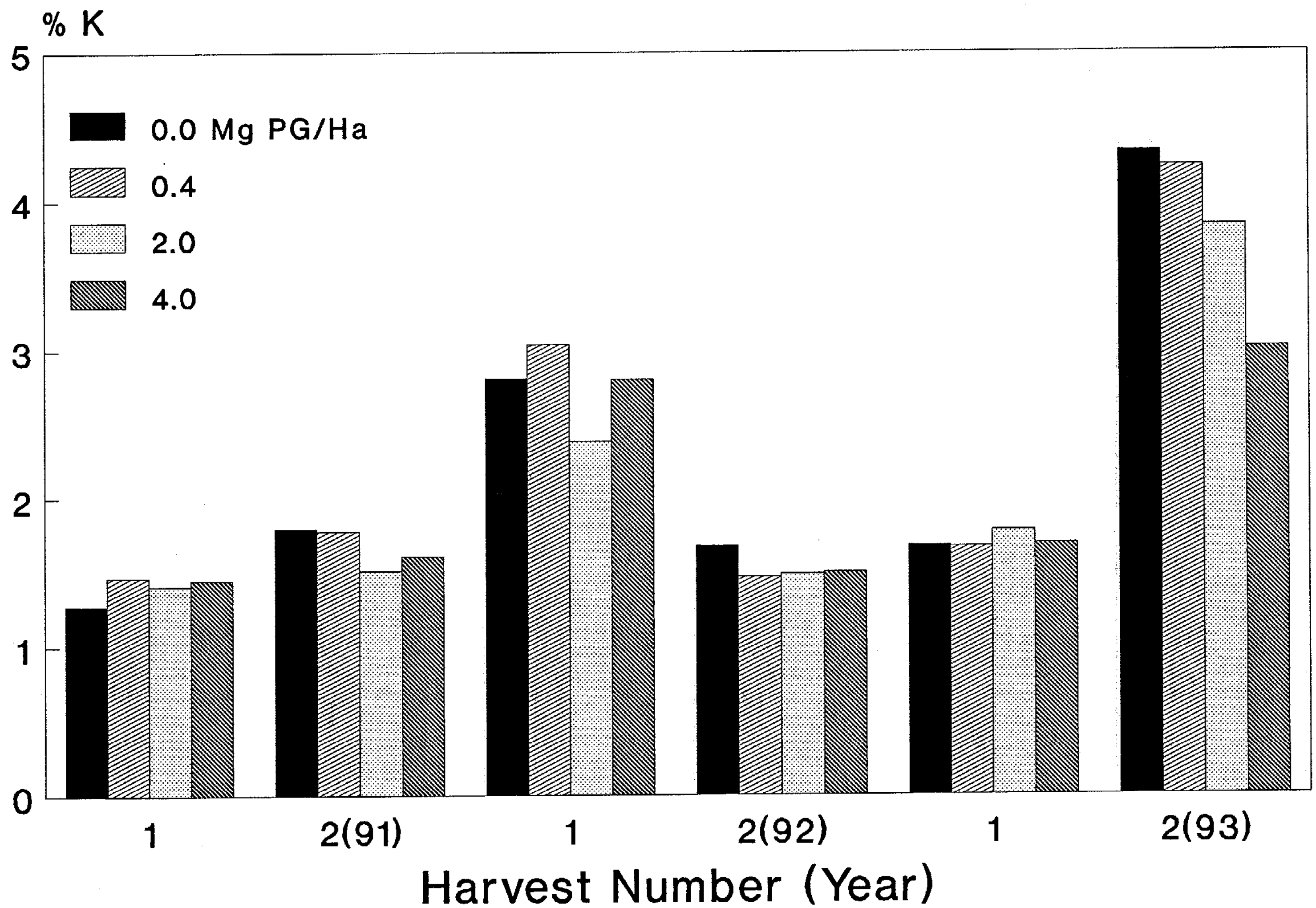


Figure 24. Potassium concentrations in regrowth annual ryegrass forage from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter are not significantly different.

The %K in the individual harvests are given in Figure 24. Harvest 2 in 1990-91 indicated slight evidence of a linear decrease in %K with PG rates.

In hay, the PG-treated forages had low 3-year mean %K relative to those in control forage, but the differences were not significant.

Under the conditions of the experiment, PG showed no negative or positive effects on K uptake. These made the results different from those of the bahiagrass experiment where PG appeared to have enhanced K uptake.

Magnesium content. The annual and 3-year mean %Mg in ryegrass regrowth forage showed no effects of PG (Table 31). The increasing %Mg in regrowth forage with the years may be due to effect of dolomite applied before PG application.

Table 31. Magnesium concentrations in annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			Mean
	1990-91	1991-92	1992-93	
A. Regrowth:	%Mg			
Mg PG ha^{-1}				
0.0 (C)	0.38a[1]	0.43a	0.55a	0.45a
0.4	0.36a	0.43a[2]	0.51a[2]	0.43a
2.0	0.33a	0.42a	0.44a	0.39a
4.0	0.28a	0.40a	0.51a	0.40a
Tests:[3]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	%Mg			
Mg PG ha^{-1}				
0.0 (C)	0.41a	0.50a	0.50a	0.48a
0.4	0.32a	0.51a[2]	0.50a[2]	0.47a
2.0	0.38a	0.48a	0.39a	0.43a
4.0	0.34a	0.46a	0.48a	0.46a
Tests:				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]Excluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

There were also no treatments effects of PG on %Mg in hay. The control had a 3-year mean of 0.48% Mg while the PG-fertilized showed a range of from 0.43 to 0.47% Mg.

The %Mg in several individual regrowth harvests showed low %Mg in forages that received 4.0 Mg PG ha^{-1} (Figure 25) relative to that in the control forages. However, the first harvests in 1992-93 contradicted this trend. It is fair to conclude, again under the conditions of the experiment, that PG had no negative or positive effects on Mg uptake by annual ryegrass.

B.1.4. Other Forage Quality Measures

Nitrogen:sulfur (N:S) ratio. Application of PG effectively reduced the annual average N:S ratios in 1990-91 and 1991-92 harvests but not in 1992-93 (Table 32). When averaged over the 3-year period, the 3-year DMRT indicated the effectiveness of PG rates in the order of 4.0>2.0, 0.4>C.

Table 32. N:S ratios in annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			Mean
	1990-91	1991-92	1992-93	
A. Regrowth:	------------ N:S	------------------------		
Mg PG ha^{-1}				
0.0(C)	23.96a[1]	26.36a	37.73a	29.84a
0.4	17.44b	21.65b[2]	38.09a[2]	25.72b
2.0	18.29b	19.72b	38.20a	24.84b
4.0	12.07c	16.89c	38.06a	22.34c
Tests:[3]				
P(linear)	0.0051	0.0250	ns	0.0019
P(quadratic)	ns	ns	ns	ns
B. Hay:	------------ N:S	------------------------		
Mg PG ha^{-1}				
0.0(C)	23.67a	15.27a	12.58a	15.88a
0.4	23.26a	10.98a[2]	10.28a[2]	12.03a
2.0	15.03b	13.08a	9.53a	12.05a
4.0	14.45b	12.71a	12.03a	12.79a
Statistics:				
P(linear)	0.0273	ns	ns	0.0460
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]Excluded in the tests for linear or quadratic trends.
[2]ns=not significant (P>0.05).

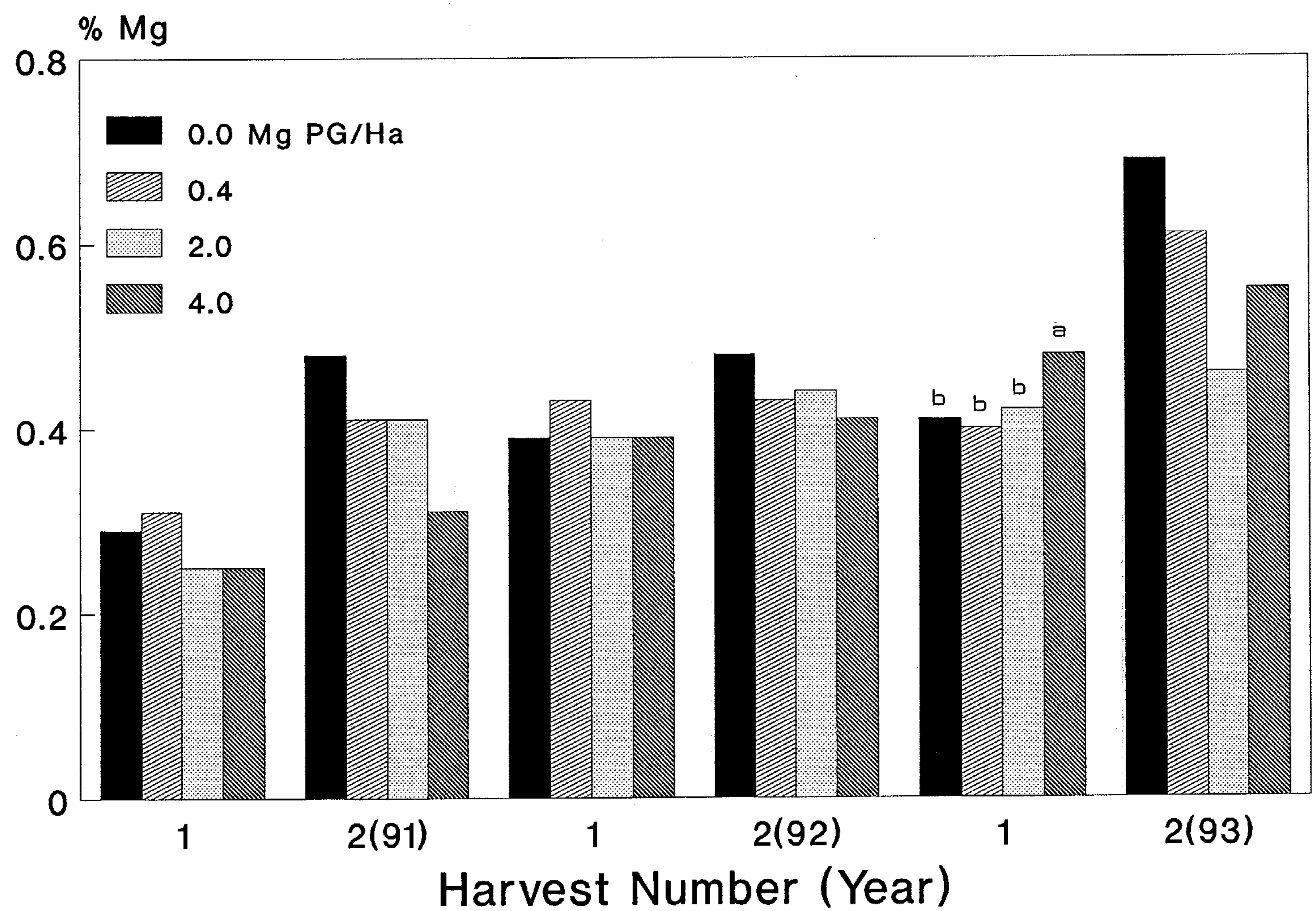


Figure 25. Magnesium concentrations in regrowth annual ryegrass forage from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

Except for the 4.0 Mg PG ha^{-1} rate in 1990-91, all the ratios were higher than the ideal dietary ratio range of 12:1 to 15:1 for cattle (McDowell, et al., 1993).

The linear test showed N:S decreased linearly with PG rates in 1990-91, 1991-92, and when averaged over the 3-year period.

The N:S ratios in the individual regrowth harvests are graphically presented in Figure 26. The individual harvests showed that only in the 1990-91 harvests were there significant treatment differences. Figure 26 also shows that the PG treatments, as they were applied in this study, were not as effective in bringing the N:S ratios down to the ideal range of 12:1 to 15:1 for cattle. The very high N:S ratios in 1992-93 were due to the very low %S (Table 26) and relatively high %N (Table 28) during that season.

Again, the 3-month gap between PG application and seeding was simply too long. Also, it is clear that where PG is applied to tilled land and mixed with the top 15 cm soil, annual applications will be the most effective and economical rather than the one-time rates applied between years. Unlike the case of bahiagrass, however, annual rates much higher than the 0.4 Mg PG ha^{-1} seemed to be required.

The N:S ratios in hay forage were significantly different between treatments only in 1990-91. The DMRT indicated the order as C, 0.4>2.0, 4.0. Both 1990-91 and 3-year mean linear tests indicated that N:S decreased linearly with PG rates. The N:S ratios in hay in 1992-93 were relatively low due primarily to low %N in the forage (Table 28).

Calcium: phosphorus(Ca:P)ratio. The 3-year mean Ca:P ratios ranged from 1.07 to 1.33 in regrowth and from 1.56 to 1.91 in hay for all treatments. All values were within the ideal ratio range of from 1:1 to 2:1 (Table 33).

The Ca:P for individual harvests are given in Figure 27. Again, the values were within the ideal Ca:P range of 1:1 to 2:1.

In vitro organic matter digestibility (IVOMD). The annual and 3-year mean %IVOMD showed no significant effects of PG on regrowth forage digestibility (Table 34). The %IVOMD of the individual harvests (Figure 28) also showed no effect of PG.

In hay, the 3-year DMRT showed that the 4.0 Mg PG ha^{-1} rate may have adversely affected %IVOMD. But the differences of 1.3 to 1.8 units are probably too small to be of nutritional significance.

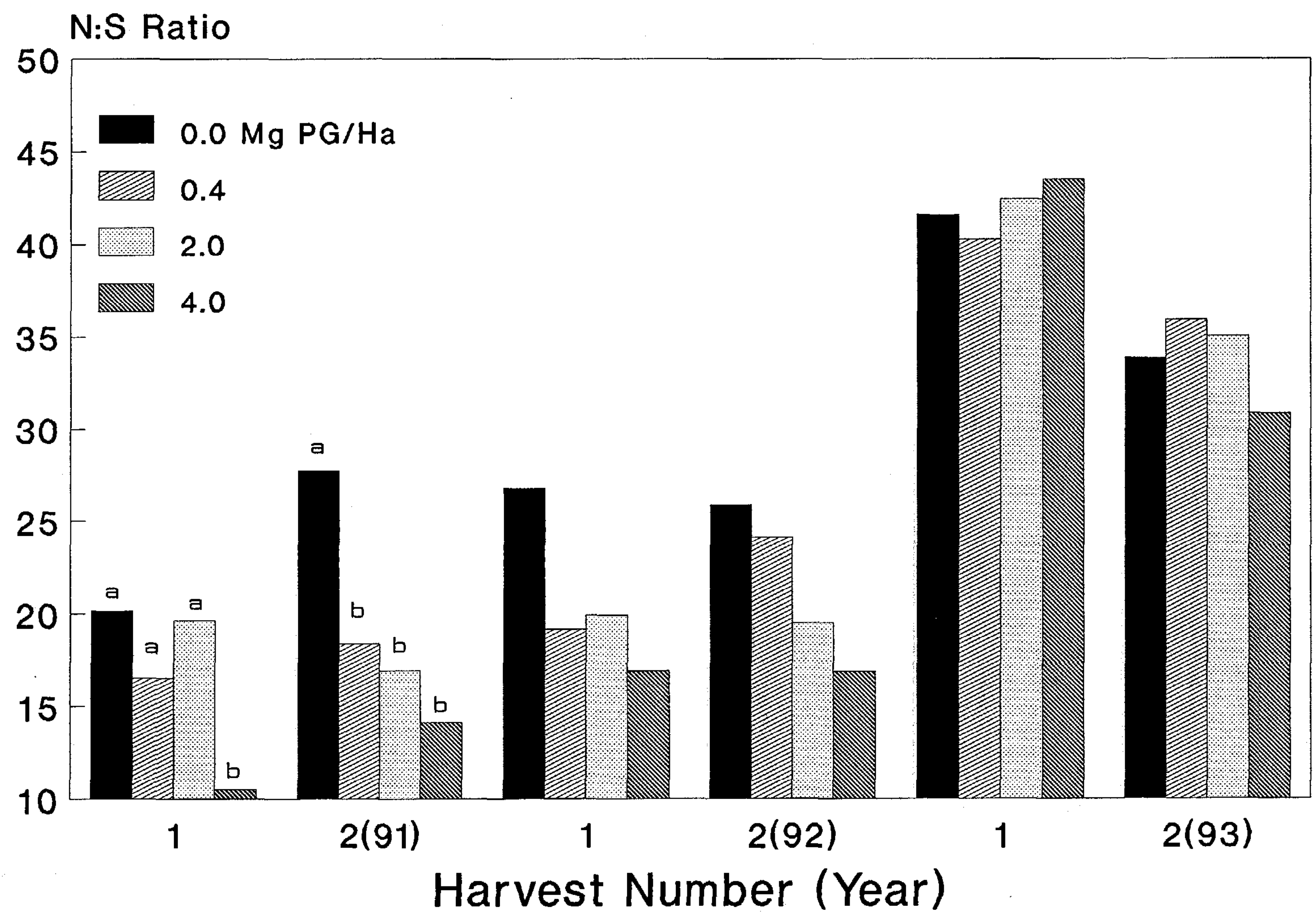


Figure 26. N:S ratios in regrowth annual ryegrass forage from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter or with the same letter(s) are not significantly different.

Table 33. Ca:P ratios in annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			Mean
	1990-91	1991-92	1992-93	
A. Regrowth:	Ca:P			
Mg PG ha^{-1}				
0.0(C)	1.05	1.36	0.92	1.07
0.4	0.93	1.31	1.05	1.06
2.0	1.16	1.64	1.26	1.33
4.0	1.11	1.47	1.15	1.22
Statistics:[1]				
B. Hay:	Ca:P			
Mg PG ha^{-1}				
0.0(C)	1.18	1.41	1.94	1.56
0.4	0.89	1.53	2.16	1.63
2.0	1.47	1.79	2.39	1.91
4.0	1.05	1.59	1.85	1.57
Statistics:				

[1]No statistical analysis was done with the data. It was more important to know the ratios in both regrowth and hay forages.

B.1.5. Fluoride in Forage

The annual average F contents in the control regrowth forage ranged from 7.2 to 11.3 with a 3-year mean of 8.4 mg F kg^{-1}. The range for PG-fertilized forages was 6.2 - 14.6, with a 3-year mean of 10.5 mg F kg^{-1} (Table 35). The annual analysis showed no significant effects of PG, but the 3-year analysis indicated a slightly significant linear trend (P{linear}=0.0864), F increasing with PG rates.

The potential effects of PG on tissue F are graphically presented in Figure 29. There was not, however, a single harvest that showed a significant DMRT. In the first harvest of 1990-91, however, the linear test showed slightly (P{linear}=0.0663) significant effects of PG, with F increasing linearly with PG rates.

At the rates used in the study, the highest F value noted remained far below the acceptable limit of 30 mg F kg^{-1}.

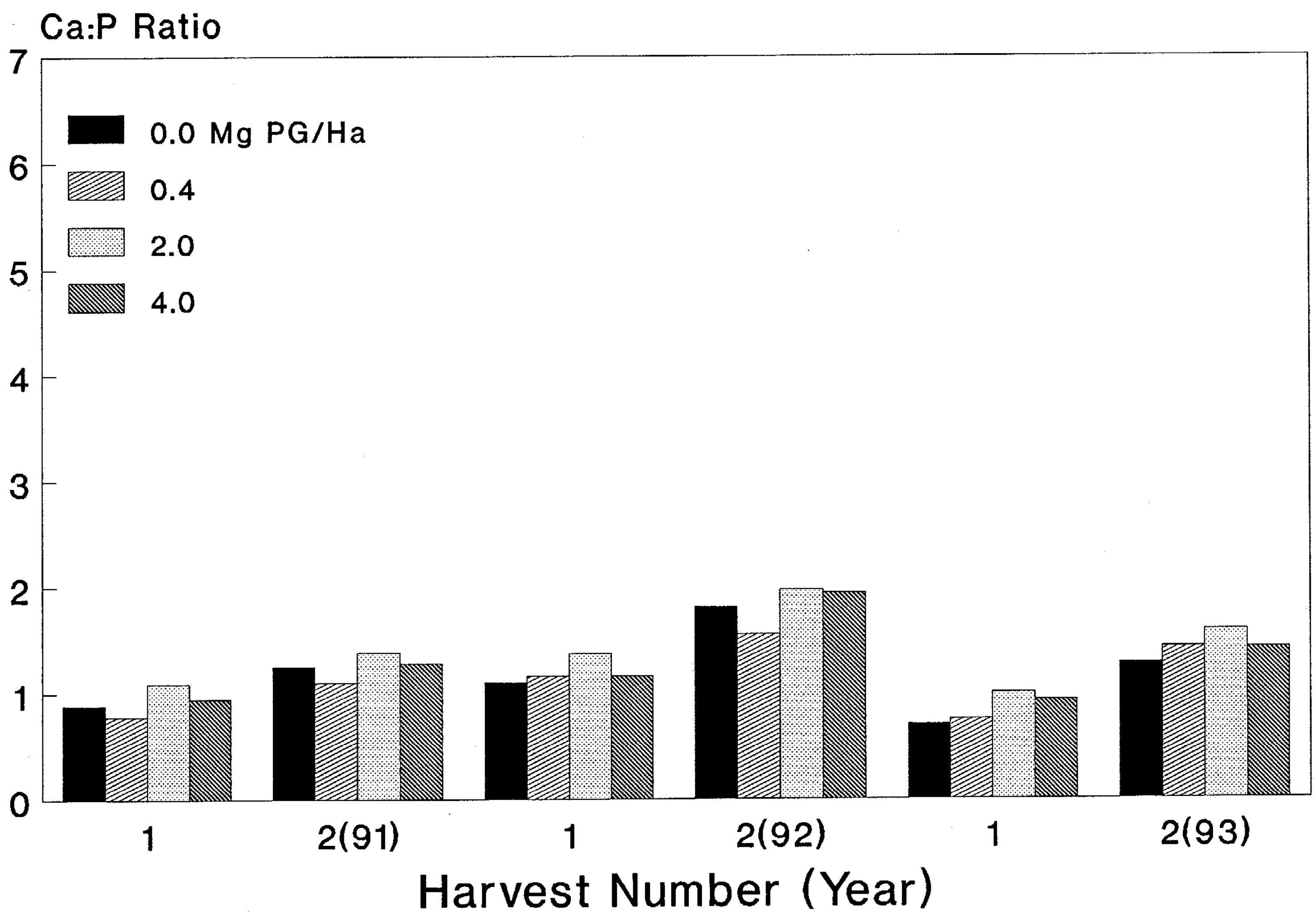


Figure 27. Ca:P ratios in regrowth annual ryegrass forage from plots which were amended with PG, 1990-91 to 1992-93. No statistical analysis was done with the data.

Table 34. In vitro organic matter digestibility (%IVOMD) of annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			
	1990-91	1991-92	1992-93	Mean
A. Regrowth:	%IVOMD			
Mg PG ha^{-1}				
0.0(C)	74.1a[1]	78.2a	79.0a	77.1a
0.4	75.8a	80.4a[2]	77.5a[2]	77.9a
2.0	72.1a	77.1a	77.7a	75.8a
4.0	74.7a	79.1a	77.4a	77.1a
Tests:[3]				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns
B. Hay:	%IVOMD			
Mg PG ha^{-1}				
0.0(C)	67.8a	65.6a	69.1a	67.5a
0.4	64.7a	65.8a[2]	69.3a[2]	66.6a
2.0	66.0a	66.8a	68.0a	66.9a
4.0	66.7a	65.9a	65.1a	65.9b
Tests:				
P(linear)	ns	ns	ns	0.0050
P(quadratic)	ns	ns	ns	0.0050

[1]Means with the same letter(s) are not different.
[2]Excluded in the tests for linear or quadratic trends.
[2]ns=not significant (P>0.05).

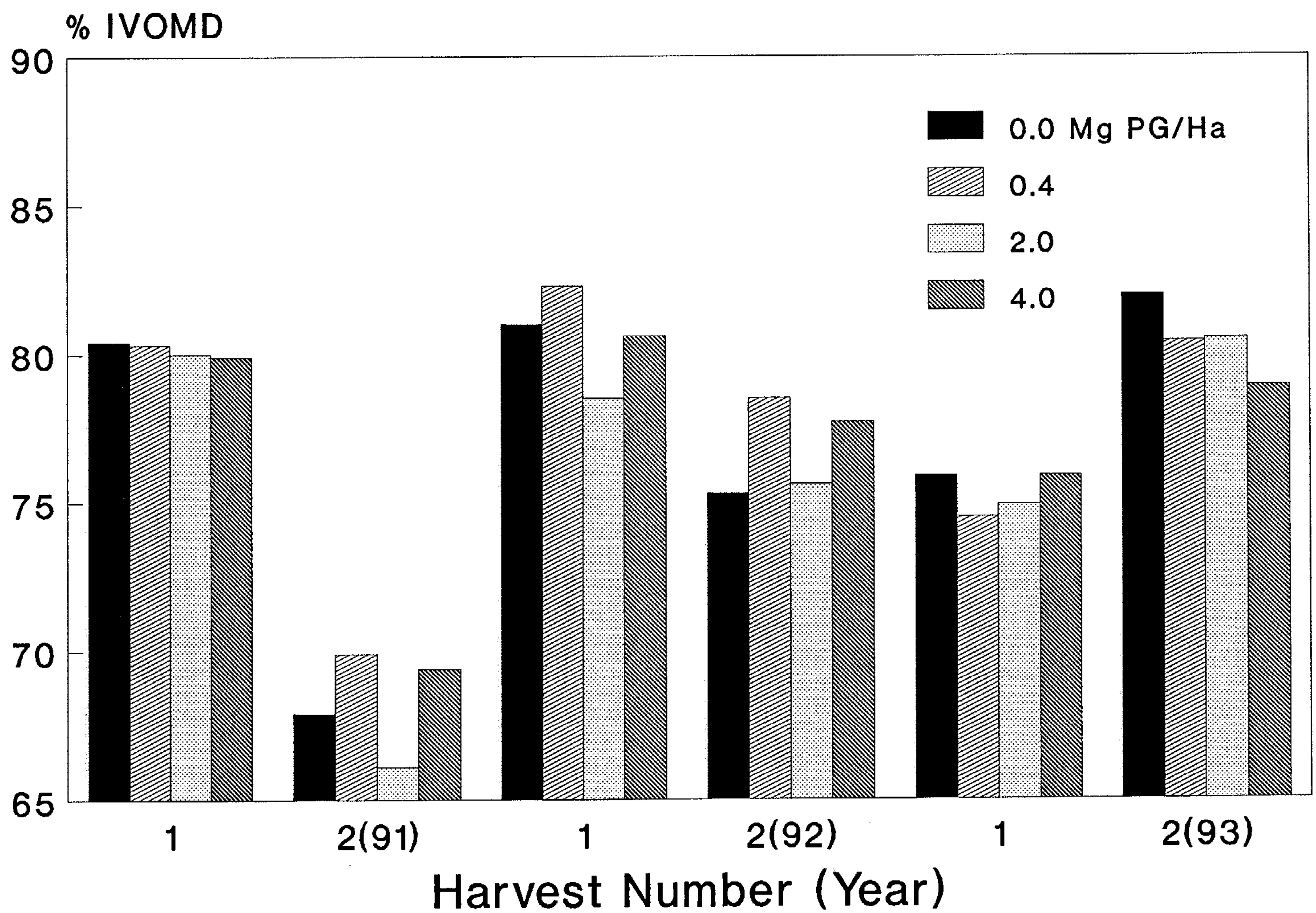


Figure 28. In vitro organic matter digestibility (IVOMD) of regrowth annual ryegrass forage from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter are not significantly different.

Table 35. Fluoride concentrations in annual ryegrass regrowth and hay forages from plots which were amended with PG, by year and averaged over a 3-year period, 1990-91 to 1992-93.

Treatment	Year			Mean
	1990-91	1991-92	1992-93	
A. Regrowth:	mg F kg^{-1}			
Mg PG ha^{-1}				
0.0(C)	11.3a[1]	7.3a	7.2a	8.4a
0.4	11.3a	6.2a[2]	8.8a[2]	8.4a
2.0	12.4a	7.8a	9.5a	9.6a
4.0	14.6a	8.5a	10.5a	10.5a
Tests:[3]				
P(linear)	ns	ns	ns	0.0864
P(quadratic)	ns	ns	ns	ns
B. Hay:	mg F kg^{-1}			
Mg PG ha^{-1}				
0.0(C)	8.5a	5.2a	8.0a	7.2a
0.4	6.4a	4.4a[2]	8.3a[2]	6.4a
2.0	6.2a	5.7a	8.3a	6.7a
4.0	8.8a	4.9a	9.2a	7.6a
Tests:				
P(linear)	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]Ecluded in the tests for linear or quadratic trends.
[3]ns=not significant (P>0.05).

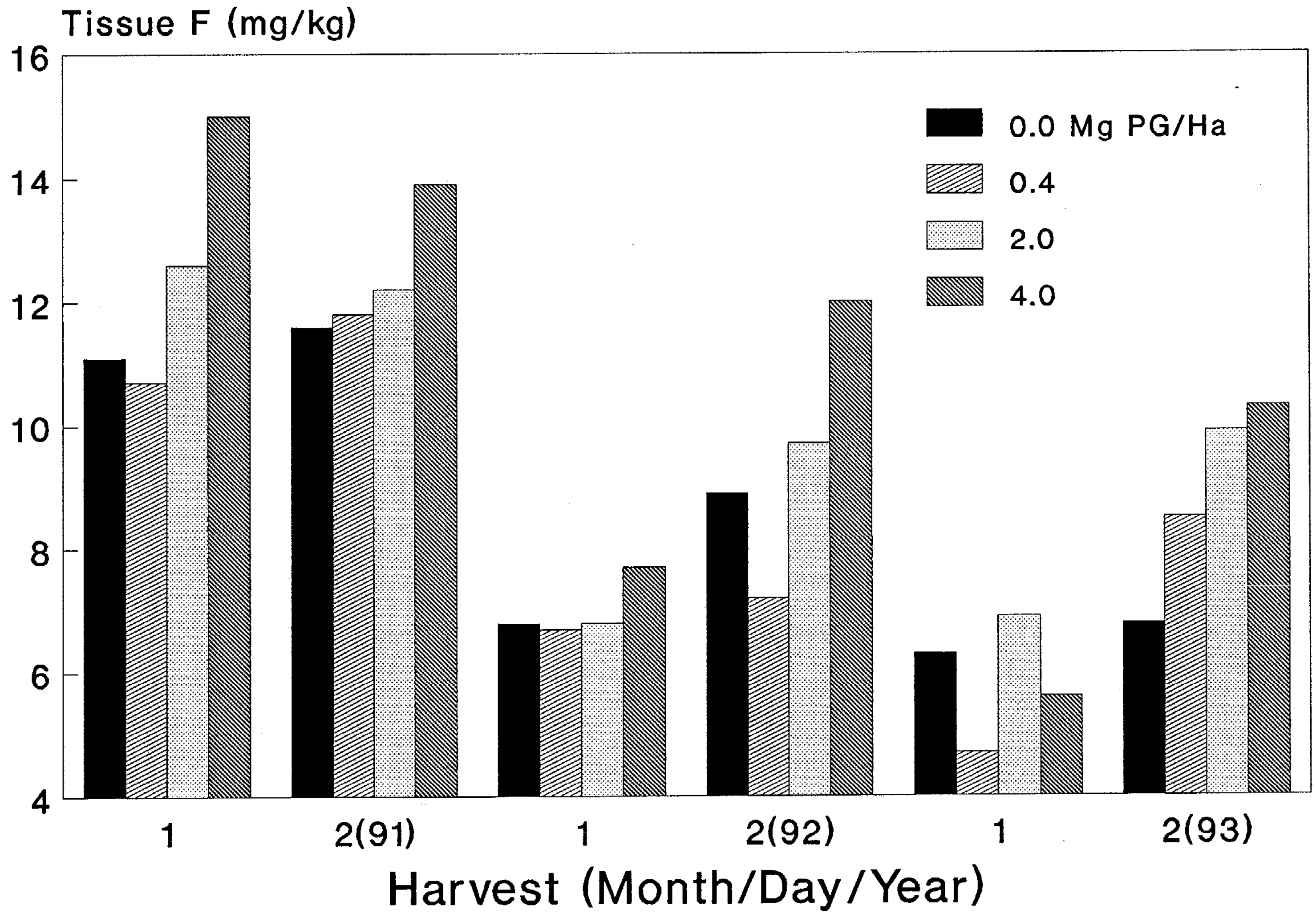


Figure 29. Fluoride concentrations in regrowth annual ryegrass froage from plots which were amended with PG, 1990-91 to 1992-93. Treatments in each harvest without any letter are not significantly different.

B.2. Effects of PG on Soil pH, Calcium, Phosphorus, Potassium, Magnesium and on Certain Micronutrients

B.2.1. Soil pH

The 3-year mean pH values at the top 15 cm soil were 5.4 for the control and ranged from 5.2 to 5.6 for the PG-treated. Similar narrow ranges of values were noted for the rest of the depths (Table 36). Although the plots with one-time applications of 2.0 and 4.0 Mg PG ha^{-1} showed low pH values at 30-45 cm depth and below relative to those of the control, the differences were very slight, did not reach any level of significance, and probably had no physiological effect on ryegrass (Table 36). The application of dolomite a few months before PG application would probably have more effect on soil pH than the PG treatments.

The annual pH values are graphically presented in Figure 30. The 1990-91 and the 1991-92 graphs indicated a similar trend as the 3-year mean data in relation to PG rates. Only at 45-60 cm depth was there a decreasing trend on pH with PG in 1992-93.

B.2.2. Soil Macronutrients

Calcium. The 3-year mean soil Ca levels, by depth, did not differ at all depths with the various rates of PG application from the top 15 cm down to 30-45 cm depth (Table 37). At 45-60 and 60-75 cm depths, soil Ca increased linearly with PG rates, with the 4.0 Mg PG ha^{-1} treatment resulting in higher soil Ca than all the other treatments at 45-60 cm. The same high PG rate resulted in higher Ca than the control at 60-75 cm depth. The results indicate the movement of Ca downward and accumulation of Ca at 45-75 cm depths.

Figure 31 shows that the downward movement of Ca began at the end of 1990-91 and continued to the end of 1992-93. The DMRT showed that the differences in Ca reached a level of significance in 1992-93 at 45-60 cm depth. The differences were very slight and probably had no physiological significance.

Phosphorus. The 3-year mean P levels were low in all PG-treated plots from the top 15 cm down to 45-60 cm depth relative to those in the control. Soil P levels then went up at 60-75 and 75-90 cm depths in the plots treated with 4.0 Mg PG ha^{-1} exceeding those in the control at the same depths. The trend in the values with depths indicates the movement of P from the upper horizons down to lower depths and accumulating therein (Table 38).

The annual P levels are graphically presented in Figure 32. It appeared that the P impurities from PG may have significantly increased Mehlich 1 extractable P at the top 15 cm of the soil during the first year. However, despite the apparent differences in P levels among the control and the PG-treated soils at the top 15 cm depth, the differences did not attain any level of significance. Treatment effects were also noted in 1990-91 at 30-45 cm depth, showing significantly higher P levels in the control than in the PG-treated soils. In 1991-92, the statistics indicated a slightly significant decreasing linear trend at 15-30 cm depth which then slightly significant increased with PG rates at the 75-90 cm depth, indicating depletion of P at the upper layer and accumulation of P at the soil layers below. This process is graphically illustrated in Figure 32 (1992 and 1993).

Potassium. The 3-year mean soil K levels, by depth, did not differ with the various rates of application (Table 39). However, soil K levels in the control plots tended to be higher than those in the PG-treated plots below 15 cm. Soil K appeared to continue to move downward to as deep as 75-90 cm or beyond.

The annual soil K concentrations by depth as affected by PG rates by depth are given in Figure 33. In 1990-91 no significant effects of treatments were noted, but an accumulation of K appeared to have occurred at 60-75 cm depth. In 1991-92 there was again no significant effect of treatments, but the data indicate an accumulation of K at 75-90 cm depth. In 1992-93, a significant effect of treatments was noted at 30-45 cm depth, with soil K decreasing linearly with PG rates. Soil K at the highest PG rate then went up at the 45-60 and the 60-75 cm depths. Overall, however, it is fair to conclude from the study that PG had little or no effect on soil K.

Magnesium. The 3-year average data showed an obvious trend for reduced soil Mg in the 0-45 cm depths with increasing PG rates, but the differences due to PG treatments were only significant at the 30-45 cm depth. At 75-90 cm depth, a significant linear trend with soil Mg increasing with PG rates was also indicated.

The annual soil Mg levels are given in Figure 34. The 1992 and 1993 data showed an obvious trend for reduced Mg with PG rates at the top 15 cm of the soil. As early as 1990-91, soil Mg appeared to have began accumulate at 75-90 cm depth compared to the Mg level for the control at that depth. A more noticeable accumulation in soil Mg occurred in 1992-93 at 60-75 and 75 to 90 cm depths.

All these observations indicate the replacement of soil Mg by Ca from PG resulting in the movement of soil Mg from the upper into deeper soil horizons.

Table 36. pH of a Florida Spodosol soil under annual ryegrass which was amended with PG, averaged over a 3-year period, 1990-91 to 1992-93, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	pH					
0.0(C)	5.4a[1]	5.3a	5.3a	5.0a	4.9a	4.9a
0.4	5.6a	5.5a	5.2a	4.9a	4.7a	4.9a
2.0	5.2a	5.0a	5.0a	4.6a	4.4a	4.7a
4.0	5.4a	5.3a	5.0a	4.7a	4.7a	4.8a
<u>Tests:</u>[2]						
P(linear)	ns	ns	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

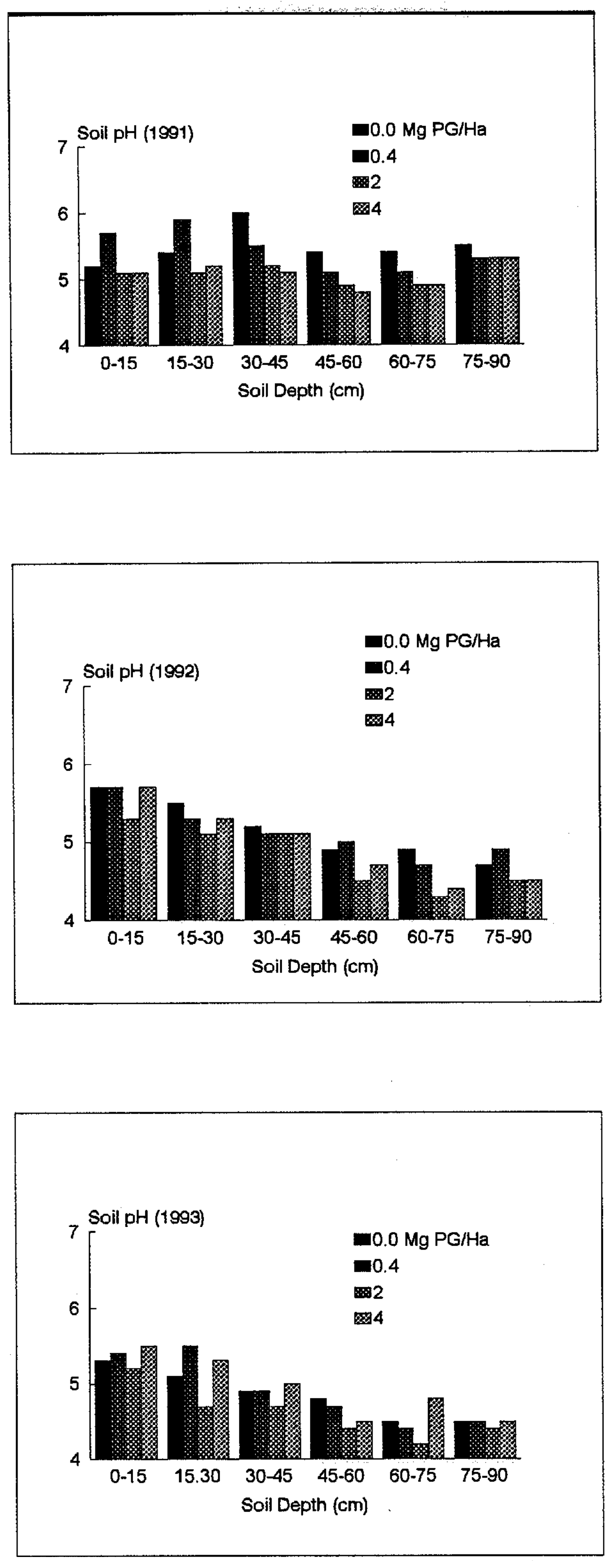
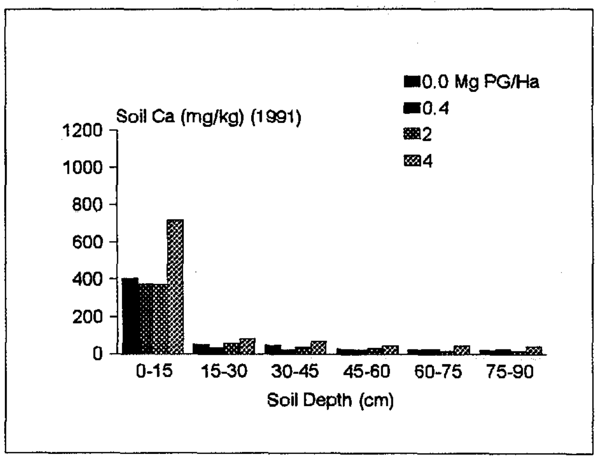


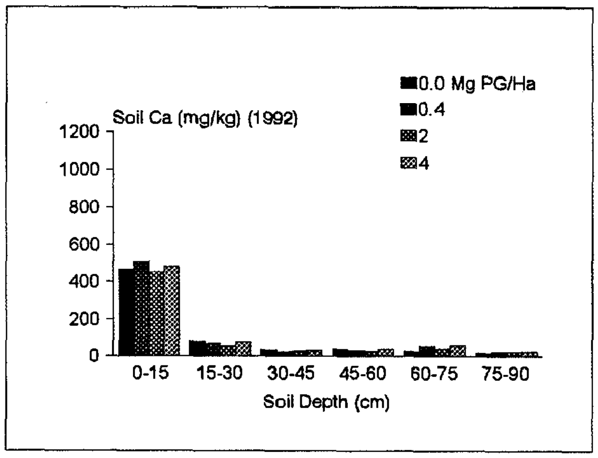
Figure 30. pH of a Florida Spodosol soil under annual ryegrass which was amended with PG, 1990-91 to 1992-93, by depth. Treatments at each depth without any letter are not significantly different.

Table 37. Calcium concentrations in a Florida Spodosol soil under annual ryegrass which was amended with PG, averaged over a 3-year period, 1990-91 to 1992-93, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	mg Ca kg^{-1}					
0.0(C)	479.3a[1]	62.0a	37.7a	28.3b	22.7b	19.0a
0.4	460.6a	64.5a	27.3a	22.8b	32.8ab	21.8a
2.0	465.8a	53.5a	27.2a	27.5b	33.2ab	18.8a
4.0	629.3a	99.7a	40.7a	44.8a	47.5a	31.8a
Tests:[2]						
P(linear)	ns	ns	ns	0.0139	0.0393	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).





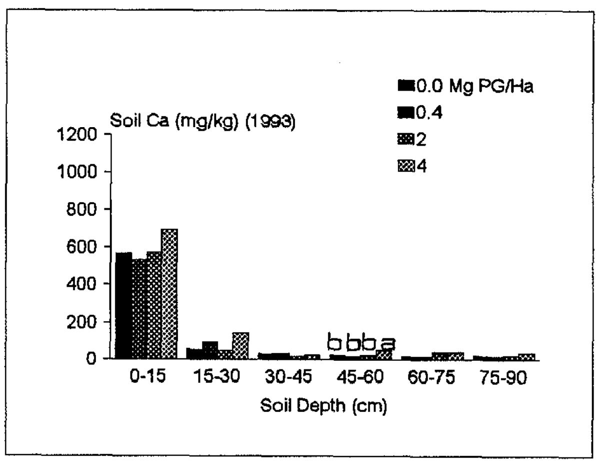
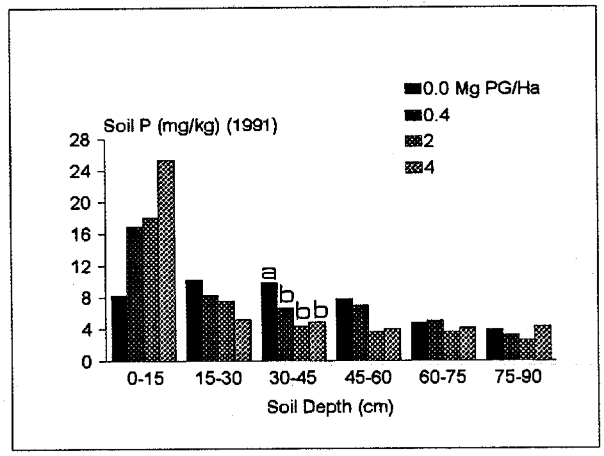


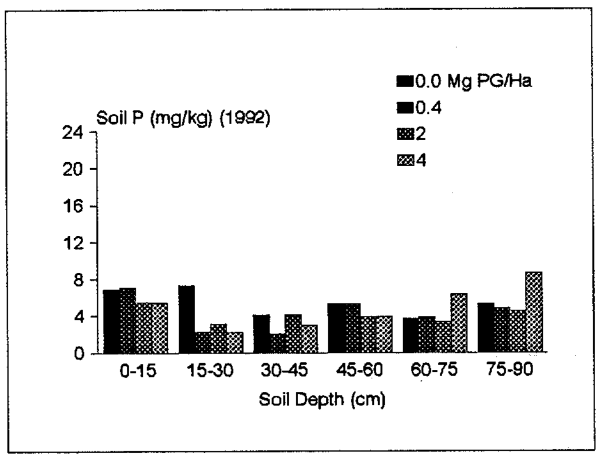
Figure 31. Calcium concentrations in a Florida Spodosol soil under annual ryegrass which was amended with PG, 1990-91 to 1992-93, by depth. Treatments at each depth without any letter or with the same letter(s) are not significantly different.

Table 38. Phosphorus concentrations in a Florida Spodosol soil under annual ryegrass which was amended with PG, averaged over a 3-year period, 1990-91 to 1992-93, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
$Mg\ PG\ ha^{-1}$			$mg\ P\ kg^{-1}$			
0.0(C)	12.72a[1]	6.90a	6.67a	5.67a	3.97a	5.10a
0.4	11.18a	4.48b	3.75a	5.38a	4.62a	4.37a
2.0	10.57a	4.08b	3.00a	3.42a	3.62a	3.23a
4.0	9.80a	3.73b	3.32a	3.23a	4.82a	7.00a
Tests:[2]						
P(linear)	ns	0.0249	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).





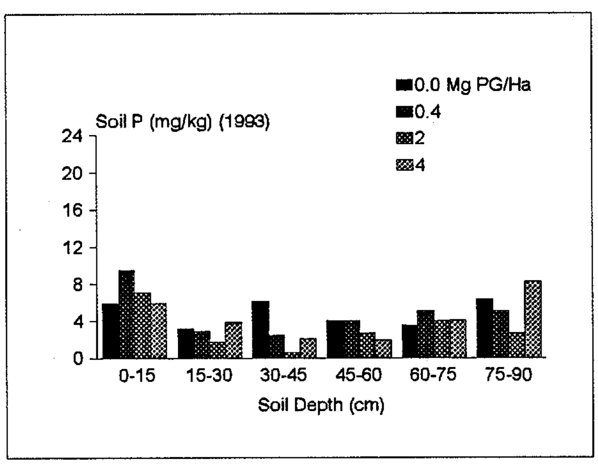


Figure 32. Phosphorus concentrations in a Florida Spodosol soil under annual ryegrass which was amended with PG, 1990-91 to 1992-93, by depth. Treatments at each depth without any letter or with the same letter(s) are not significantly different.

Table 39. Potassium concentrations in a Florida Spodosol soil under annual ryegrass which was amended with PG, averaged over a 3-year period, 1990-91 to 1992-93, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	mg K kg^{-1}					
0.0(C)	28.67a[1]	7.97a	7.00a	6.82a	5.33a	5.25a
0.4	20.15a	7.95a	3.93a	3.37a	3.70a	2.82a
2.0	33.80a	6.97a	4.65a	3.72a	4.08a	3.27a
4.0	16.18a	7.43a	6.00a	5.30a	5.07a	4.05a
Statistics:[1]						
P(linear)	ns	ns	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

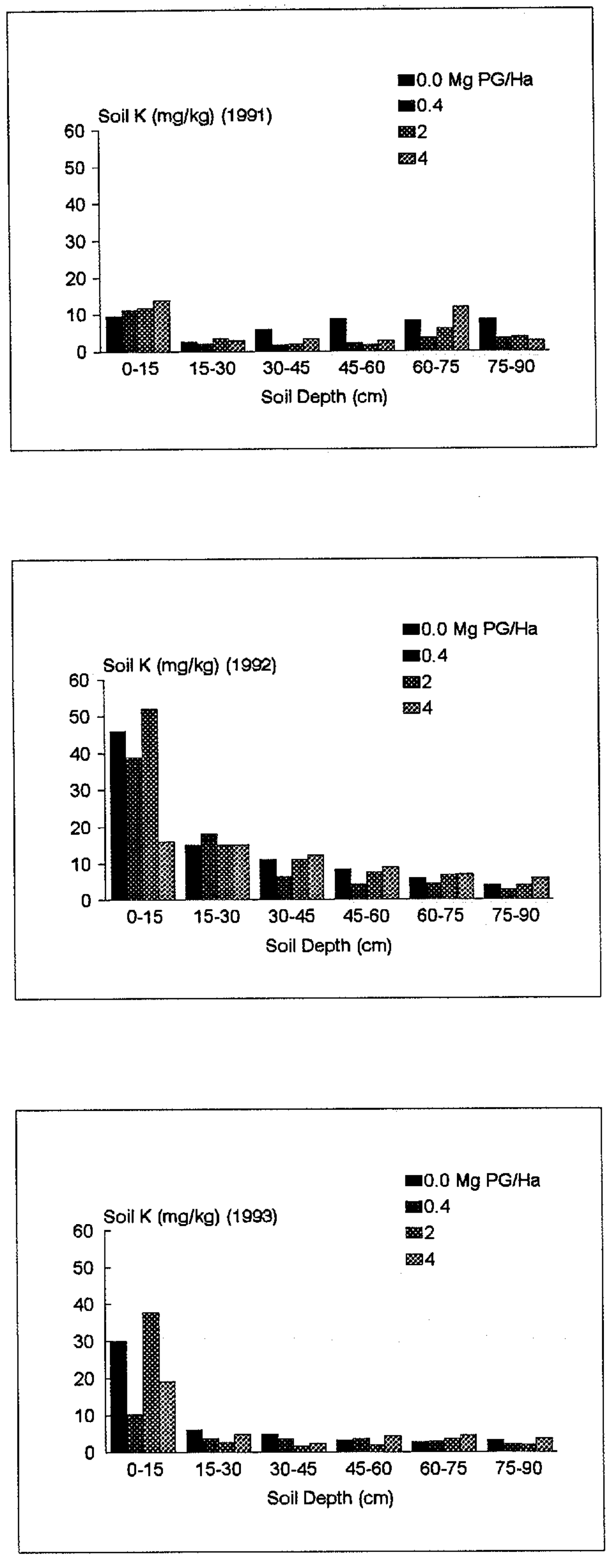
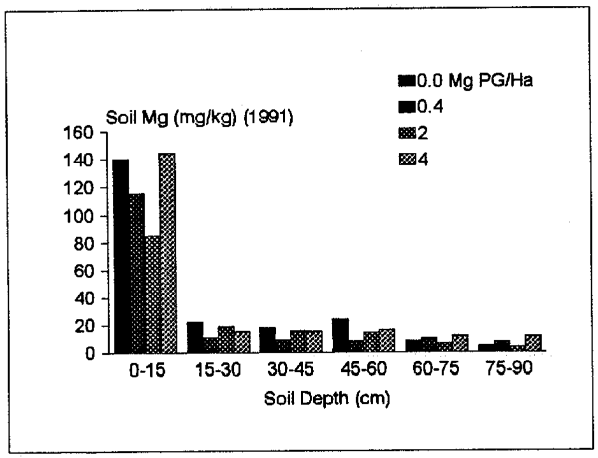


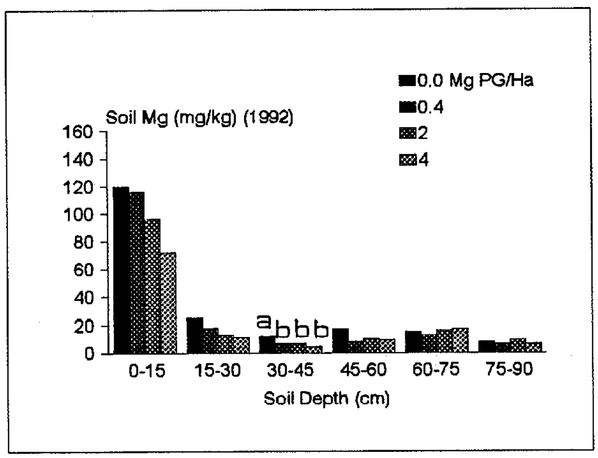
Figure 33. Potassium concentrations in a Florida Spodosol soil under annual ryegrass which was amended with PG, 1990-91 to 1992-93, by depth. Treatments at each depth without any letter are not significantly different.

Table 40. Magnesium concentrations in a Florida Spodosol soil under annual ryegrass which was amended with PG, averaged over a 3-year period, 1990-91 to 1992-93, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	---------- mg Mg kg^{-1} ----------					
0.0(C)	136.48a[1]	23.50a	15.17a	12.88a	10.05a	6.72a
0.4	116.64a	19.87a	9.28b	7.88a	10.02a	6.47a
2.0	99.73a	15.33a	10.13b	11.70a	13.35a	6.97a
4.0	98.73a	14.72a	7.78b	11.57a	14.23a	10.57a
Tests:[2]						
P(linear)	ns	ns	0.0180	ns	ns	0.0407
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).





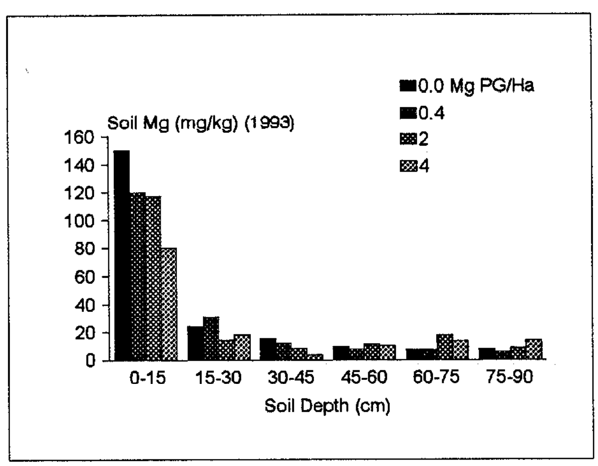


Figure 34. Magnesium concentrations in a Florida Spodosol soil under ryegrass which was amended with PG, 1990-91 to 1992-93, by depth. Treatments at each depth without any letter or with the same letter(s) are not significantly different.

B.2.3. Soil Micronutrients

The 3-year mean micronutrient levels showed no effects of PG on Cu, Fe, Na, and Zn at all depths (Tables 41, 41A, and 41B). The linear test for Mn indicated a decreasing trend with PG rates at the 15-30 cm depth (Table 41A). Chloride also decreased linearly with PG rates at 15-30 and 30-45 cm depths (Table 41B). At 30-45 cm depth, the control plots had significantly higher Cl than the plots that received 4.0 Mg PG ha^{-1} (Table 41B). Since neither Na nor Cl, as components of NaCl salt, increased with PG rates, it is fair to conclude that PG applications at the rates used in the study had no effect on NaCl concentrations in the soil.

Table 41. Copper (Cu) and iron (Fe) concentrations in a Florida Spodosol soil under annual ryegrass which was amended with PG, averaged over a 3-year period, 1990-91 to 1992-93, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	mg Cu kg^{-1}					
0.0(C)	0.11a[1]	0.09a	0.10a	0.12a	0.07a	0.07a
0.4	0.10a	0.07a	0.06a	0.07a	0.07a	0.07a
2.0	0.11a	0.07a	0.08a	0.09a	0.09a	0.07a
4.0	0.10a	0.08a	0.06a	0.09a	0.07a	0.11a
Tests:[2]						
P(linear)	ns	ns	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns
Mg PG ha^{-1}	mg Fe kg^{-1}					
0.0(C)	8.35a	6.82a	6.27a	11.72a	12.90a	17.92a
0.4	13.62a	8.32a	11.25a	22.70a	40.22a	34.48a
2.0	8.30a	5.32a	4.28a	26.47a	47.68a	22.58a
4.0	7.72a	5.82a	10.27a	37.68a	81.67a	57.53a
Tests:						
P(linear)	ns	ns	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

Table 41A. Manganese (Mn) and sodium (Na) concentrations in a Florida Spodosol soil under annual ryegrass which was amended with PG, averaged over a 3-year period, 1990-91 to 1992-93, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	mg Mn kg^{-1}					
0.0(C)	0.53a[1]	0.08a	0.08a	0.07a	0.05a	0.05a
0.4	0.43a	0.11a	0.06a	0.05a	0.06a	0.05a
2.0	0.48a	0.07a	0.05a	0.08a	0.09a	0.05a
4.0	0.38a	0.06a	0.07a	0.07a	0.06a	0.11a
Tests:[2]						
P(linear)	ns	0.0147	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns
Mg PG ha^{-1}	mg Na kg^{-1}					
0.0(C)	12.82a	7.95a	9.93a	10.32a	10.30a	9.70a
0.4	14.58a	9.02a	8.42a	9.03a	10.02a	8.47a
2.0	13.97a	7.42a	7.53a	8.70a	10.50a	7.52a
4.0	9.78a	5.97a	8.08a	9.73a	10.75a	8.70a
Tests:						
P(linear)	ns	ns	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

Table 41B. Zinc (Zn) and chloride (Cl) concentrations in a Florida Spodosol soil under annual ryegrass which was amended with PG, averaged over a 3-year period, 1990-91 to 1992-93, by depth.

Treatment	Depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
Mg PG ha^{-1}	------------------ mg Zn kg^{-1} ------------------------					
0.0(C)	1.43a[1]	0.47a	0.56a	0.69a	0.59a	0.45a
0.4	1.08a	1.45a	0.36a	0.36a	0.48a	0.44a
2.0	1.50a	0.35a	0.41a	0.47a	0.46a	0.37a
4.0	0.90a	0.58a	0.34a	0.54a	0.43a	1.01a
Tests:[2]						
P(linear)	ns	ns	ns	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns
Mg PG ha^{-1}	------------------mg Cl kg^{-1} ----------------------					
0.0(C)	7.17a	6.17ab	9.00a	11.83a	11.70a	11.33a
0.4	11.33a	6.67a	5.67ab	9.00a	14.00a	11.17a
2.0	8.33a	4.00ab	4.33ab	6.17a	14.30a	15.50a
4.0	4.33a	2.50b	1.50b	9.67a	10.20a	7.00a
Tests:						
P(linear)	ns	0.0207	0.0545	ns	ns	ns
P(quadratic)	ns	ns	ns	ns	ns	ns

[1]Means with the same letter(s) are not different.
[2]ns=not significant (P>0.05).

PART TWO: AGRONOMIC EXPERIMENTS

A. BAHIAGRASS EXPERIMENT

A.1. Amendment Rates, PG Versus Other Amendments, and Annual Versus Initial Applications on Forage Yields, Percent Dry Matter (DM), Nutrient Contents, and Other Forage Quality Measures

The annual (An) PG rates were 0.2, 0.4, 1.0, and the initial (In) rates were 2.0 and 4.0 Mg PG ha^{-1}. The annual and initial rates for $CaCO_3$ corresponded to each PG rate computed on the basis of Ca in PG. The annual rates for elemental S corresponded to 0.2 and 0.4 Mg PG ha^{-1} and the initial rate corresponded to 1.0 Mg PG ha^{-1} computed on the basis of S in PG. A 0.0 Mg PG ha^{-1} rate served as control. The slopes were determined using multiple regression and used in the analysis of variance (ANOVA) for the various statistical tests and comparisons.

A.1.1. Forage Dry Matter (DM) Yields

Table 42 shows the total forage yields of bahiagrass, averaged across the annual and the initial rates. The forage yields for the individual annual and initial rates for each of the amendments are presented graphically in Figures 35, 35A, and 35B for 1990 through 1992 to show the trends in yields.

Table 42. Group treatments and total[1] forage dry matter (DM) yields of bahiagrass, averaged across annual and initial application rates, 1990-1992.

Group treatments[2]	Year			Mean
	1990	1991	1992	
	--------- Mg DM ha^{-1}	-------------		
PG	4.65	11.55	6.57	7.60
PG+dolomite[3]	4.23	11.29	6.19	7.27
PG+$CaCO_3$[3]	4.42	11.16	6.28	7.30
PG_{all}[4]	4.43	11.33	6.35	7.39
S (elemental)	4.21	10.18	5.79	6.74
$CaCO_3$	4.38	10.72	5.85	6.98
Control	3.93	10.27	5.68	6.63

[2]See Table 44 for the comparative statistics.
[3]Total of 3 harvests in 1990, 5 in 1991, and 6 in 1992.
[4]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

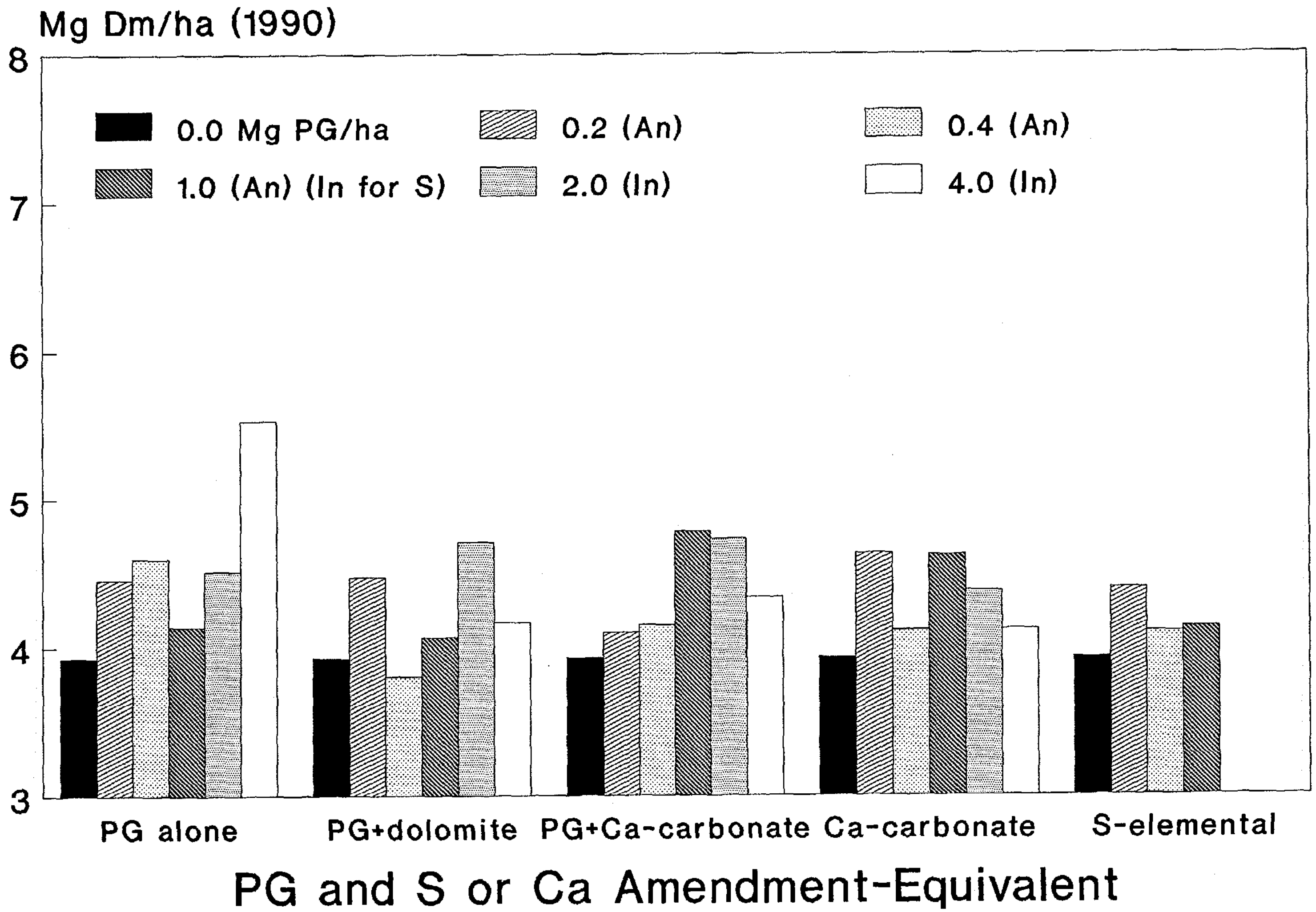


Figure 35. Total regrowth forage dry matter yieldsof bahiagrass, 1990, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial (In) rates, 1990.

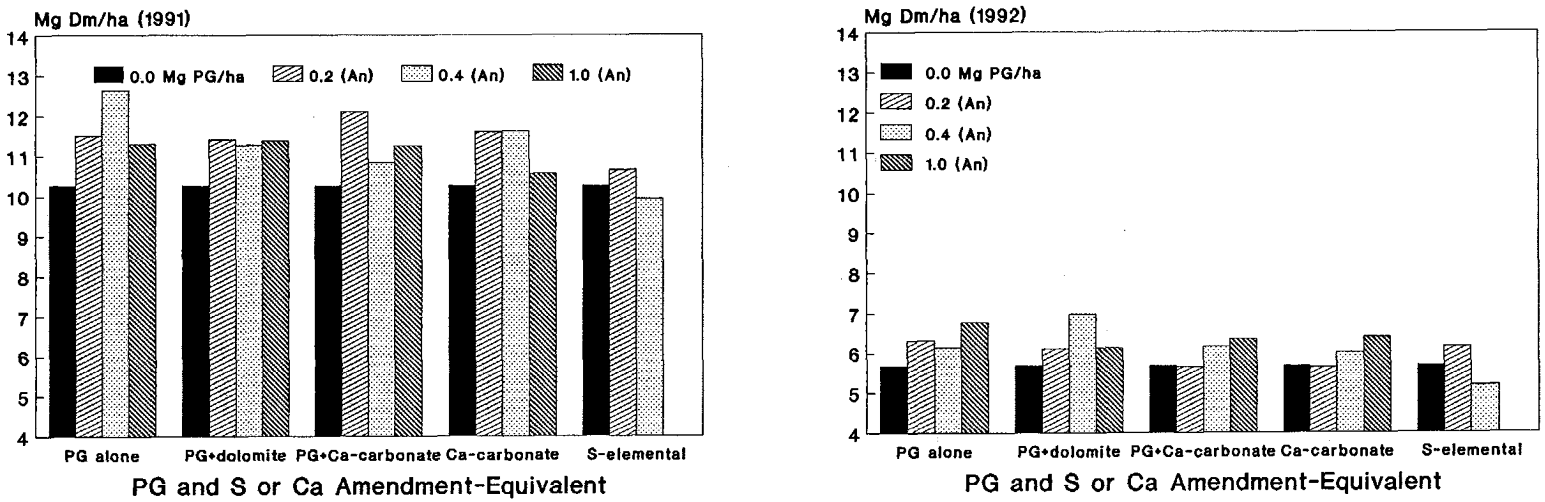


Figure 35A. Total regrowth forage dry matter yieldsof bahiagrass, 1991 and 1992, from plots which were amended with PG and other S or Ca mendments applied at the annual (An) rates, 1990-1992.

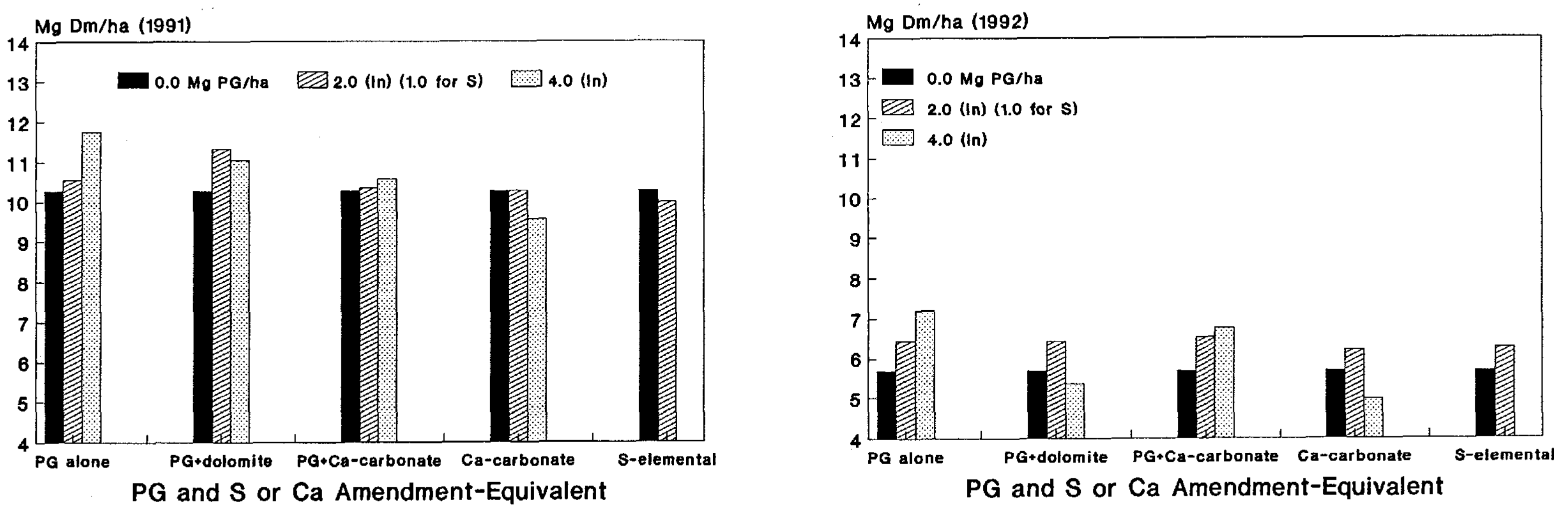


Figure 35B. Total regrowth forage dry matter yields of bahiagrass, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

The forage yields from plots fertilized with the various types of PG amendments apparently exceeded those from the control plots by 7.6 to 18.3% in 1990, 8.7 to 12.5% in 1991, 9.0 to 15.7% in 1992, and by 9.7 to 14.6% when averaged over the 3-year period. The yields from plots fertilized with PG exceeded only slightly but consistently the yields from plots that received PG+$CaCO_3$ or PG+dolomite. The 3-year mean yield from all PG-fertilized plots (PG_{all}) also exceeded the yields from the control, the elemental S, and the $CaCO_3$ plots by 11.5, 9.6, and 5.9%, respectively.

Effects of rates. The slopes and the intercepts for the linear equations for forage yields for the various amendments are given in Table 43 with the statistics.

In 1990, using all the rates in computing the slopes or rate effects of the various amendments, PG showed a significant slope of 0.18 Mg DM per Mg PG ha^{-1} (Table 43). With an intercept of 4.17 Mg DM ha^{-1}, the significant slope meant a 17% increase in yield for the 4.0 Mg PG ha^{-1} application rate. When the analyses for the annual rates were done separately from the initial rates in 1991 and 1992, PG gave a significant annual rates slope of 0.19 Mg DM per Mg PG ha^{-1} in 1991 but not in 1992. However, when averaged over the 3-year period, the PG annual rates increased forage yield by 0.23 Mg DM per Mg PG ha^{-1}.

In 1992, the global test (P{AR*GT*FREQUENCY}=0.1891) was not significant. There was, however, an indication that the 1992 slope of 0.22 Mg DM per Mg PG ha^{-1} for the initial PG rates may be different (P=0.0458) from zero. For the 4.0 Mg PG ha^{-1} rate and an intercept of 5.88 Mg DM ha^{-1}, the said slope would mean a 15% increase in yield. The 3-year mean for the initial rates showed an increase of 0.14 Mg DM per Mg PG ha^{-1}. With an intercept of 7.25 Mg DM ha^{-1}, this significant slope gave an average increase of 8% in yield for the 4.0 Mg PG ha^{-1} rate over the 3-year period (Table 43).

The effects of the annual rates and the initial rates, as treatments PG_{all} An (averaged over all treatments containing PG applied annually) and PG_{all} In (averaged over all treatments containing PG applied initially), respectively, were not significant in 1991 and 1992 (Table 43, C). When averaged over the 3-year period, PG_{all} annual, but not PG_{all} initial, significantly increased the forage yield of bahiagrass by 0.12 Mg DM per Mg PG ha^{-1}.

In 1991, elemental S at the annual rates of 33 and 66 kg S ha^{-1} gave a slope of -0.71 Mg DM per Mg PG (equivalent to 165 kg elemental S) ha^{-1}. When averaged over the 3-year period, the annual rates reduced forage yield by 0.43 Mg DM per Mg PG ha^{-1}. The initial rate (165 kg elemental S ha^{-1}) also reduced forage yield in 1991 by 0.45 Mg DM per Mg PG ha^{-1}, but not in 1990 and 1992 or when averaged over the 3-year period (Table 43).

The annual rates of $CaCO_3$ had no effect on bahiagrass yield. But the high initial rates of $CaCO_3$ reduced forage yield by 0.32 Mg DM per Mg PG (equivalent to 206 kg Ca as $CaCO_3$) ha^{-1} in 1991 and by 0.12 Mg DM per Mg PG ha^{-1} when averaged over the 3-year period (Table 43).

Table 43. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on total forage dry matter (DM) yields of bahiagrass, 1990-1992.

Treatment	Year			Mean
	1990[1]	1991	1992	
Intercept	--------- Mg DM ha^{-1} ----------			
	4.17	11.35	5.88	7.25
Statistics:	-------- (P-value)[2] -----------			
AR*GT	0.0069			
AR*GT*FREQUENCY[3]		0.0009	ns	
AR*GT*FREQUENCY*YEAR				0.0002
Slope	--------- Mg DM/Mg PG ha^{-1} ------			
A. Rates, Annual (An):				
PG An Slope	0.18***	0.19**	0.28ns	0.23**
S An Slope	0.03ns	-0.71***	-0.23ns	-0.43**
$CaCO_3$ An Slope	0.00ns	-0.11ns	0.12ns	0.06ns
PG+$CaCO_3$ An Slope	0.08*	-0.04ns	0.11ns	0.10ns
PG+dolomite An Slope	0.03ns	0.00ns	0.23ns	0.02ns
B. Rates, Initial (In):				
PG In Slope	0.18***	-0.03ns	0.22**	0.14***
S In Slope	0.03ns	-0.45**	0.13ns	-0.13ns
$CaCO_3$ In Slope	0.00ns	-0.32***	-0.07ns	-0.12**
PG+$CaCO_3$ In Slope	0.08*	-0.13ns	0.16ns	0.03ns
PG+dolomite In Slope	0.03ns	-0.04ns	-0.02ns	0.01ns
C. Rates, Avg Annual and Avg Initial:				
PG_{all} Avg An Slope	0.09**	0.05ns	0.16ns	0.12**
PG_{all} Avg In Slope	0.09**	-0.07ns	0.12ns	0.06ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), *P<0.10 (slightly significant), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

Referring to Table 42 and to Figures 35, 35A, and 35B, it can be concluded that modest increases of 10 to 15% in forage yield over that of the control were attained in all three years at relatively low annual rates of 0.2 to 1.0 Mg PG ha^{-1}. To the ranchers, a 10% increase in forage yield in bahiagrass pastures would mean a 10% increase in the stocking rate.

PG versus other amendments. The statistics for the various comparisons, such as between amendments and between annual and initial rates, are given in Table 44. For the comparisons PG_{all} vs S or PG_{all} vs $CaCO_3$, all the treatments containing PG were analyzed as a single treatment and compared against all the treatments containing elemental S or $CaCO_3$.

Table 44. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on total bahiagrass forage yields, 1990-1992.

Comparisons	Year			Mean
	1990[1]	1991	1992	
Statistics:	-------- (P-value)[2]	-----	-----	-----
AR*GT	0.0069			
AR*GT*FREQUENCY		0.0009	ns	
AR*GT*FREQUENCY*YEAR				0.0002
PG vs other amendments:[3]				
PG_{all} vs S	ns	0.0001	ns	0.0024
PG_{all} vs $CaCO_3$	ns	0.0138	ns	0.0091
PG vs PG+$CaCO_3$	0.0951	ns	ns	ns
PG vs PG+dolomite	0.0059	ns	ns	0.0046
Annual vs Initial rates:[4]				
PG An vs In	-	ns	ns	ns
S An vs In	-	ns	ns	ns
$CaCO_3$ An vs In	-	0.0066	ns	0.0093
PG+$CaCO_3$ An vs In	-	ns	ns	ns
PG+dolomite An vs In	-	ns	ns	ns
PG_{all} Avg An vs Avg In	-	ns	ns	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed using the rates applied for that span of years.

The comparative statistics for PG versus other amendments, using the slopes computed across all rates and across all treatments containing PG, showed significant P-values for PG_{all} vs S in 1991 and when averaged over the 3-year period (Table 44). Thus, the various PG amendments analyzed across all rates as a single treatment, PG_{all}, had significantly greater rate of increase in forage yields per unit treatment rate (slope) in 1991 and when averaged over the 3-year period than elemental S at the corresponding rates. This comparison shows that PG is a better amendment than elemental S to enhance the forage yields of bahiagrass while supplying S to bahiagrass pastures.

The comparison PG_{all} vs $CaCO_3$ also gave significant P-values in 1991 and when averaged over the 3-year period (Table 44). Hence, the various PG amendments analyzed across all rates as a single treatment, PG_{all}, gave significantly higher rate of increase in forage yields in 1991 and when averaged over the 3-year period than did $CaCO_3$ at the corresponding rates. The use of PG, as a source of Ca, is more likely to enhance the forage yield of bahiagrass than would $CaCO_3$.

In 1990 and when averaged over the 3-year period, PG, averaged across all rates, gave higher rate of increase in forage yields than did PG+dolomite. The comparative statistics for PG vs PG+$CaCO_3$ showed also a slightly significant P-value in 1990. It appeared that addition of lime to PG, as it was with the application of $CaCO_3$, affected bahiagrass forage yield adversely in the type of soil used in the study. This may explain the poor responses of bahiagrass to the limed PG amendments at both the annual and the initial rates particularly during the first two years, 1990 and 1991 (Table 43).

Annual versus initial rates. No comparisons between the annual and the initial rates were made during the first year as all rates in 1990 were considered annual as well as initial. The slopes for the annual rates in 1991 and 1992 for the various amendments were computed using the actual rates that had been applied at each span of years. Thus, the slopes for the annual rates used in the comparisons with the slopes for the initial rates were 1/2 and 1/3 the slopes of the annual rates in Table 43 in 1991 and 1992, respectively (Statistical Analysis and Data Presentation, pp. 8-10).

The comparison between $CaCO_3$ annual versus initial rates showed significant P-values in 1991 and when averaged over the 2-year period. Hence, the negative slopes for the high initial rates in Table 43 were significantly different from the non-significant slopes for the low annual rates. This difference implied that for bahiagrass growing on the kind of soil used in the study, the large one-time application rates of $CaCO_3$ as a source of Ca or as lime material could adversely affect the forage yields of bahiagrass over a 3-year period compared to the effects of the low annual rates (see Figures 35A and 35B).

The annual vs the initial rates comparisons for PG, PG+$CaCO_3$, PG+dolomite, PG_{all}, and elemental S were not significant in 1991, 1992, and when averaged over the 3-year period (Table 44). Hence, the slopes or the effects of the annual rates and the initial rates of these amendments on forage yield of bahiagrass were not significantly different.

A.1.2. Percent Dry Matter (%DM)

Table 45 shows very little variations in %DM of bahiagrass forage within each year among the various group treatments. The annual %DM means are presented in Figures 36, 36A, and 36B to show the trends.

Table 45. Group treatments and percent dry matter (%DM) of bahiagrass forage, averaged across annual and initial application rates, 1990-1992.

Group treatments[1]	Year			Mean
	1990	1991	1992	
	%DM			
PG	34.9	31.1	26.8	30.1
PG+dolomite[2]	34.8	31.1	27.7	30.4
PG+$CaCO_3$[3]	35.2	31.7	27.1	30.1
PG_{all}[3]	35.0	31.3	27.2	30.2
S (elemental)	35.0	30.9	27.6	30.4
$CaCO_3$	34.7	31.1	27.5	30.3
Control	35.3	30.4	27.3	30.1

[1]The comparative statistics showed no significant P-values.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. The %DM slopes for the annual or the initial rates of the various amendments were not significant. The statistics for the effects of annual or initial rates on %DM of bahiagrass forage showed no P-values less than 0.10.

PG versus other amendments. The comparisons between the amendments showed that their effects on %DM of bahiagrass forage were also not different.

Annual versus initial rates. There were no differences between the effects of the annual rates and the initial rates of the various amendments on %DM of bahiagrass forage.

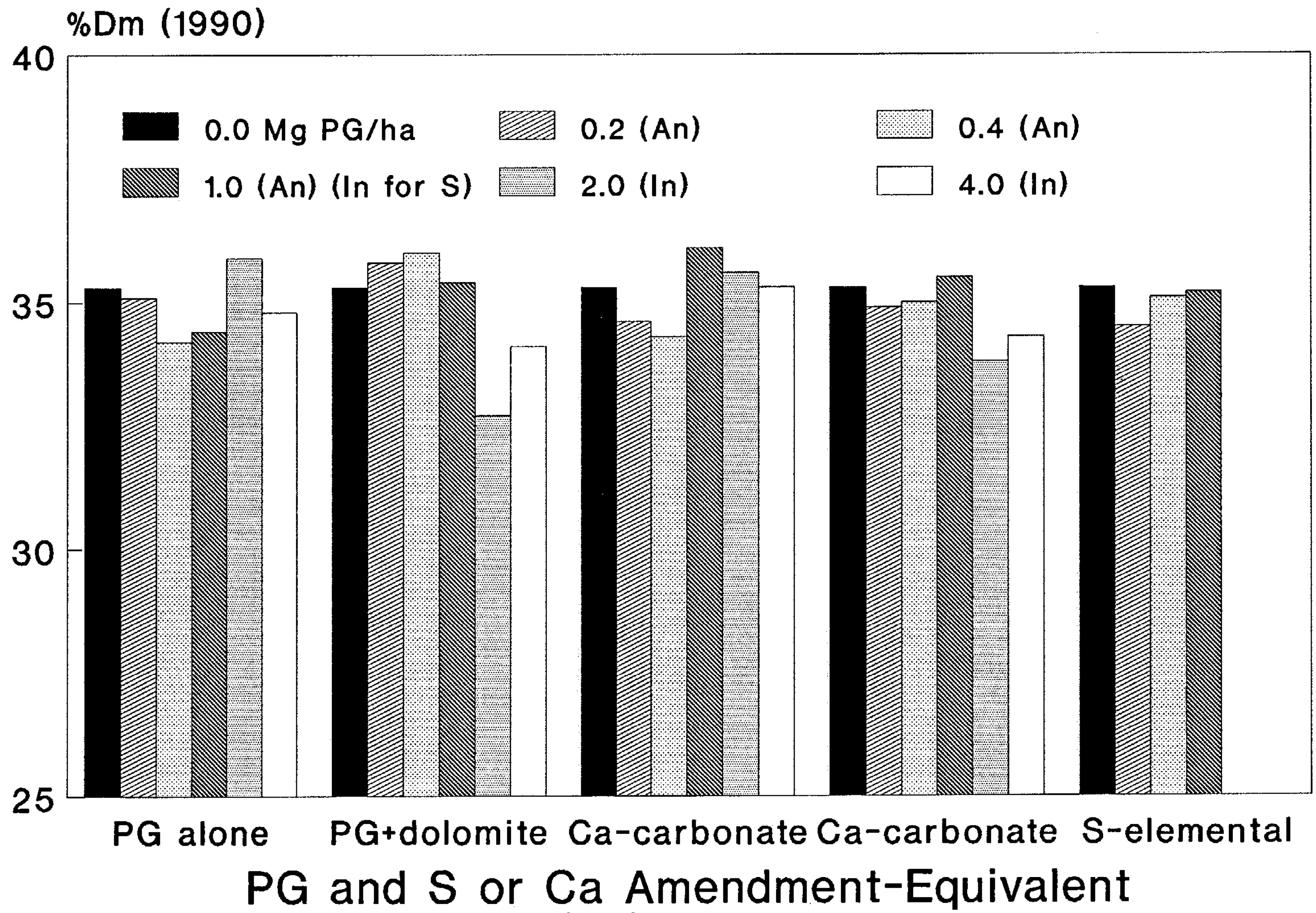


Figure 36. Percent dry matter (%DM) of bahiagrass regrowth forage, 1990, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial (In) rates, 1990.

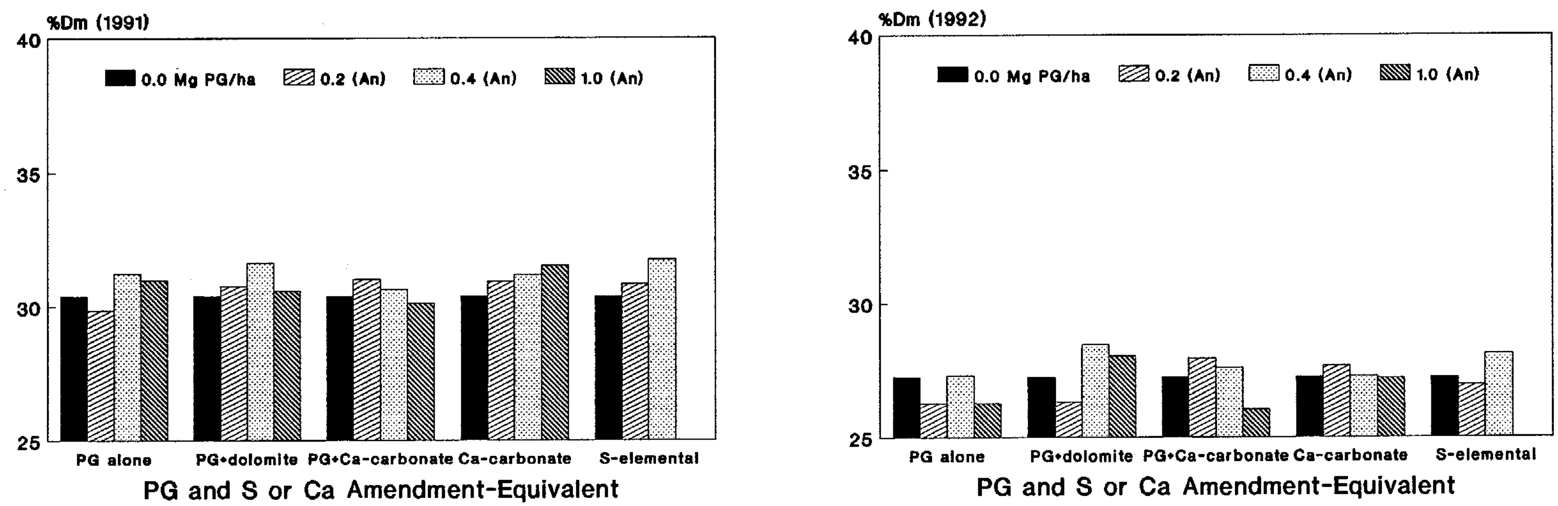


Figure 36A. Percent dry matter (%DM) of bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

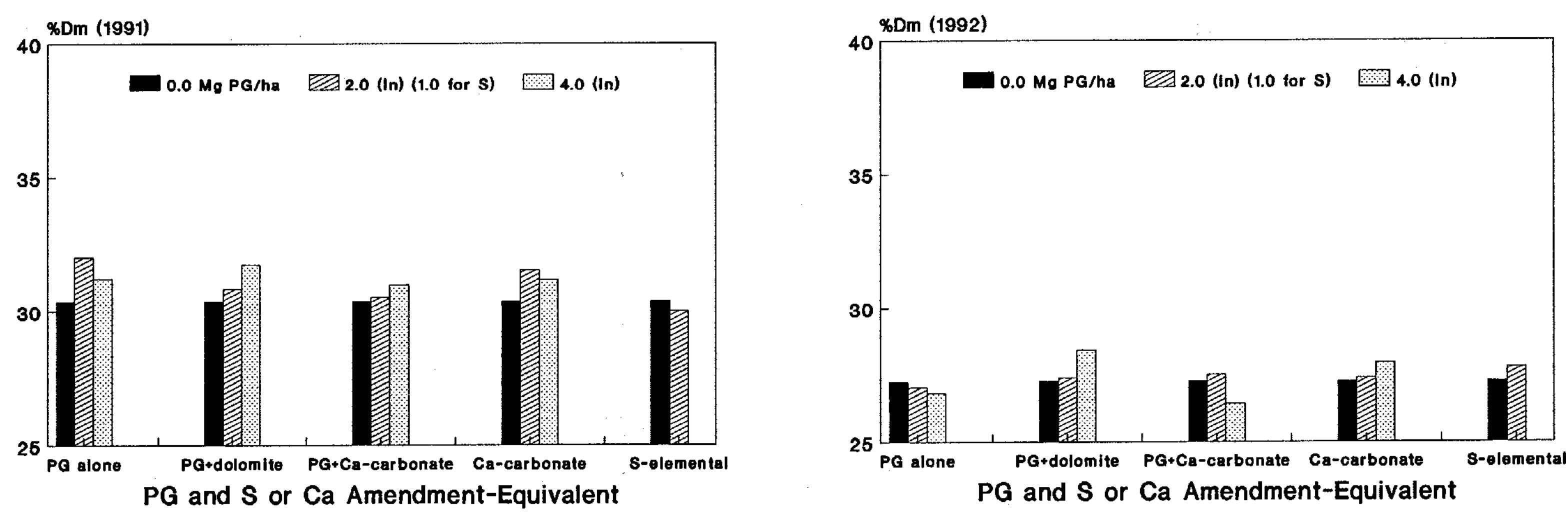


Figure 36B. Percent dry matter (%DM) of bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

A.1.3. Nutrients in Forage and Other Quality Measures

Sulfur content. The %S in bahiagrass forage, averaged across all rates, and the group treatments are given in Table 46. Figures 37, 37A, and 37B show the trends in %S with the annual and the initial rates for each of the amendments.

Table 46. Group treatments and S concentrations in bahiagrass forage, averaged across annual and initial application rates, 1990-1992.

Group treatments[1]	Year		
	1990	1991	1992
	------------- %S ----------------		
PG	0.30	0.31	0.34
PG+dolomite[2]	0.32	0.31	0.32
$PG+CaCO_3$[2]	0.30	0.32	0.35
PG_{all}[3]	0.31	0.31	0.34
S (elemental)	0.26	0.29	0.29
$CaCO_3$	0.22	0.23	0.28
Control	0.22	0.18	0.19

[1]See Table 48 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. In 1990, PG increased %S in bahiagrass forage by 0.027% per Mg PG ha^{-1} (Table 47). The annual rates in 1991 and 1992 increased %S by 0.040% and 0.070% per Mg PG ha^{-1}, respectively. Similar range of increases in %S with the years were noted for $PG+CaCO_3$, PG+dolomite, and PG_{all} annual. The increasing effects of the annual rates with the years were most likely due to the residual PG from PG applied in the previous year or years.

The rates of PG, $PG+CaCO_3$, and PG+dolomite applied initially increased S contents in bahiagrass forage in 1990 and 1991 by 0.023 to 0.033% per Mg PG ha^{-1}. But by 1992, PG showed only a slightly significant slope of 0.015%, and the slopes for $PG+CaCO_3$ and PG+dolomite were not significant. Similarly, PG_{all} initial increased S contents in forage in 1990 and 1991 but showed no significant slope in 1992 (Table 47). These trends indicate that significant portions of the large initial rates of PG applied in 1990 must have moved beyond the main root zone after two years from application or, if still present, must have been transformed into less available forms, or both.

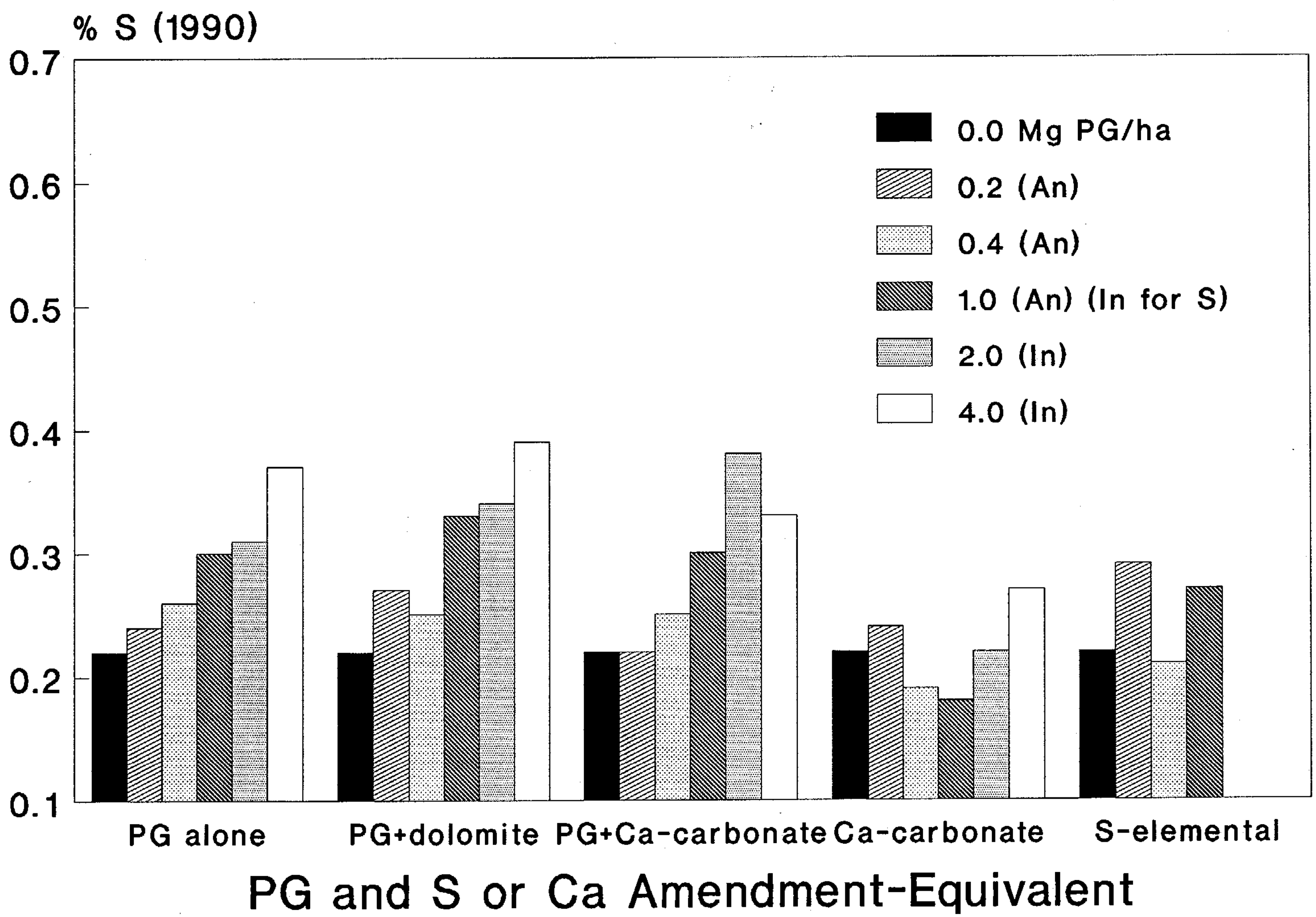


Figure 37. Sulfur concentrations in bahiagrass regrowth forage, 1990, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial (In) rates, 1990.

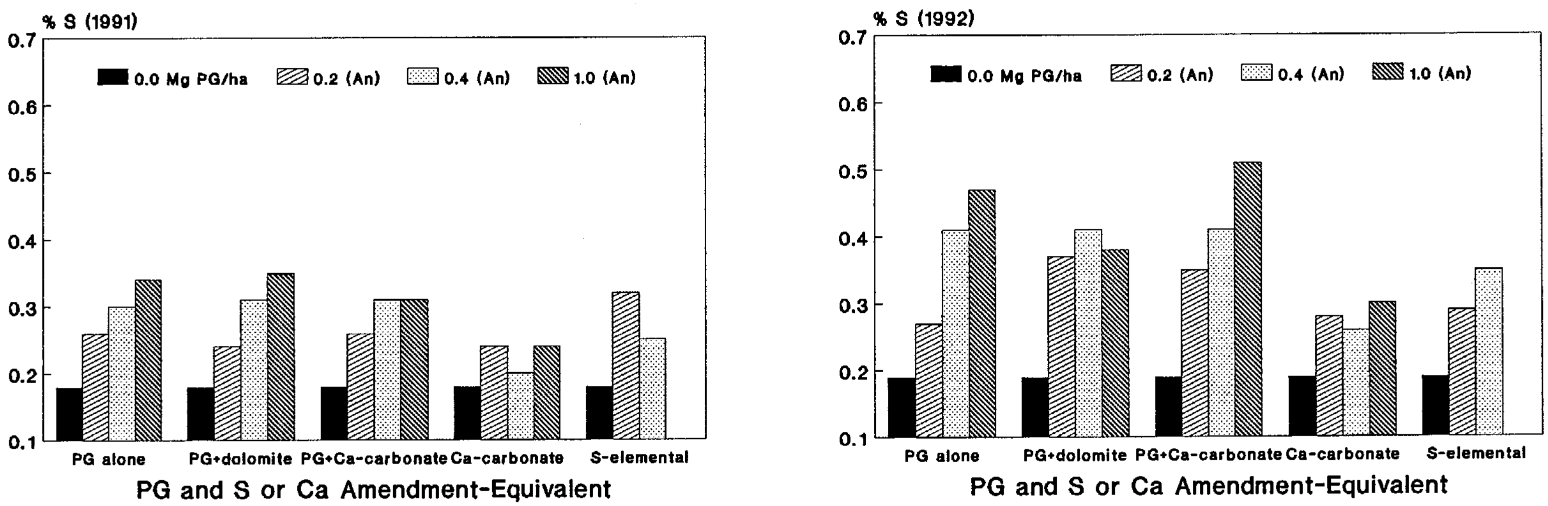


Figure 37A. Sulfur concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

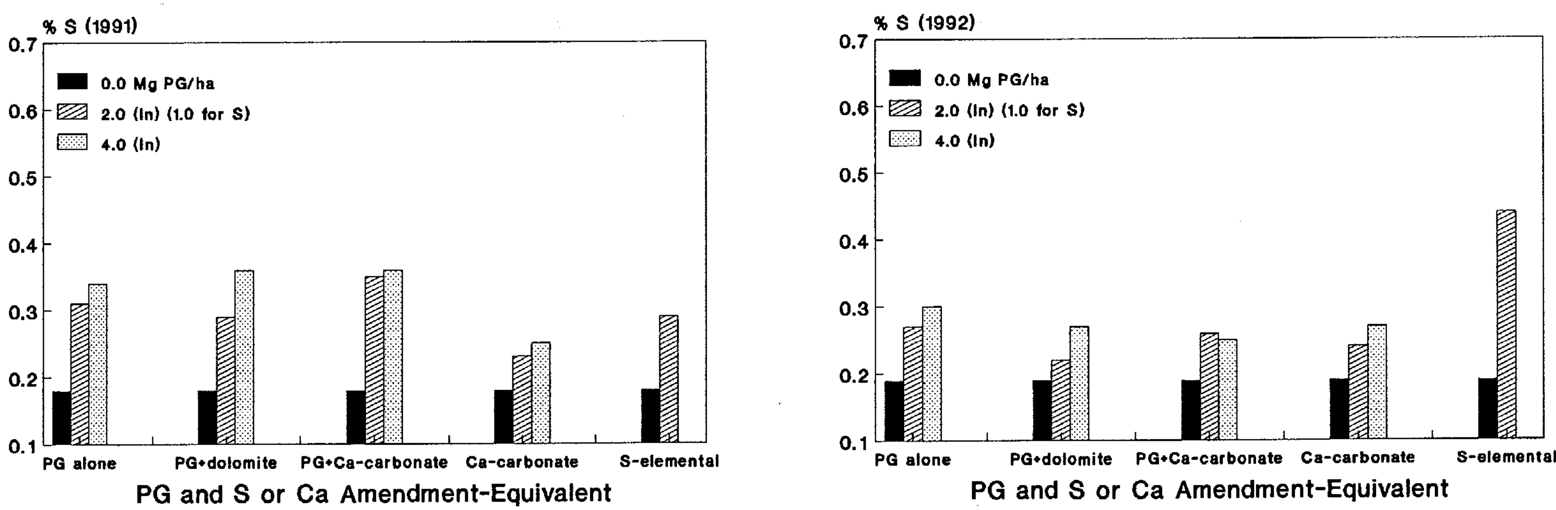


Figure 37B. Sulfur concentrations in bahiagrass regrowth forage, 199 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the

Table 47. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on S concentration in bahiagrass forage, 1990-1992.

Treatment		Year	
	1990[1]	1991	1992
Intercept	------------ %S ---------------		
	0.216	0.217	0.217
	----------- (P-value)[2] --------		
AR*GT	0.0001		
AR*GT*FREQUENCY[3]		0.0001	0.0001
Slope	------------ %S/Mg PG ha^{-1} ----		
A. Rates, Annual (An):			
PG An Slope	0.027***	0.040***	0.070***
S An Slope	0.016*	0.030**	0.007ns
$CaCO_3$ An Slope	0.003ns	0.005ns	-0.019ns
PG+$CaCO_3$ An Slope	0.028***	0.037***	0.098***
PG+dolomite An Slope	0.033***	0.043***	0.075***
B. Rates, Initial (In):			
PG In Slope	0.027***	0.024***	0.015*
S In Slope	0.016*	0.025***	0.071***
$CaCO_3$ In Slope	0.003ns	0.007ns	-0.006ns
PG+$CaCO_3$ In Slope	0.028***	0.030***	0.007ns
PG+dolomite In Slope	0.033***	0.023***	0.008ns
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	0.029***	0.040***	0.081***
PG_{all} Avg In Slope	0.029***	0.025***	0.010ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), *P<0.10 (slightly significant), **P<0.05, ***P<0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

Elemental S at the two annual rates of 33 and 66 kg S ha^{-1} increased %S in bahiagrass forage in 1990 and 1991. The single initial rate of 165 kg S ha^{-1} also increased %S by 0.016, 0.025, and 0.071% per Mg PG or S-equivalent rate ha^{-1} in 1990, 1991, and 1992, respectively. The trend for the one-time application rate indicates that more elemental S applied in 1990 was being converted to plant usable S (SO_4-S) with the years.

Treatment $CaCO_3$, not being an S source, had no effect on %S in bahiagrass forage (Table 47).

PG versus other amendments. In 1990, PG_{all} was slightly (P=0.0630) more effective than elemental S in increasing %S in bahiagrass forage. By 1991 and 1992, PG_{all} and elemental S had become equally effective in increasing %S in the forage (Table 48). The various PG amendments also were equally effective in increasing S contents in bahiagrass in all three years (Table 48). The statistics for PG_{all} vs $CaCO_3$ showed significant P-values in favor of the former in all three years, the latter not being a source of S.

Table 48. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on S concentrations in bahiagrass forage, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
Statistics:	-------- (P-value)[2]	-------------	
AR*GT	0.0001		
AR*GT*FREQUENCY		0.0001	0.0001
PG vs other amendments:[3]			
PG_{all} vs S	0.0630	ns	ns
PG_{all} vs $CaCO_3$	0.0001	0.0001	0.0001
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	ns
Annual vs initial rates:[4]			
PG An vs In	-	ns	ns
S An vs In	-	ns	0.0001(-)
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	0.0257(-)	0.0008
PG+dolomite An vs In	-	ns	0.0243
PG_{all} Avg An vs Avg In	-	0.0577(-)	0.0003

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

The increasing effect of elemental S, applied initially in 1990, over the years on tissue S (Table 47) implies that elemental S may be a better long-term source of S for bahiagrass than the readily soluble PG. The drawback, however, is that elemental S applied at such a high rate could also reduce the forage yield of bahiagrass (Table 43).

Annual versus initial rates. The comparative statistics for the annual versus the initial rates of PG on %S in bahiagrass show non-significant P-values in 1991 and 1992 (Table 48), indicating that the effects (slopes) of the annual and the initial rates on S contents were not different. The P-value for $PG+CaCO_3$ was significant while that for PG_{all} was slightly significant in 1991, both indicating that the annual and the initial rates slopes, showed certain levels of difference. The negative signs after the P-values indicated that the annual rates slopes were less than the initial rates slopes for $PG+CaCO_3$ and PG_{all} in 1991, contrary to the actual values of the slopes in Table 47. The statistics, however, are correct. As explained earlier, the annual rates slopes used in these comparisons were actually 1/2 the 1991 annual slopes in Table 47. Table 47 and the comparative statistics in 1992 for $PG+CaCO_3$, PG+dolomite, and PG_{all} show that, in general, PG would be better applied, as a source of S, to bahiagrass pastures at small annual rates rather than at large rates applied once at the beginning of a 3-year cycle.

Thus, for soils similar to the one used in this study, PG, as a source of S for bahiagrass, may be applied at 0.2 to 0.4 Mg PG ha^{-1} annually or at 2.0 to 4.0 Mg PG ha^{-1} applied once every three years. These rates should keep %S levels around 0.32% (Figures 37, 37A, and 37B), the upper S-requirement level for grazing ruminants. While certain of these rates resulted in %S in bahiagrass in excess of 0.40%, the maximum tolerable level cited by NRC (1980), McDowell et al. (1993) stated that ruminants can tolerate more S from natural feed than from added sulfate.

Knowing the pre-treatment %S in bahiagrass pastures, the response slopes for PG in Table 47 should be helpful in determining the PG rates to use to attain a desirable range of S contents in these pastures.

Calcium content. Table 49 shows the %Ca in bahiagrass forage, averaged across the annual and the initial rates, for the various amendments. Figures 38, 38A, and 38B show the trends in %Ca with the rates.

Effects of rates. The PG annual rates increased %Ca in bahiagrass by 0.026% per Mg PG ha^{-1} only in 1990 (Table 50). The non-significant slopes in 1991 and 1992 cannot be explained since more PG was applied during these years. The $PG+CaCO_3$ and PG+dolomite annual rates, however, maintained relatively constant increases in %Ca in all years by 0.020 to 0.029% per Mg PG ha^{-1}.

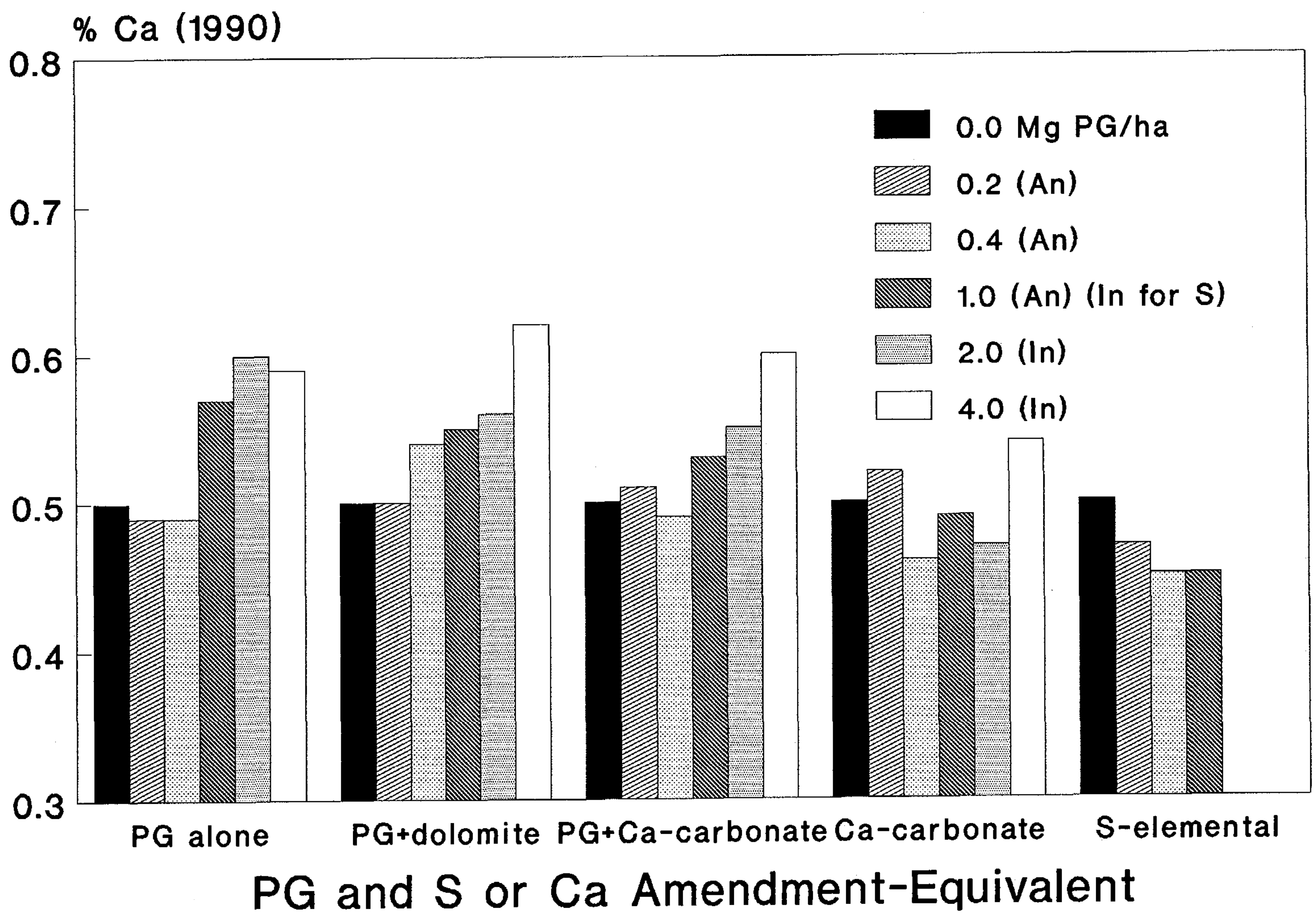


Figure 38. Calcium concentrations in bahiagrass regrowth forage, 1990, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial rates, 1990.

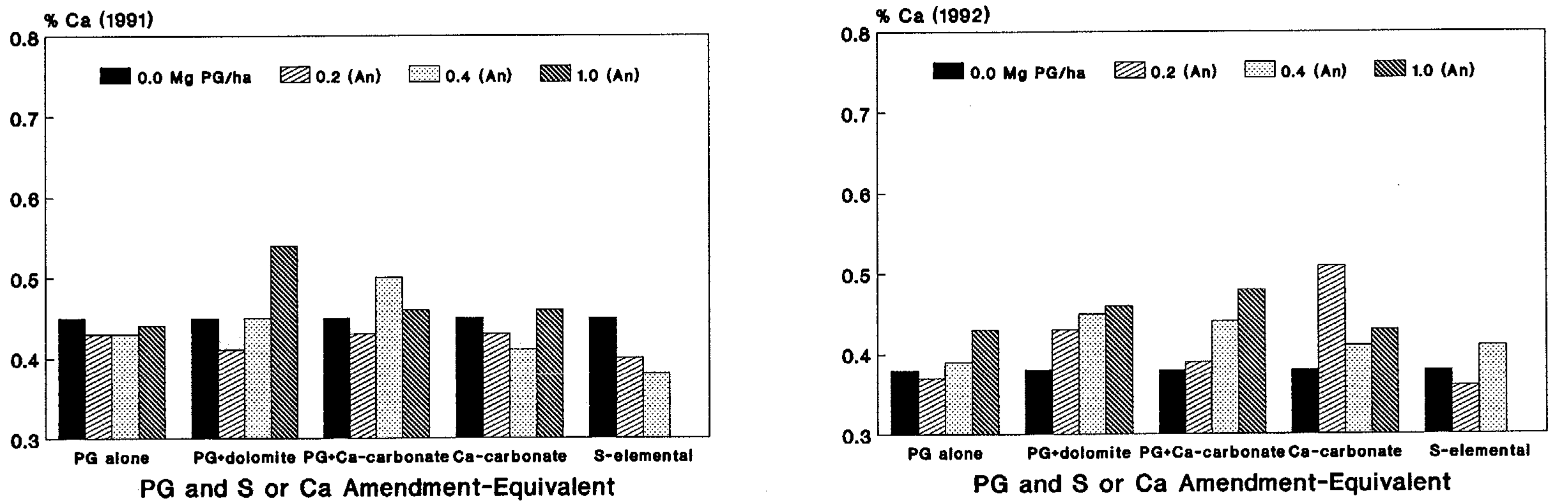


Figure 38A. Calcium concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

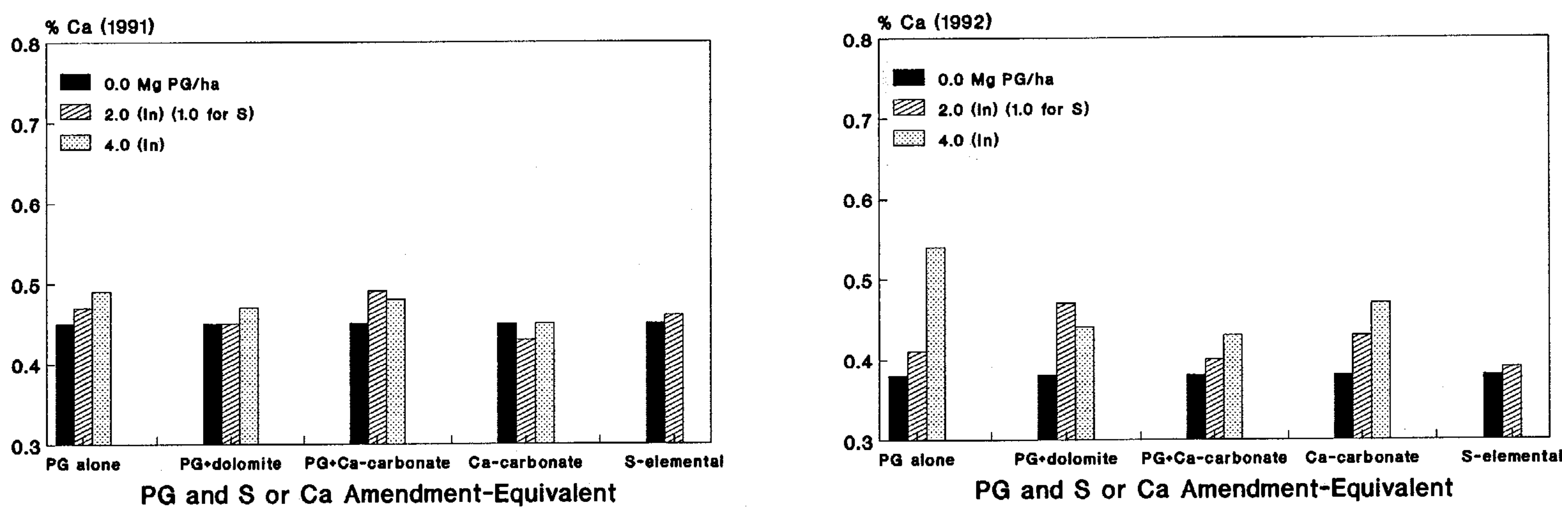


Figure 38B. Calcium concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

The average slopes for the treatments containing PG applied at annual rates (PG_{all} An) were 0.024, 0.021, and 0.022 in 1990, 1991, and 1992, respectively (Table 50).

Table 49. Group treatments and Ca concentrations in bahiagrass forage, averaged across annual and initial application rates, 1990-1992.

Group treatments[1]	Year		
	1990	1991	1992
	%Ca		
PG	0.55	0.45	0.43
PG+dolomite[2]	0.55	0.46	0.45
PG+$CaCO_3$[3]	0.53	0.47	0.43
PG_{all}[3]	0.54	0.46	0.44
S (elemental)	0.46	0.41	0.39
$CaCO_3$	0.49	0.44	0.45
Control	0.50	0.45	0.38

[1]See Table 51 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Only in 1992 was the slope for the annual rates of $CaCO_3$ significant increasing Ca content by 0.024% per Mg PG or unit equivalent rate ha^{-1}. This indicates that Ca from $CaCO_3$ took some time to become available for plant use.

The large initial rates of PG increased %Ca in bahiagrass forage by 0.026, 0.014, and 0.022% per Mg PG ha^{-1} in 1990, 1991, and 1992, respectively (Table 50). With the years, the slopes for PG+$CaCO_3$ decreased from 0.020 in 1990 to 0.015% in 1991, and to non-significance in 1992. The slopes for PG+dolomite also decreased from 0.026 in 1990 to 0.010 in 1991 and 0.014% in 1992. The slopes for PG_{all} initial decreased from 0.024 in 1990 to 0.013 and 0.014% in 1991 and 1992, respectively. All these indicate that large portions of Ca from PG applied in 1990 were being lost from the main root zone, or converted into less available forms, or both, as it was suggested with S in PG.

Again, only in 1992 did the initial rates of $CaCO_3$ increase the %Ca slope by 0.016%, once again indicating that more Ca from $CaCO_3$ was becoming more available with time.

Table 50. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on Ca concentrations in bahiagrass forage, 1990-1992.

Comparison	Year 1990[1]	1991	1992
Intercept	%Ca		
	0.476	0.416	0.384
	(P-value)[2]		
AR*GT	0.0001		
AR*GT*FREQUENCY[3]		0.0002	0.0129
Slope	$\%Ca/Mg\ PG\ ha^{-1}$		
A. Rates, Annual (An):			
PG An Slope	0.026***	0.008ns	0.022ns
S An Slope	-0.010ns	-0.010ns	0.007ns
$CaCO_3$ An Slope	0.006*	0.011ns	0.024**
PG+$CaCO_3$ An Slope	0.020***	0.025***	0.027**
PG+dolomite An Slope	0.026***	0.029***	0.027**
B. Rates, Initial (In):			
PG In Slope	0.026***	0.014***	0.022***
S In Slope	-0.010ns	0.015*	0.002ns
$CaCO_3$ In Slope	0.006*	0.005ns	0.016**
PG+$CaCO_3$ In Slope	0.020***	0.015***	0.007ns
PG+dolomite In Slope	0.026***	0.010**	0.014**
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	0.024***	0.021***	0.022**
PG_{all} Avg In Slope	0.024***	0.013***	0.014***

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), *P<0.10 (slightly significant), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

PG versus other amendments. The comparative statistics for PG_{all} vs $CaCO_3$ for %Ca in bahiagrass forage show significant P-values in 1990 and 1991, but not in 1992 (Table 51). Thus, the average slopes during the first two years for all the treatments containing PG were significantly higher than the slopes for $CaCO_3$. With increasing supply of Ca from $CaCO_3$ and the loss of some of Ca the from the one-time PG applications from the main root zones with time, the two slopes approached a similar value and lost any significant differences by 1992.

Table 51 also shows that the P-values for PG vs PG+$CaCO_3$ and PG vs PG+dolomite were not significant in all three years, although slight ($P<0.10$) differences were indicated in 1991. The negative sign after the P-values in 1991 indicated that the PG slope was slightly less than those of PG+$CaCO_3$ and PG+dolomite.

Table 51. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on Ca concentrations in bahiagrass forage, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
<u>Statistics:</u>	-------- (P-value)[2] --------------		
AR*GT	0.0001		
AR*GT*FREQUENCY		0.0002	0.0129
<u>PG vs other amendments:</u>[3]			
PG_{all} vs S	0.0001	0.0200	ns
PG_{all} vs $CaCO_3$	0.0001	0.0377	ns
PG vs PG+$CaCO_3$	ns	0.0624(-)	ns
PG vs PG+dolomite	ns	0.0838(-)	ns
<u>Annual vs initial rates:</u>[4]			
PG An vs In	-	0.0420(-)	0.0012(-)
S An vs In	-	0.0155(-)	ns
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	ns	ns
PG+dolomite An vs In	-	ns	ns
PG_{all} Avg An vs Avg In	-	ns	0.0387

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant ($P>0.05$), but $P<0.10$ referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

The P-values for PG_{all} vs S were significant for %Ca in bahiagrass forage in 1990 and 1991, elemental S not being a Ca source, but not in 1992 (Table 51). The non-significant difference in the slopes in 1992 could be due to the greater influence of the loss of Ca from the high initial rates of the various PG amendments applied in 1990 on the average (PG_{all}) slopes than that of the Ca from PG applied that year.

Annual versus initial rates. Table 51 shows significant P-values for PG annual versus initial rates in 1991 and 1992. The negative signs indicated that the annual rates slopes were significantly less than the initial rates slopes in both years. There were no differences between annual and initial rates for PG+dolomite or PG+$CaCO_3$. The significant P-value for PG_{all} annual versus PG_{all} initial in 1992 would indicate that, in general and for the long term, PG would be better applied to supply Ca to bahiagrass pastures at small rates annually than at high one-time rates applied at the beginning of a 3-year period.

Referring to Figures 38, 38A, and 38B and considering the results in Table 50 and the various comparisons, PG, as a source of Ca, needs to be applied at 1.0 Mg PG ha^{-1} annually.

Nitrogen content. The %N in bahiagrass averaged across annual and initial amendment rates are given in Table 52. Only in 1990 did the various PG amendments showed apparently higher %N than the control by 6 to 7% with 1.36% for the control and 1.45% N for PG_{all}. The trends in %N with the annual and the initial rates for the various amendments in 1990, 1991, and 1992 are graphically presented in Figures 39, 39A, and 39B. The trends in 1990 indicated some apparent positive effects of PG and elemental S on %N in bahiagrass forage.

Table 52. Group treatments and N concentrations in bahiagrass forage, averaged across annual and initial application rates, 1990-1992.

Group treatments[1]	Year		
	1990[1]	1991	1992
	------------- %N -----------------		
PG	1.44	1.46	1.43
PG+dolomite[2]	1.45	1.47	1.43
PG+$CaCO_3$[2]	1.46	1.47	1.43
PG_{all}[3]	1.45	1.47	1.43
S (elemental)	1.42	1.49	1.43
$CaCO_3$	1.44	1.46	1.38
Control	1.36	1.48	1.50

[1]The comparative statistics showed no significant P-values.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

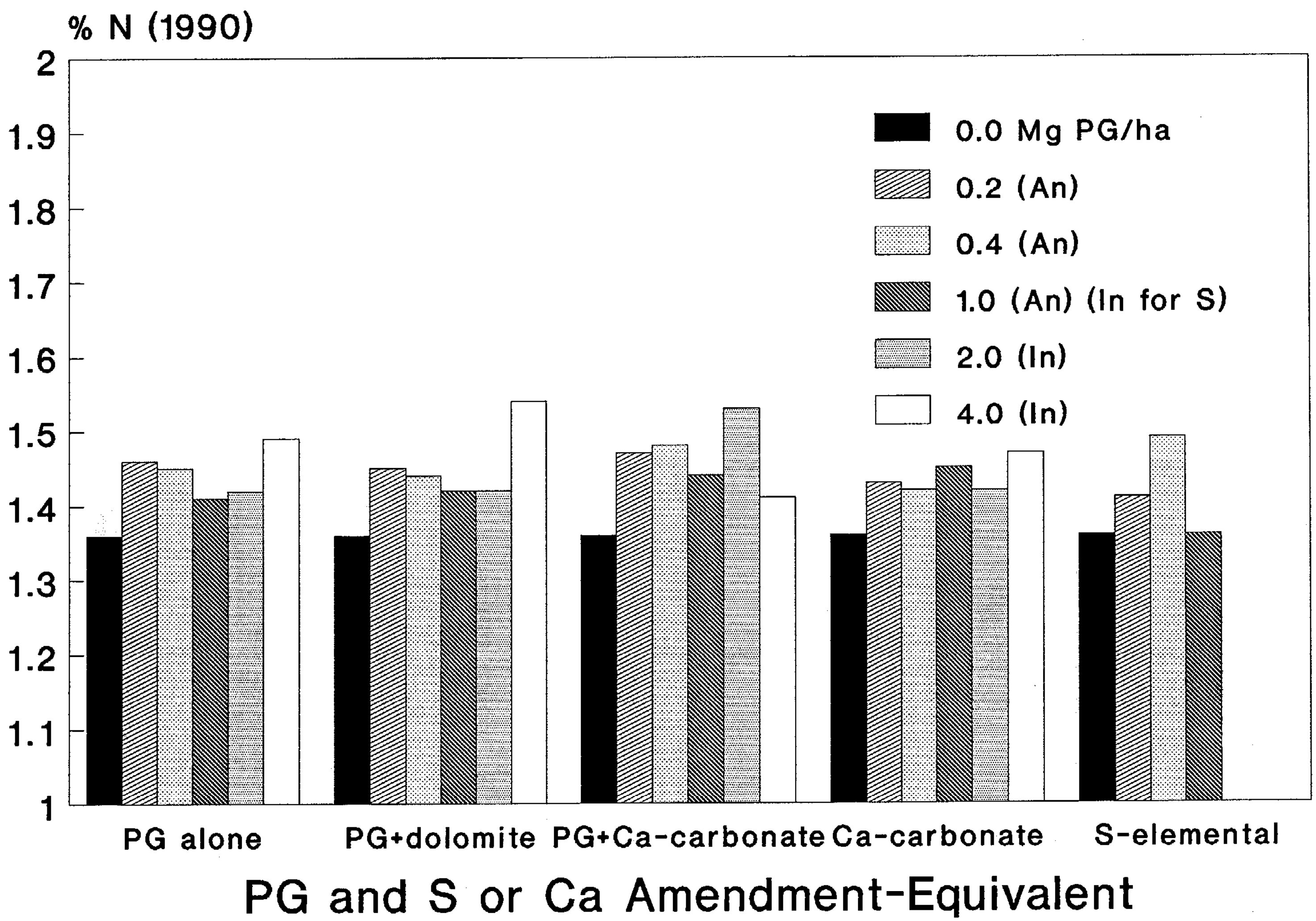


Figure 39. Nitrogen concentrations in bahiagrass regrowth forage, 1990, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial rates, 1990.

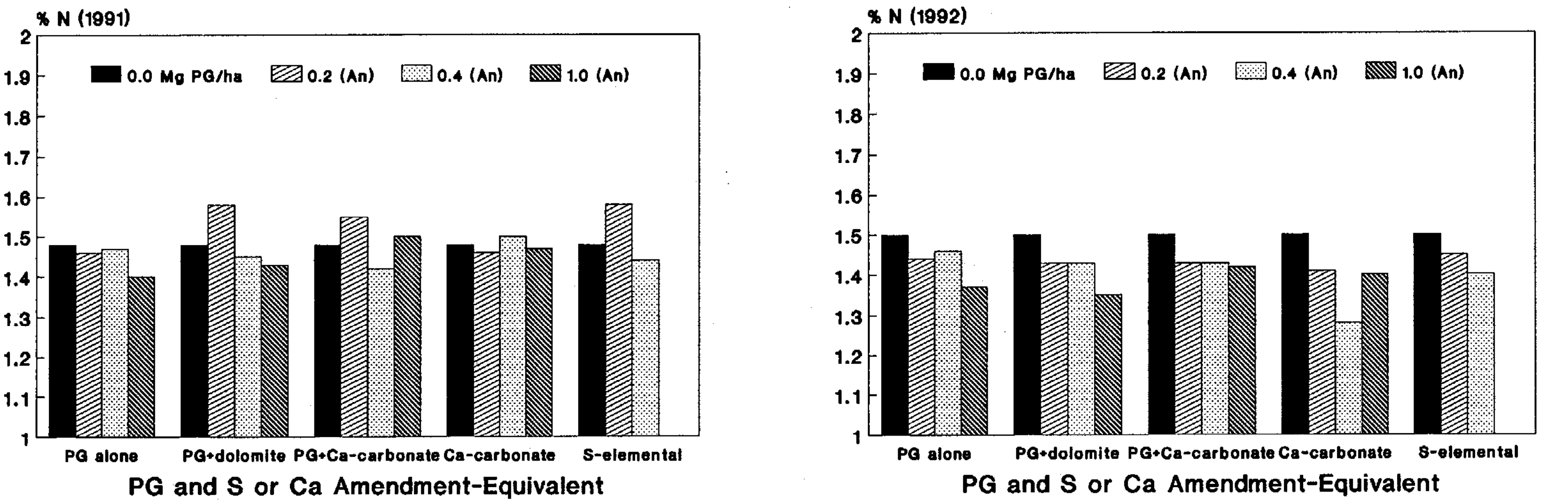


Figure 39A. Nitrogen concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

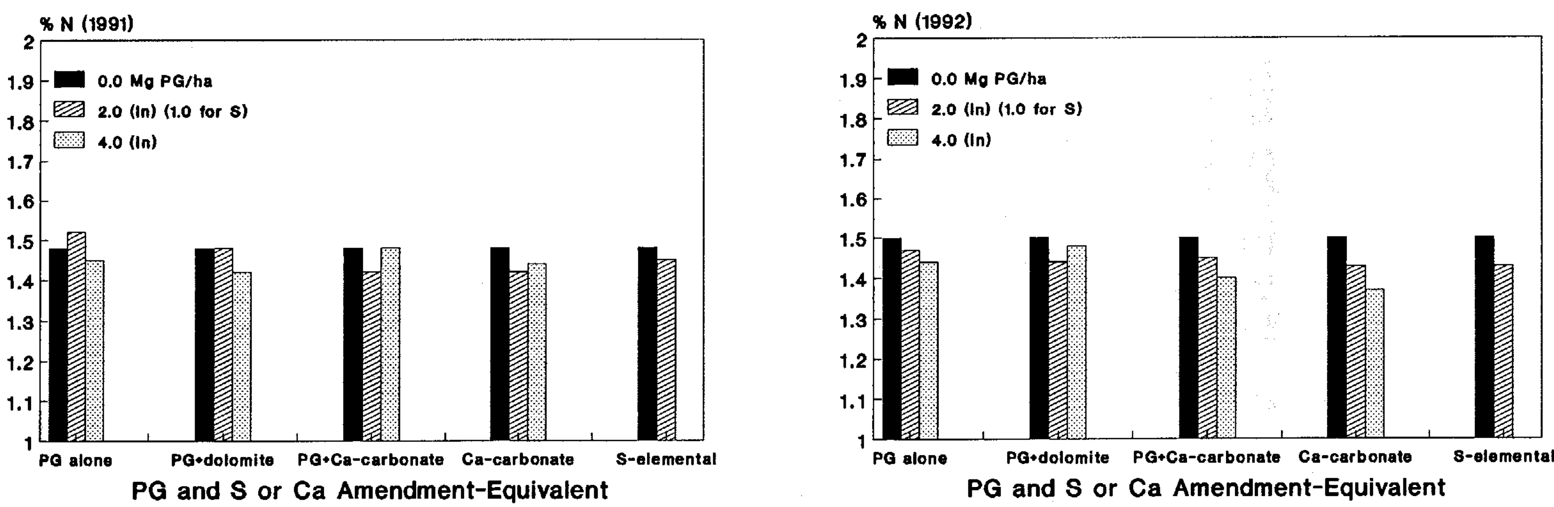


Figure 39B. Nitrogen concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

Effects of rates. The statistics showed that the %N slopes were not significant for any of the amendments at the annual or the initial rates in all three years.

PG versus other amendments. The comparative statistics also showed no significant differences between the various PG amendments and between PG_{all} and S or PG_{all} and $CaCO_3$ in all three years on %N.

Annual versus initial rates. Again, the statistics showed that the effects of annual or initial rates of the various amendments on %N in bahiagrass were not significantly different in all three years.

Phosphorus content. The %P in bahiagrass forage, averaged across annual and initial amendment rates, showed little variations within each year with the various treatments including the control (Table 53). The trends in %P with the annual and the initial rates for each of the amendments are shown in Figures 40, 40A, and 40B.

Table 53. Group treatments and P concentrations in bahiagrass forage, averaged across annual and initial application rates, 1990-1992.

Group treatments[1]	Year		
	1990	1991	1992
	%P		
PG	0.23	0.20	0.23
PG+dolomite[2]	0.21	0.19	0.23
PG+$CaCO_3$[3]	0.21	0.20	0.23
PG_{all}[3]	0.22	0.20	0.23
S (elemental)	0.22	0.20	0.23
$CaCO_3$	0.21	0.20	0.22
Control	0.22	0.20	0.23

[1]See Table 55 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. The %P slopes for PG were not significant in all three years at both the annual and the initial rates. Both PG+$CaCO_3$ and PG+dolomite decreased %P in bahiagrass forage by 0.003% per Mg PG ha^{-1} in 1990, but not thereafter. The various PG amendments (PG_{all} An and/or In), decreased %P by 0.002% per Mg PG ha^{-1} in 1990, but not in 1991 and 1992.

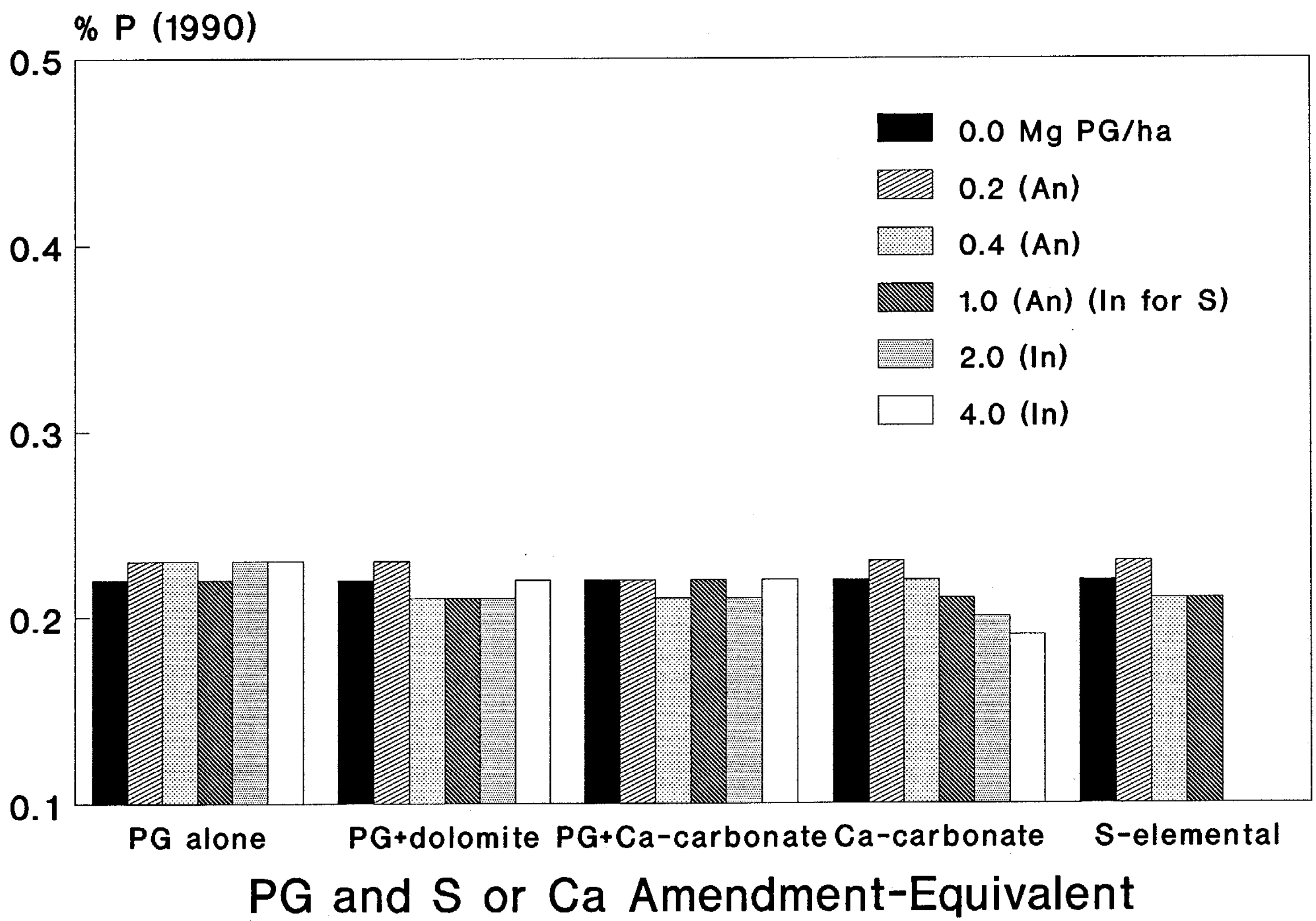


Figure 40. Phosphorus concentrations in bahiagrass regrowth forage, 1990. from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial (In) rates, 1990.

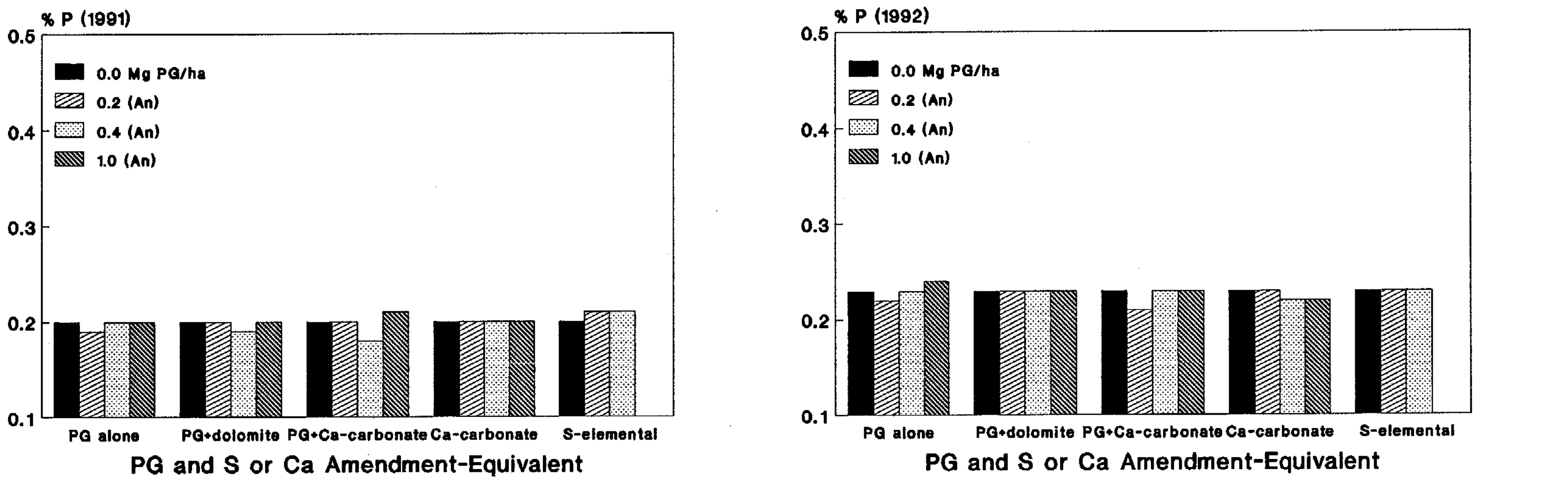


Figure 40A. Phosphorus concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

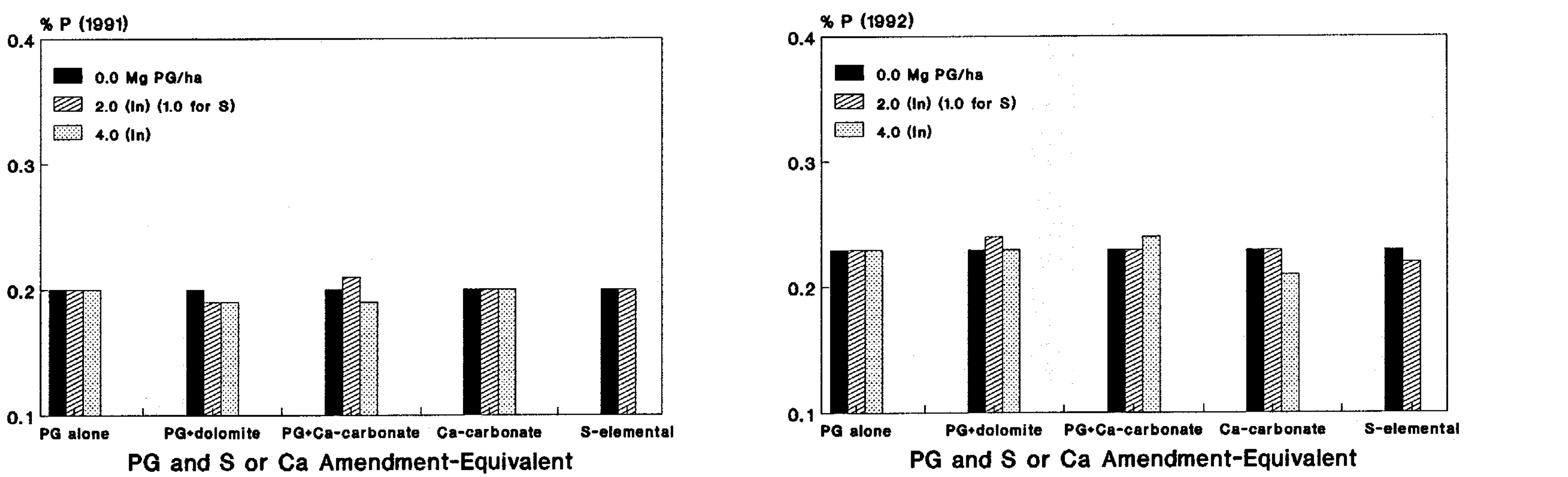


Figure 40B. Phosphorus concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

Treatment $CaCO_3$ also decreased %P in the forage by 0.006% per Mg PG or unit equivalent rate ha^{-1} in 1990, but not thereafter.

The %P slopes for elemental S were not significant in all three years.

Table 54. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on P concentrations in regrowth bahiagrass forage, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
Intercept	------------ %P ---------------		
	0.226	0.199	0.228
	----------- (P-value)[2] --------		
AR*GT	0.0001		
AR*GT*FREQUENCY[3]		ns	0.0568
Slope	------------ %P/Mg PG ha^{-1} ----		
A. Rates, Annual (An):			
PG An Slope	0.000ns	ns	ns
S An Slope	-0.003ns	ns	ns
$CaCO_3$ Slope	-0.006^{***}	ns	ns
PG+$CaCO_3$ An Slope	-0.003^{**}	ns	ns
PG+dolomite An Slope	-0.003^{**}	ns	ns
B. Rates, Initial (In):			
PG In Slope	0.000ns	ns	ns
S In Slope	-0.003ns	ns	ns
$CaCO_3$ In Slope	-0.006^{***}	ns	ns
PG+$CaCO_3$ In Slope	-0.003^{**}	ns	ns
PG+dolomite In Slope	-0.003^{**}	ns	ns
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	-0.002^{**}	ns	ns
PG_{all} Avg In Slope	-0.002^{**}	ns	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), $^{*}P<0.10$ (slightly significant), $^{**}P\leq0.05$, $^{***}P\leq0.01$.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

PG versus other amendments. The P-values for PG_{all} vs $CaCO_3$ were significant in 1990 and 1992. Also in 1990, the P-value for PG vs PG+dolomite was significant while that for PG vs PG+$CaCO_3$ was slightly significant. The P-values for PG_{all} vs S were not significant in all three years.

Table 55. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on P concentrations in bahiagrass forage, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
<u>Statistics:</u>	(P-value)[2]		
AR*GT	0.0001		
AR*GT*FREQUENCY		ns	0.0568
<u>PG vs other amendments:</u>[3]			
PG_{all} vs S	ns	ns	ns
PG_{all} vs $CaCO_3$	0.0002	ns	0.0010
PG vs PG+$CaCO_3$	0.0624	ns	ns
PG vs PG+dolomite	0.0286	ns	ns
<u>Annual vs initial rates:</u>[4]			
PG An vs In	-	ns	ns
S An vs In	-	ns	ns
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	ns	ns
PG+dolomite An vs In	-	ns	ns
PG_{all} Avg An vs Avg In	-	ns	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

The overall implication from the statistics was that CaCO, at the rates used had an adverse effected on %P in bahiagrass when compared to the average effect of the limed and the unlimed PG amendments. Adding $CaCO_3$ to PG also caused a slightly significant adverse effect on %P in bahiagrass when compared to the effect of the unlimed PG. Dolomite added to PG also adversely affected %P in bahiagrass when compared to the effect of PG alone. This adverse effect of the lime materials on P content in bahiagrass could be attributed to possible reductions in the availability of fertilizer or soil PO_4-P due to direct or indirect effects of $CaCO_3$ or dolomite.

The effects of the various PG amendments, averaged across all rates and over all treatments containing PG (PG_{all}) were not different from those of elemental S in all three years.

Annual versus initial rates. Table 55 shows that the effects of the annual and the initial rates of the various amendments on %P in bahiagrass were not significantly different in 1991 and 1992.

Potassium content. The %K, averaged across annual and initial rates, in bahiagrass forage are given in Table 56. The trends in %K with the annual and the initial rates are shown in Figures 41, 41A, and 41B.

Table 56. Group treatments and K concentrations in bahiagrass forage, averaged across annual and initial application rates, 1990-1992.

Group treatments[1]	Year		
	1990[1]	1991	1992
	%K		
PG	0.99	0.60	0.73
PG+dolomite[2]	0.97	0.62	0.71
$PG+CaCO_3$[3]	0.99	0.63	0.72
PG_{all}[3]	0.98	0.62	0.72
S (elemental)	0.83	0.56	0.68
$CaCO_3$	0.87	0.57	0.66
Control	0.92	0.61	0.67

[1]See Table 58 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. The annual rates of PG increased %K in bahiagrass forage by 0.030 and 0.040% per Mg PG ha^{-1} in 1990 and 1992, respectively, but not in 1991. The annual rates of $PG+CaCO_3$ increased %K in forage in 1990 and 1992 by 0.029 and 0.035% per Mg PG ha^{-1}, respectively. The annual rates of PG+dolomite showed significant to slightly significant increases in %K in all three years. The annual rates of the various PG amendments (PG_{all} An) increased %K in bahiagrass forage by 0.030, 0.017, and 0.035% per Mg PG ha^{-1} in 1990, 1991, and 1992, respectively (Table 57).

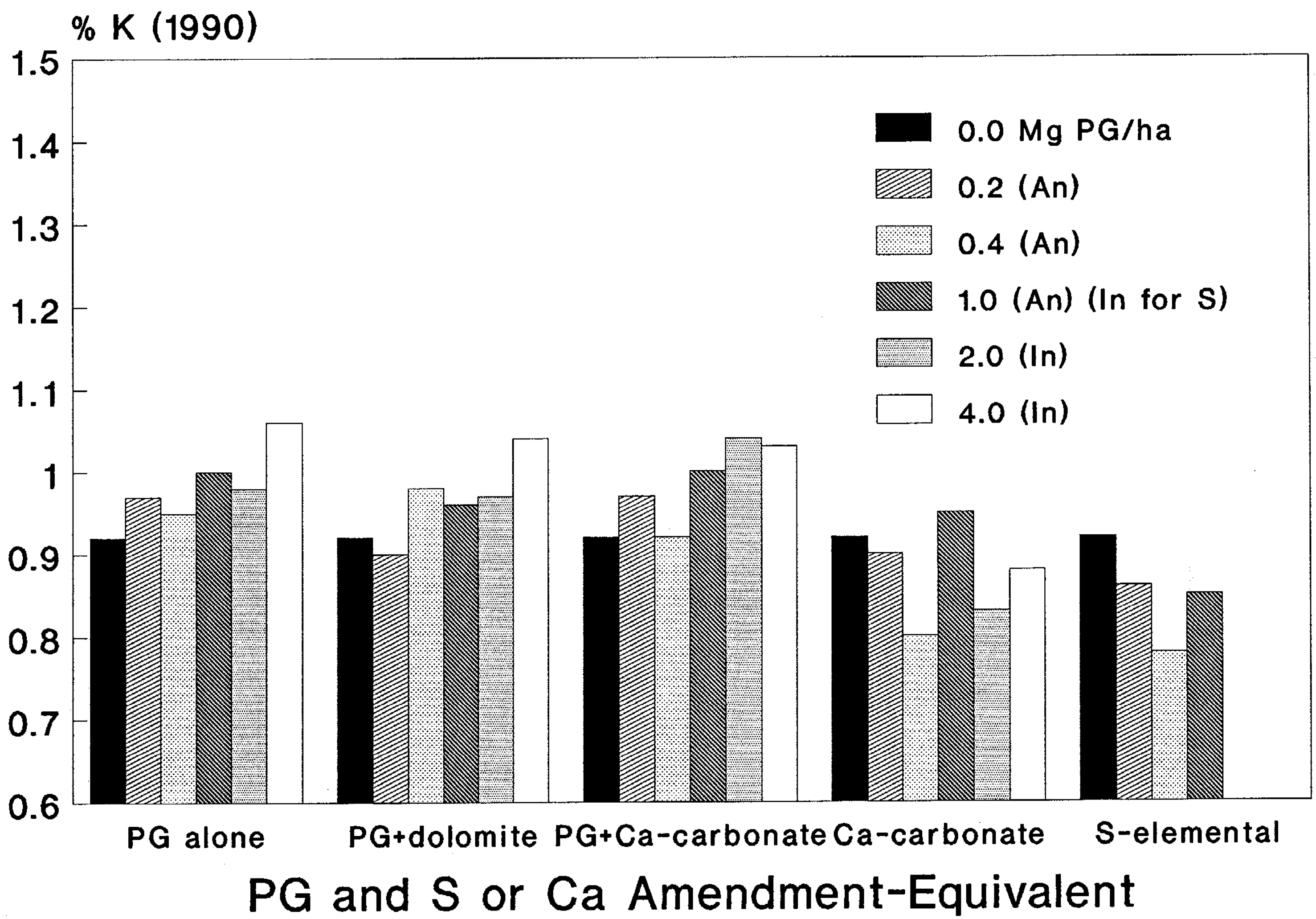


Figure 41. Potassium concentrations in bahiagrass regrowth forage, 1990, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial (In) rates, 1990.

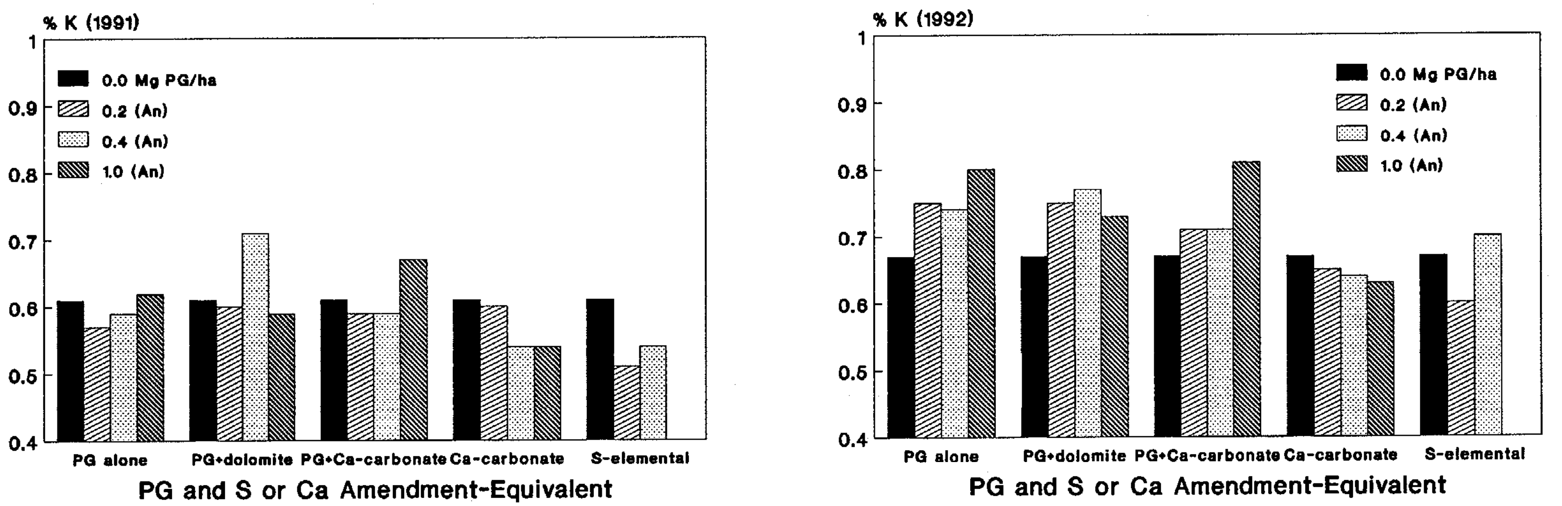


Figure 41A. Potassium concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

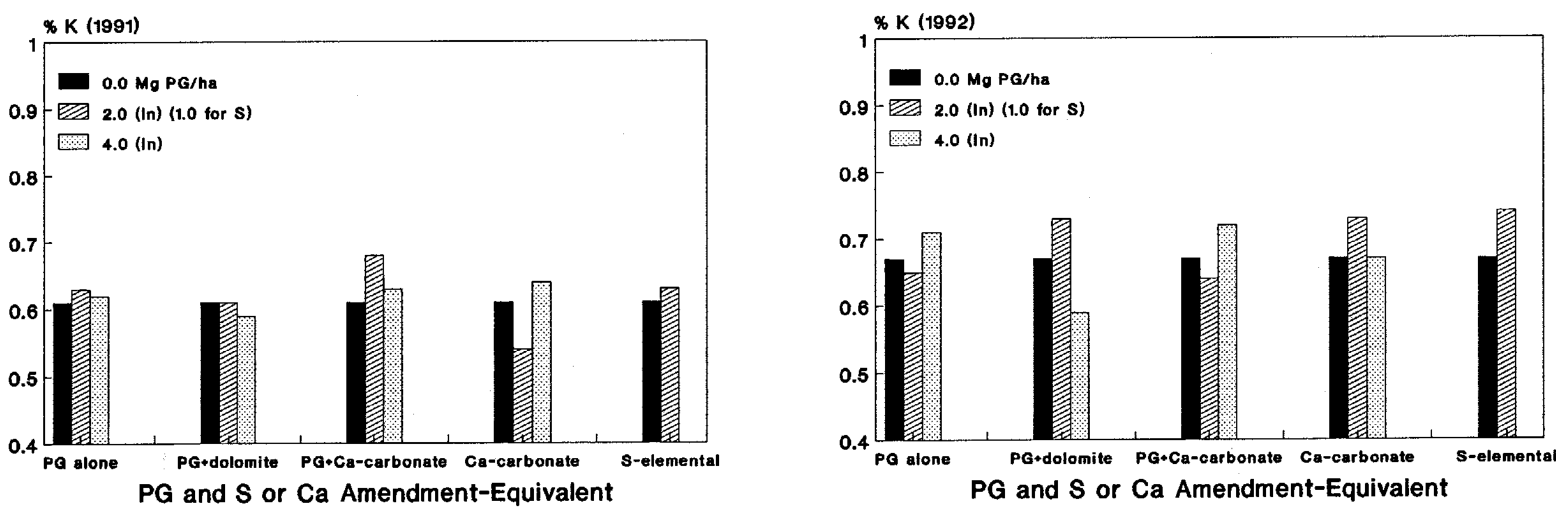


Figure 41B. Potassium concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

The significant 1990 slopes showed that the high initial rates of the various PG amendments also had positive effects on %K in bahiagrass forage. In 1991, only the slope of PG+$CaCO_3$ was significant. There were no significant %K slopes in 1992 for the various PG amendments applied at the initial rates in 1990 (Table 57).

Table 57. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on K concentrations in regrowth bahiagrass forage, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
Intercept	------------ %K	---------------	
	0.899	0.587	0.679
	----------- (P-value)[2]	--------	
AR*GT	0.0001		
AR*GT*FREQUENCY[3]		0.0062	0.0076
Slope	------------ %K/Mg PG ha^{-1}	----	
A. Rates, Annual (An):			
PG An Slope	0.030***	0.006ns	0.040**
S An Slope	-0.030**	-0.033*	-0.008ns
$CaCO_3$ An Slope	-0.007ns	-0.016ns	-0.017ns
PG+$CaCO_3$ An Slope	0.029***	-0.019ns	0.035**
PG+dolomite An Slope	0.027***	0.025*	0.030*
B. Rates, Initial (In):			
PG In Slope	0.030***	0.007ns	0.000ns
S In Slope	-0.030**	0.014ns	0.022ns
$CaCO_3$ In Slope	-0.007ns	0.002ns	0.004ns
PG+$CaCO_3$ In Slope	0.029***	0.014**	0.002ns
PG+dolomite In Slope	0.027***	0.002ns	-0.007ns
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	0.030***	0.017*	0.035***
PG_{all} Avg In Slope	0.030***	0.008ns	-0.002ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), *P<0.10 (slightly significant), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

The positive effects of PG on K content in bahiagrass were also noted in the environmental experiment (PART ONE).

The annual rates of $CaCO_3$ tended to reduce %K in bahiagrass in all three years, but the slopes did not attain any level of significance. The initial rates of $CaCO_3$ had no effect on K content in bahiagrass in 1991 and 1992 (Table 57).

It is interesting to note that elemental S, using all the rates in computing the slope in 1990, reduced %K in bahiagrass forage by 0.030% per Mg PG or unit equivalent rate ha^{-1}. The annual rates also slightly significantly decreased %K by 0.033% per Mg PG ha^{-1} in 1991. The high elemental S rate applied in 1990 showed no effect, adverse or otherwise, on %K in 1991 and 1992. Thus, it is reasonable to conclude that the adverse effect on %K in 1990 may have been due to the high rate of elemental S applied that year (165 kg S ha^{-1}). As the high concentration of elemental S around the root system decreased with time, its adverse effects on the root system, hence on K uptake, were also reduced and became insignificant by 1991 and 1992.

PG versus other amendments. The P-values for PG_{all} vs S were significant in 1990 and 1991 but not in 1992 (Table 58), indicating significant differences in the %K slopes in 1990 and 1991. The differences can be attributed primarily to the adverse effects of the high initial rates of elemental S on the root system of bahiagrass as suggested earlier. The non-significant difference in the slopes in 1992 had also been explained. With K content in forage as a variable, the comparison showed once again that PG is a better S amendment to use on bahiagrass pastures than elemental S.

The analysis for PG_{all} vs $CaCO_3$ showed significant P-values in 1990, 1991, and 1992, indicating that the %K slopes for the PG amendments, averaged over all treatments containing PG and across all rates, were significantly greater than the %K slopes for $CaCO_3$, also averaged across all the corresponding rates (Table 57). The differences in the slopes can be attributed to the positive effects of the PG amendments on K uptake by bahiagrass. The comparison points to the superiority of PG over $CaCO_3$ as a source of Ca for bahiagrass pastures with K content in forage as a test variable.

The comparison PG vs PG+$CaCO_3$ or PG vs PG+dolomite showed no significant P-values in all three years.

Annual versus initial rates. There were no differences between the effects of the annual and the initial rates for PG, PG+$CaCO_3$, and $CaCO_3$ in 1991 and 1992 on K contents of bahiagrass. For PG+dolomite, the annual rates gave greater %K slope than the initial rates in 1992. Treatment PG_{all} annual also gave significantly greater %K slope than PG_{all} initial in 1992. The results indicate that small rates of PG applied annually should be preferred over the large rates applied once in three years.

The P-value for elemental S in 1991, which was significant and with a negative sign, indicated that the second annual rates application in 1991 had greater adverse effects on K uptake by bahiagrass than the second year effect of the initial rate applied in 1990.

Table 58. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on K concentrations in bahiagrass forage, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
<u>Statistics:</u>	(P-value)[2]		
AR*GT	0.0001		
AR*GT*FREQUENCY		0.0062	0.0076
<u>PG vs other amendments:</u>[3]			
PG_{all} vs S	0.0001	0.0385	ns
PG_{all} vs $CaCO_3$	0.0001	0.0019	0.0042
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	ns
<u>Annual vs initial rates:</u>[4]			
PG An vs In	-	ns	ns
S An vs In	-	0.0287(-)	ns
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	ns	ns
PG+dolomite An vs In	-	ns	0.0473
PG_{all} Avg An vs Avg In	-	ns	0.0097

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05).
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

<u>**Magnesium content.**</u> The %Mg in bahiagrass, averaged across the annual and the initial rates of the amendments, showed little variations within years (Table 58). Figures 42, 42A, and 42B show the trends in %Mg with the annual and the initial rates.

Effects of rates. The effects of the rates of the various amendments on %Mg in bahiagrass forage were noted only in the first year (Table 60). Treatments PG, PG+$CaCO_3$, and PG+dolomite, with the %Mg slopes computed using all rates, decreased %Mg in bahiagrass forage by 0.005%, 0.007, and 0.008% per Mg PG ha^{-1} in 1990, respectively. Treatment $CaCO_3$ also showed negative slopes which, however, did not attain a level of significance.

Table 59. Group treatments and Mg concentrations in bahiagrass forage, averaged across annual and initial application rates, 1990-1992.

Group treatments[1]	Year		
	1990[1]	1991	1992
	%Mg		
PG	0.32	0.26	0.26
PG+dolomite[2]	0.31	0.25	0.26
PG+$CaCO_3$[3]	0.31	0.26	0.25
PG_{all}[3]	0.31	0.26	0.26
S (elemental)	0.34	0.27	0.27
$CaCO_3$	0.32	0.26	0.26
Control	0.32	0.27	0.28

[1]See Table 61 for the comparative statistics.
[2]% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

The average effect of the various PG amendments (PG_{all}), reduced %Mg in bahiagrass by 0.007% per Mg PG ha^{-1} in 1990. The effects of the various amendments at the annual or the initial rates in 1991 and 1992 were not significant (Table 60). Figures 42A and 42B, however, show very apparent negative effects of the 4.0 Mg PG amendments ha_{-1} applied in 1990 on %Mg in the 1991 and the 1992 harvests.

The slope for elemental S, although positive, was not significant (Table 60).

PG versus other amendments. Table 61 shows a significant P-value for PG_{all} vs S in 1990 but not in 1991 and 1992. The negative sign indicated that the average %Mg slope for PG_{all} was significantly less {negative as Table 60 shows) than the slope for elemental S. The slightly significant P-value with the negative sign for PG_{all} vs $CaCO_3$ in 1990 indicated that the average %Mg slope for PG_{all} was slightly more negative than that of $CaCO_3$.

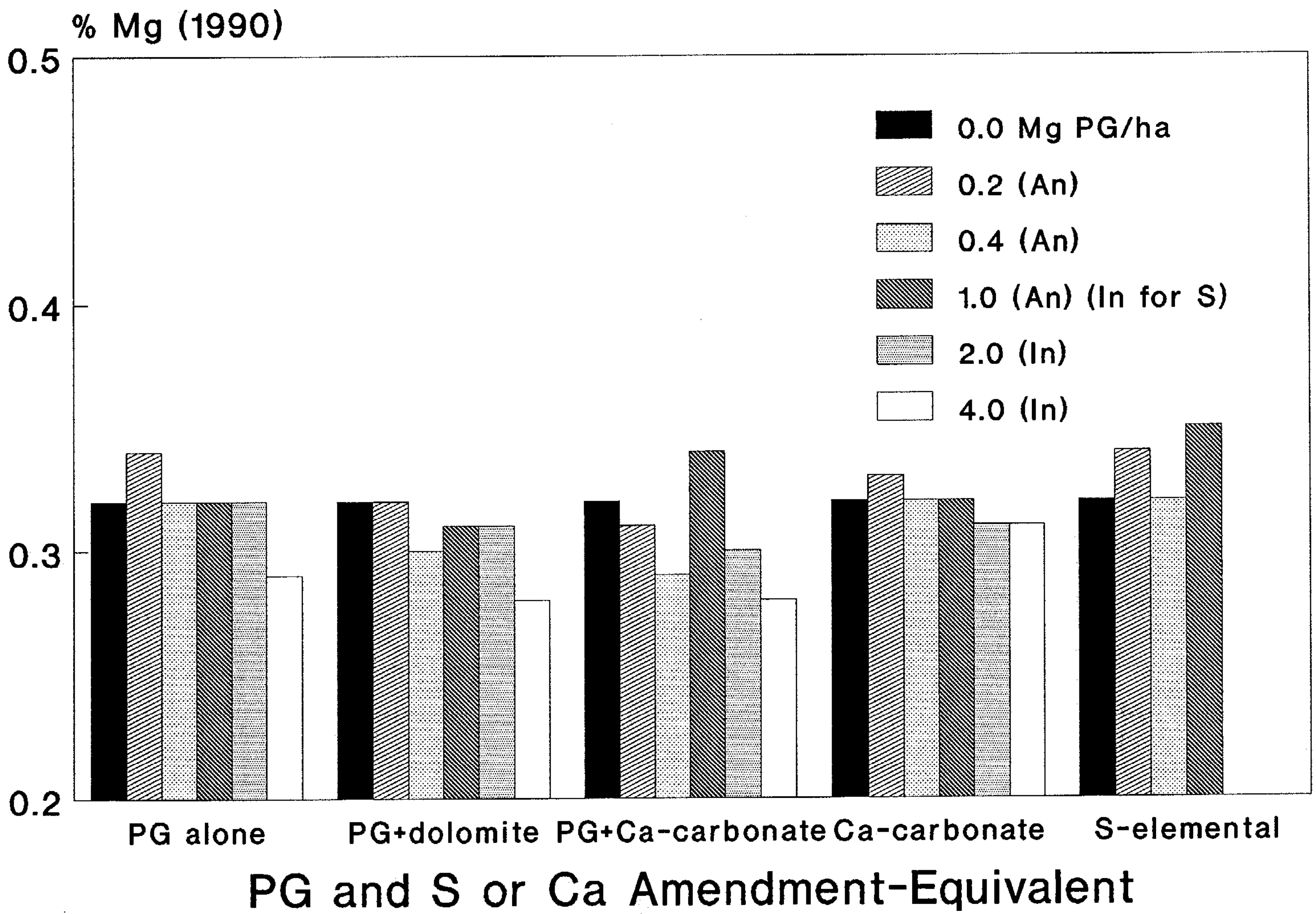


Figure 42. Magnesium concentrations in bahiagrass regrowth forage, 1990, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial (In) rates, 1990.

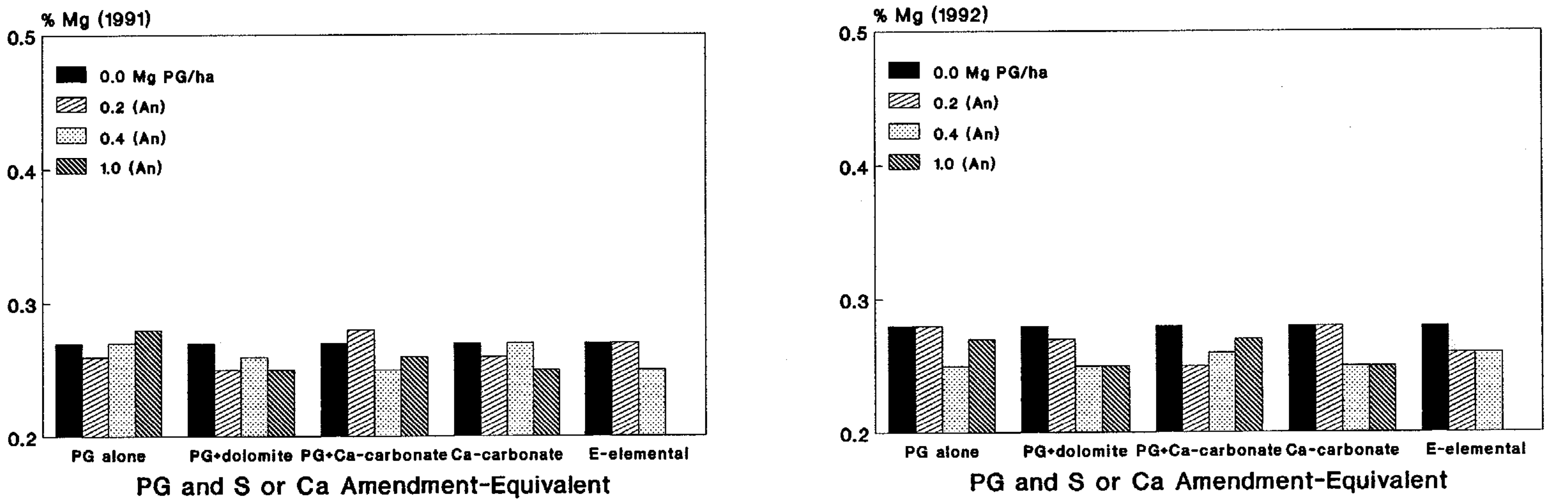


Figure 42A. Magnesium concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the annual rates, 1990-1992.

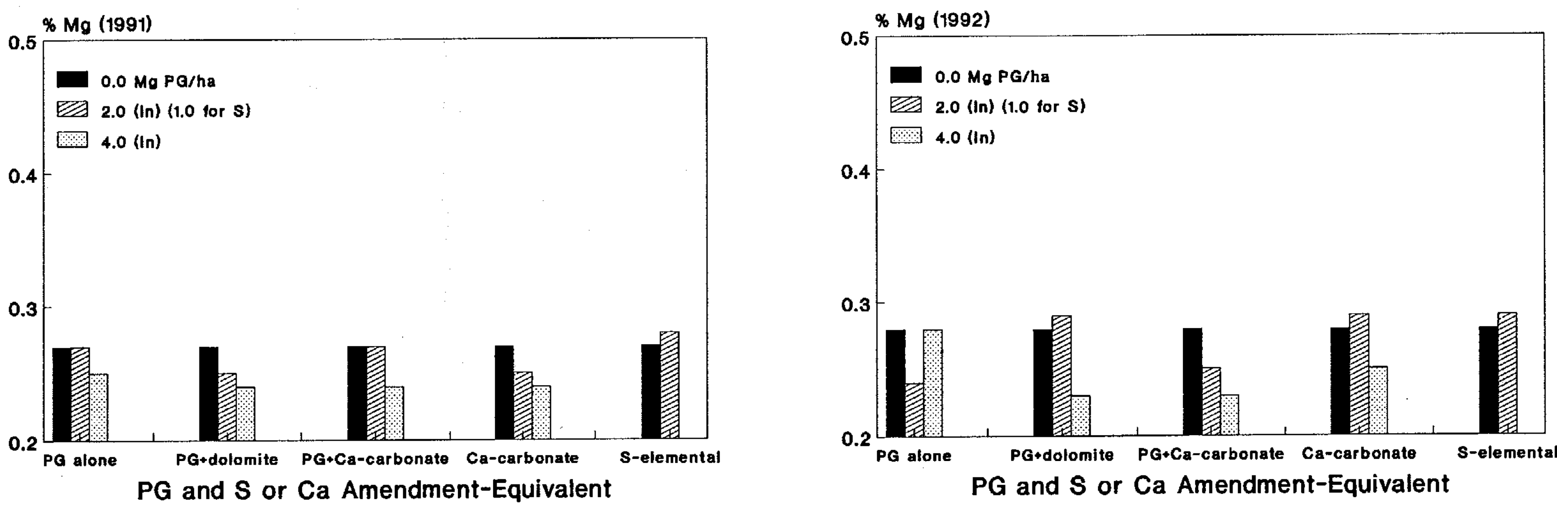


Figure 42B. Magnesium concentrations in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

The P-values for PG vs PG+$CaCO_3$ and PG vs PG+dolomite were not significant in all three years indicating similar effects on %Mg in bahiagrass for the various PG amendments (Table 61).

Table 60. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on Mg concentrations in regrowth bahiagrass forage, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
Intercept	------------ %Mg --------------		
	0.329	0.273	0.276
	----------- (P-value)[2] --------		
AR*GT	0.0003		
AR*GT*FREQUENCY[3]		ns	ns
Slope	----------- %Mg/Mg PG ha^{-1} ----		
A. Rates, Annual (An):			
PG An Slope	-0.005**	ns	ns
S An Slope	0.004ns	ns	ns
$CaCO_3$ An Slope	-0.003ns	ns	ns
PG+$CaCO_3$ An Slope	-0.007***	ns	ns
PG+dolomite An Slope	-0.008***	ns	ns
B. Rates, Initial (In):			
PG In Slope	-0.005***	ns	ns
S In Slope	0.004ns	ns	ns
$CaCO_3$ In Slope	-0.003ns	ns	ns
PG+$CaCO_3$ In Slope	-0.007***	ns	ns
PG+dolomite In Slope	-0.008***	ns	ns
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	-0.007***	ns	ns
PG_{all} Avg In Slope	-0.007***	ns	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

Annual versus initial rates. The effects of the annual and the initial rates of the various amendments on %Mg in bahiagrass forage were not different in 1991 and 1992 (Table 61).

Table 61. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on Mg concentrations in bahiagrass forage, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
<u>Statistics:</u>	-------- (P-value)[2]	-------------	
AR*GT	0.0003		
AR*GT*FREQUENCY		ns	ns
<u>PG vs other amendments:</u>[3]			
PG_{all} vs S	0.0044(-)	ns	ns
PG_{all} vs $CaCO_3$	0.0759(-)	ns	ns
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	ns
<u>Annual vs initial rates:</u>[4]			
PG An vs In	-	ns	ns
S An vs In	-	ns	ns
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	ns	ns
PG+dolomite An vs In	-	ns	ns
PG_{all} Avg An vs Avg In	-	ns	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

<u>**N:S ratio.**</u> Table 62 shows the N:S ratios in bahiagrass, averaged across the annual and the initial rates, with the various group treatments. The N:S ratios for the annual and the initial rates are given in Figures 43, 43A, and 43B.

The N:S ratios were much lower than the ideal range of 12:1 to 15:1 for cattle, primarily due to the low N contents despite N fertilization and the increased S contents in the case of the PG- and the S-fertilized forages. However, the N:S ratios of the PG- and the S-amended forages at the annual application rates were much higher than the pre-treatment pre-N fertilization N:S ratio of 4:1 (Table 3 and Figures 43 and 43A).

<u>**Effects of rates.**</u> Table 63 shows the N:S slopes for the various amendments for both the annual and the initial rates.

The PG annual rates reduced the N:S ratios by 0.574, 0.901, and 0.789 unit per Mg PG ha^{-1} in the 1990, 1991, and 1992, respectively. The annual rates of PG+$CaCO_3$ and PG+dolomite also reduced the N:S ratios in forages in all three years, and by a greater degree than did PG in 1992. The PG initial rates reduced the N:S ratios by 0.074, 0.534, and 0.340 unit per Mg PG ha^{-1} in 1990, 1991, and 1992, respectively. As it was with PG, the N:S slopes for PG+$CaCO_3$ and PG+dolomite one-time rates decreased with the years (Table 63).

Table 62. Group treatments and N:S ratios in bahiagrass forage, averaged across annual and initial application rates, 1990-1992.

Group treatments[1]	Year		
	1990[1]	1991	1992
	N:S		
PG	4.80	4.71	4.21
PG+dolomite[2]	4.53	4.71	4.46
PG+$CaCO_3$[3]	4.87	4.59	4.09
PG_{all}[3]	4.73	4.67	4.25
S (elemental)	5.46	5.13	4.93
$CaCO_3$	6.55	6.35	4.93
Control	6.18	8.22	7.89

[1]See Table 64 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

The average effect of the PG treatments applied at the annual rates (PG_{all} An) reduced the N:S ratios in forage by 0.580, 0.821, and 1.054 unit per Mg PG ha^{-1} in 1990, 1991 and 1992, respectively. The average effect of the PG treatments applied at the initial rates (PG_{all} In) reduced the N:S ratios in forage by 0.580, 0.582, and 0.287 in 1990, 1991, and 1992 harvests, respectively (Table 63).

Elemental S at the annual rates reduced the N:S ratios in regrowth in 1991 by 0.797 unit per Mg PG or unit equivalent rate ha^{-1} but not in 1992. When applied at the initial rate, elemental S reduced N:S ratios by 0.724 and 0.950 unit per Mg PG ha^{-1} in 1991 and 1992, respectively (Table 62). The non-significant effect of elemental S on N:S ratios in 1990 indicated that the elemental S had not been transformed into plant usable SO_4-S at sufficient amount to give a significant N:S slope.

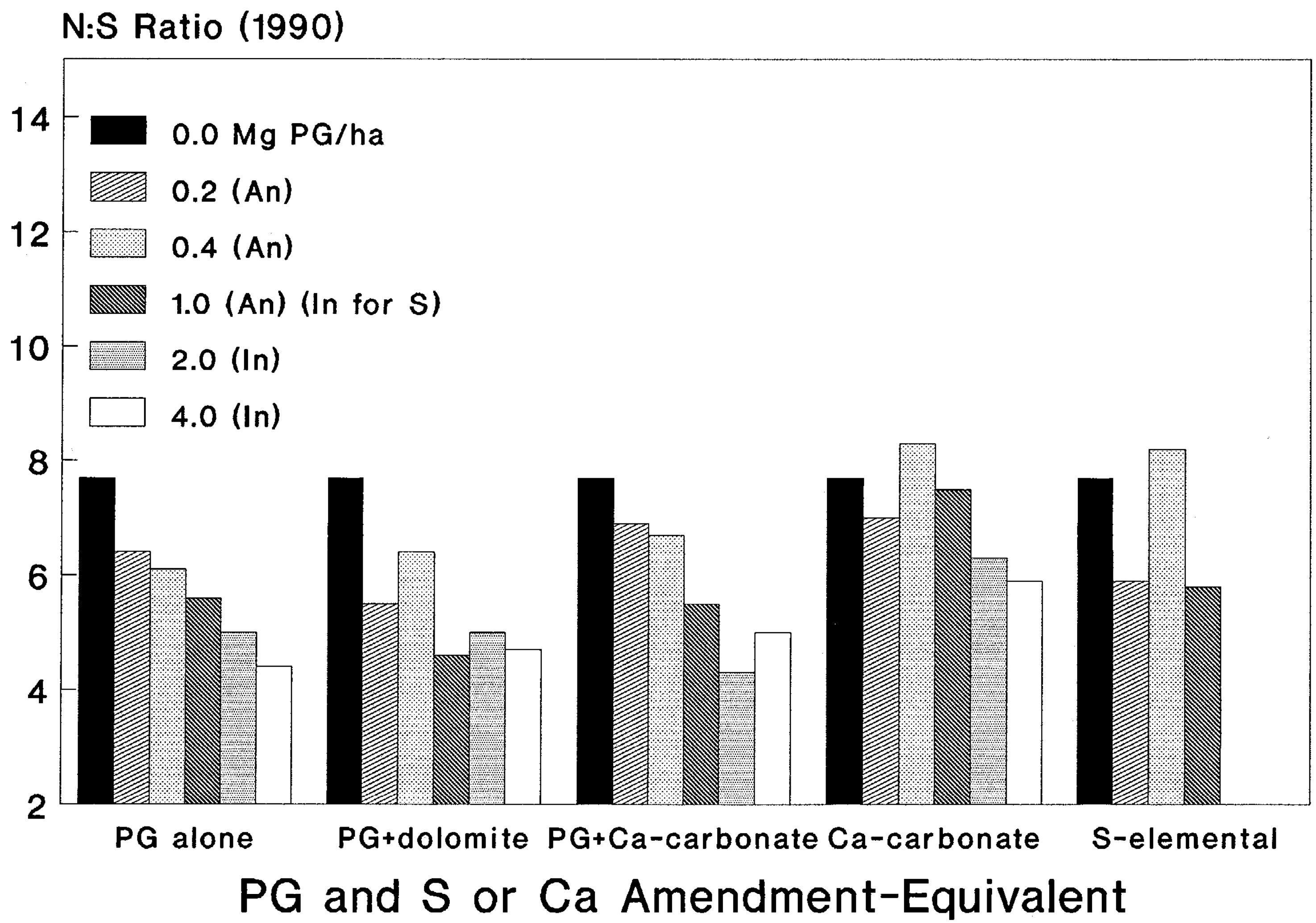


Figure 43. N:S ratios in bahiagrass regrowth forage, 1990, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial (In) rates, 1990.

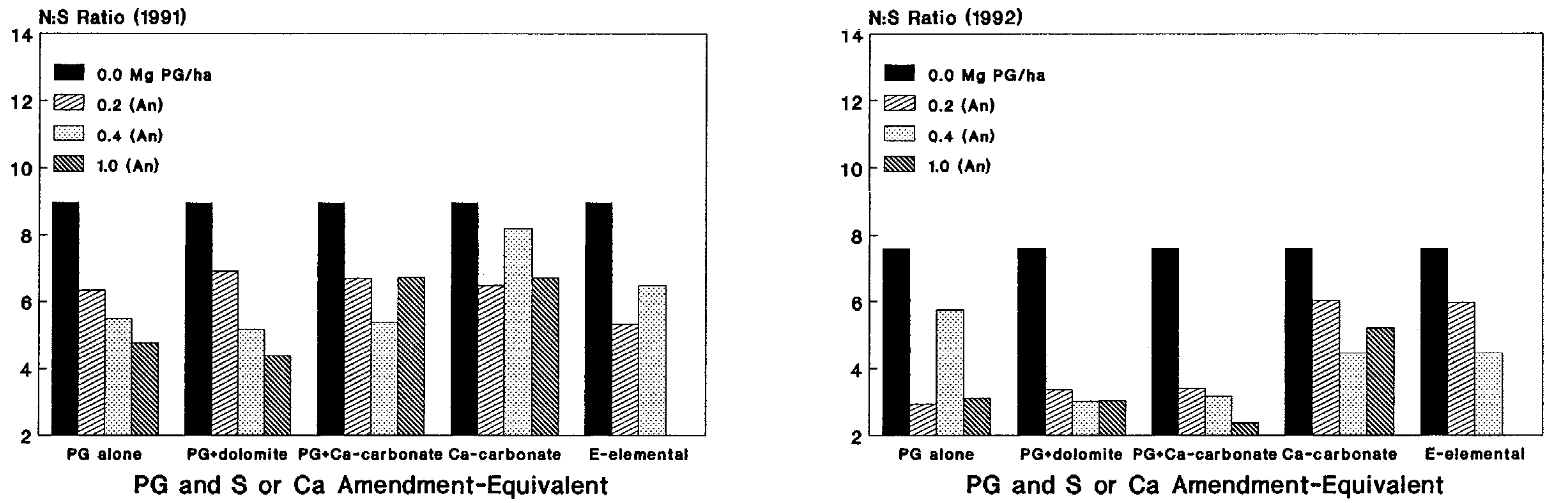


Figure 43A. N:S ratios in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

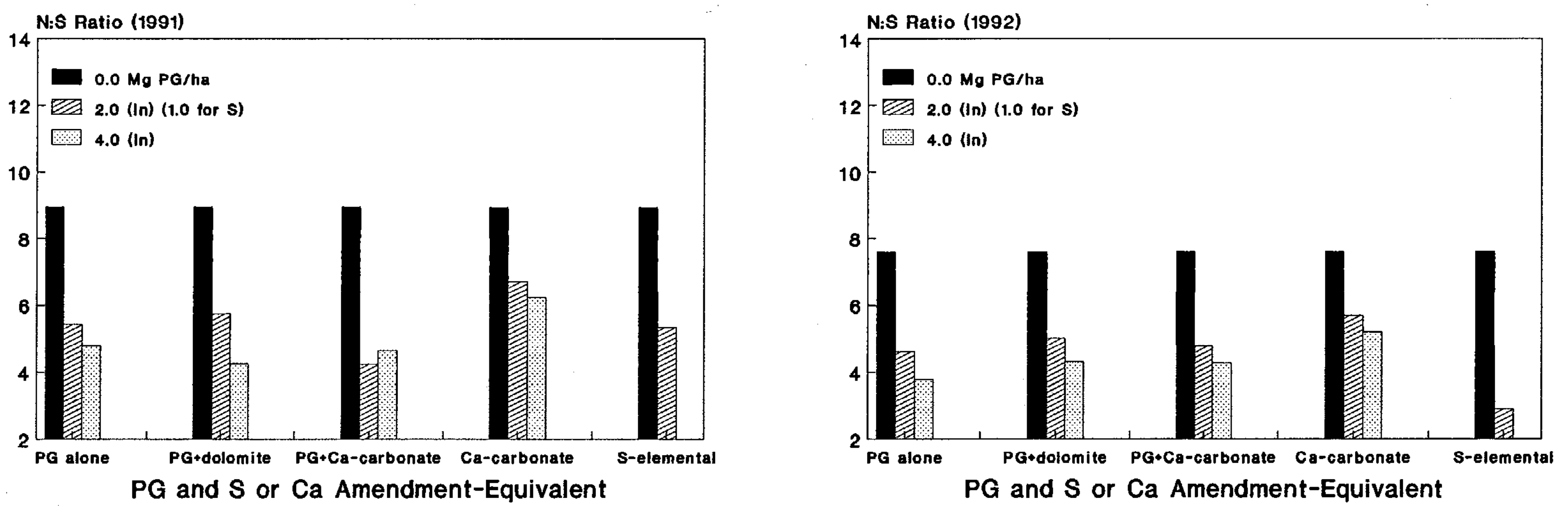


Figure 43B. N:S ratios in bahiagrass regrowth forage, 1991 and 1992, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

Calcium carbonate, which does not supply S, showed no significant effect on N:S ratios (Table 63).

Table 63. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on N:S ratios in bahiagrass forage, 1990[1]-1992.

Comparison		Year	
	1990[1]	1991	1992
Intercept	------------	N:S	--------------
	7.307	7.522	6.688
	-----------	(P-value)[2]	--------
AR*GT	0.0001		
AR*GT*FREQUENCY[3]		0.0001	0.0001
Slope	------------	N:S/Mg PG ha^{-1}	---
A. Rates, Annual (An):			
PG An Slope	-0.574***	-0.901***	-0.789***
S An Slope	-0.319ns	-0.797**	-0.501ns
$CaCO_3$ An Slope	0.041ns	-0.069ns	-0.220ns
PG+$CaCO_3$ An Slope	-0.554***	-0.529**	-1.229***
PG+dolomite An Slope	-0.613***	-1.034***	-1.144***
B. Rates, Initial (In):			
PG In Slope	-0.574***	-0.534***	-0.340**
S In Slope	-0.319ns	-0.724***	-0.950***
$CaCO_3$ In Slope	0.041ns	-0.265ns	-0.082ns
PG+$CaCO_3$ In Slope	-0.554***	-0.661***	-0.274**
PG+dolomite In Slope	-0.613***	-0.552***	-0.246*
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	-0.580***	-0.821***	-1.054***
PG_{all} Avg In Slope	-0.580***	-0.582***	-0.287***

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), *P<0.10 (slightly significant), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

PG versus other amendments. The comparative statistics show that the N:S slopes for the various PG amendments were not different from one another in all years (Table 64). The non-significant P-values for PG_{all} vs S showed that the PG amendments and the elemental S were equally effective in reducing N:S ratios in bahiagrass forage. The analysis for PG_{all} vs $CaCO_3$ showed that the N:S slopes for PG_{all} in all three years were different from those of $CaCO_3$, the latter not being a source of S.

Annual versus initial rates. The N:S slopes for the annual and the initial rates of PG, PG+dolomite, and $CaCO_3$ were not different in all three years (Table 64). In 1991, the P-values for PG+$CaCO_3$ and PG_{all} were significant. Hence, the annual rates, based on the actual rates that had been applied by 1991, were less effective in reducing the N:S ratios than the initial rates. The annual rates of elemental S were also much less effective in reducing the N:S ratio in bahiagrass forage in 1992 (Table 64). The annual slopes used in these comparisons were 1/2 and 1/3 the actual slopes in Table 63 for 1991 and 1992, respectively.

Table 64. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on N:S ratio in bahiagrass forage, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
Statistics:	-------- (P-value)[2]	--------------	
AR*GT	0.0001		
AR*GT*FREQUENCY		0.0001	0.0001
PG vs other amendments:			
PG_{all} vs S	ns	ns	ns
PG_{all} vs $CaCO_3$	0.0001(-)	0.0001(-)	0.0001(-)
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	ns
Annual vs initial rates:			
PG An vs In	-	ns	ns
S An vs In	-	ns	0.0014
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	0.0058	ns
PG+dolomite An vs In	-	ns	ns
PG_{all} Avg An vs Avg In	-	0.0393	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05).
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

In vitro organic matter digestibility (IVOMD). The %IVOMD, averaged across the annual and the initial rates, given in Table 65 showed little variation with the various group treatments. The %IVOMD with the annual and the initial rates are given in Figures 44 and 44A.

Effects of rates. Only PG+dolomite in 1990 showed a slightly significant %IVOMD slope of 0.22 per Mg PG ha^{-1} (Table 66). This effect is clearly indicated in Figure 44. Figure 44A also shows some apparent positive trends for the various PG amendments on %IVOMD for some annual and initial rates in 1991.

PG versus other amendments. The 1990 analysis for PG_{all} vs S indicated slight (P=0.0688) evidence that PG might be a better amendment than elemental S to improve the IVOMD of bahiagrass forage (Table 67). The 1990 analysis for PG vs PG+dolomite showed a significant evidence that the addition of dolomite to PG might improve the %IVOMD of bahiagrass forage (Table 67).

Annual versus initial rates. The statistics in Table 67 show that the effects of the annual and the initial rates for the various amendments on %IVOMD were not significantly different.

Table 65. Group treatments and in vitro organic matter digestibility (IVOMD) of bahiagrass forage, averaged across annual and initial application rates, 1990-1991.

Group treatments	Year		
	1990[1]	1991	1992[a]
	%IVOMD		
PG	52.8	51.6	-
PG+dolomite[1]	53.4	51.5	-
$PG+CaCO_3$[1]	52.9	51.4	-
PG_{all}[2]	53.0	51.5	-
S (elemental)	52.4	50.9	-
$CaCO_3$	52.6	50.0	-
Control	52.6	50.9	-

[1]1% by weight added to bring PG pH in water (1:1) to 5.5.
[2]Average over all treatments containing PG.
[a]No analysis was done with the 1992 harvests.

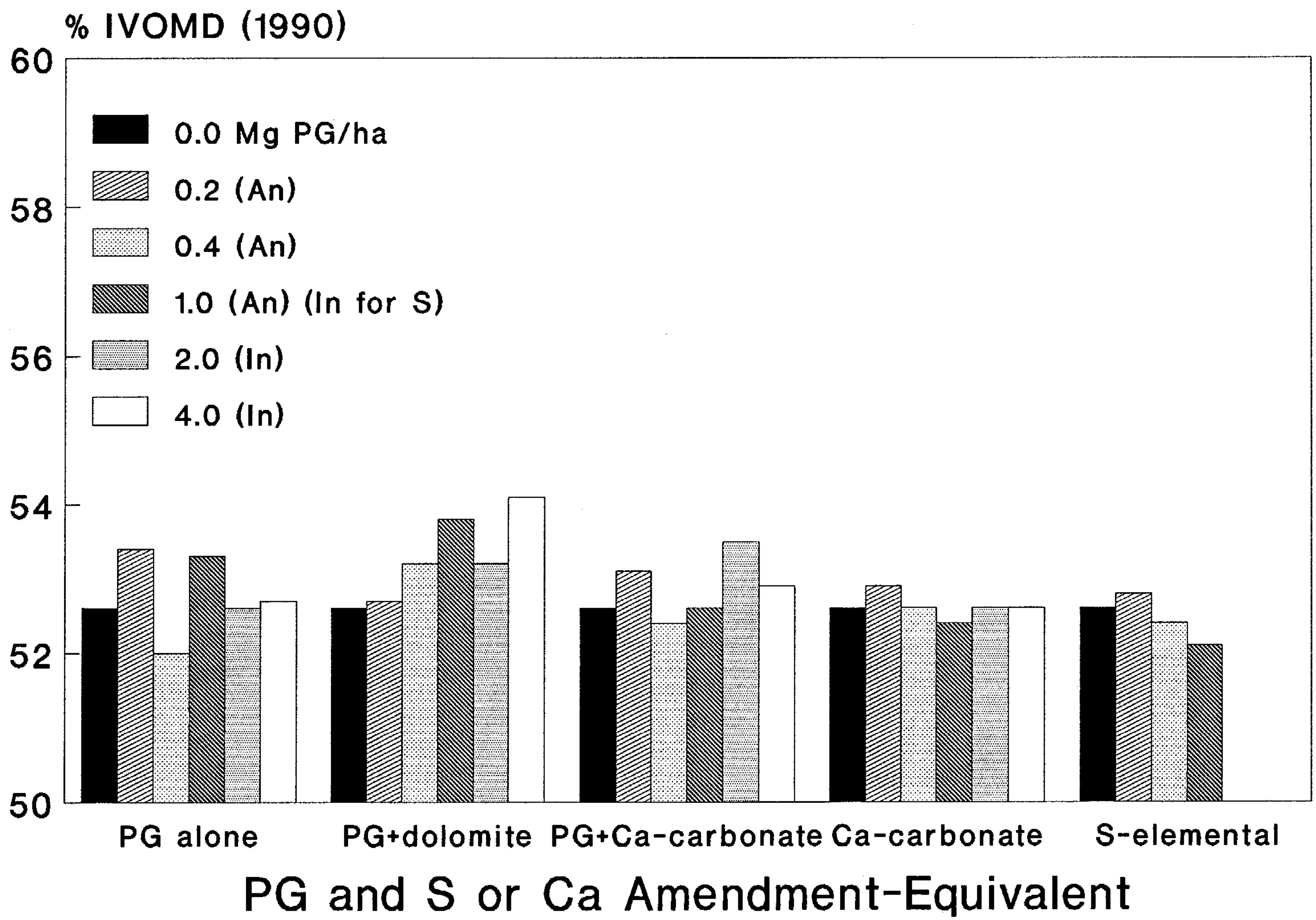


Figure 44. In vitro organic matter digestibility (%IVOMD) of bahiagrass regrowth forage, 1990, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial (In) rates, 1990.

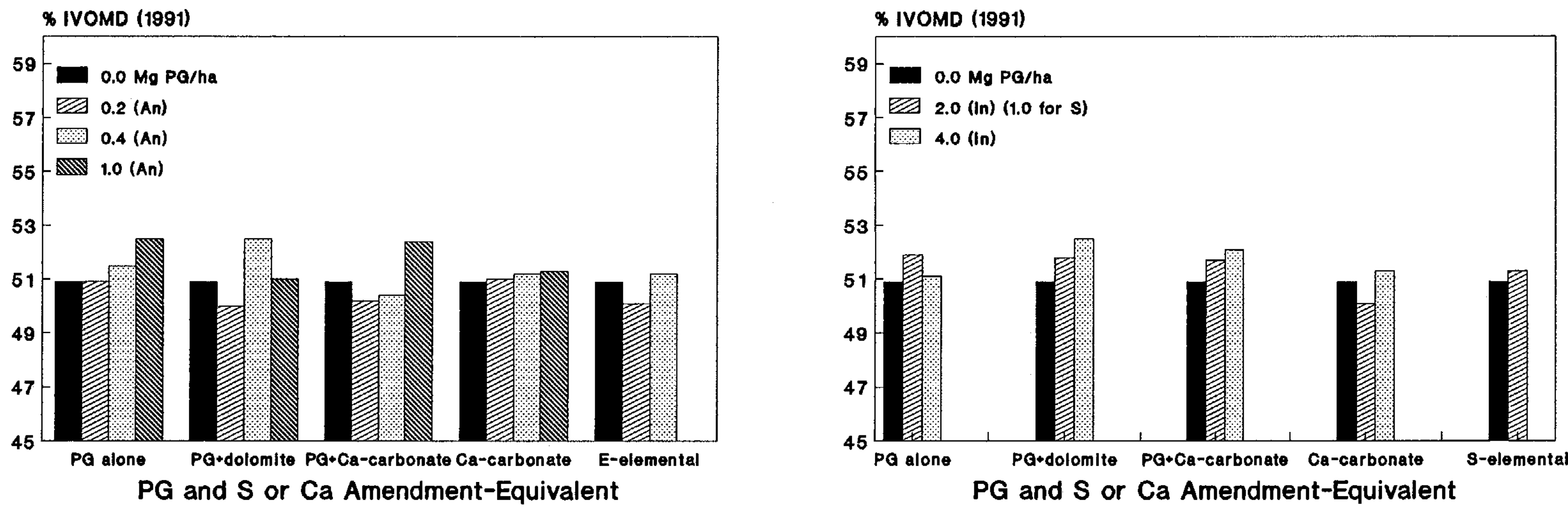


Figure 44A. In vitro organic matter digestibility (%IVOMD) of bahiagrass regrowth forage, 1991, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992, or at the initial rates (In) rates in 1990.

Table 66. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on in vitro organic matter digestibility (IVOMD) of regrowth bahiagrass forage, 1990-1991.

Comparison	Year		
	1990[1]	1991	1992
Intercept	------------	%IVOMD	------------
	52.77	50.22	-
	-----------	(P-value)[2]	---------
AR*GT	0.0591		
AR*GT*FREQUENCY[3]		ns	-
Slope	-----------	%IVOMD/Mg PG ha^{-1}	---
A. Rates, Annual (An):			
PG An Slope	-0.03ns	ns	-
S An Slope	-0.23ns	ns	-
$CaCO_3$ An Slope	-0.06ns	ns	-
PG+$CaCO_3$ An Slope	0.03ns	ns	-
PG+dolomite An Slope	0.22**	ns	-
B. Rates, Initial (In):			
PG In Slope	-0.03ns	ns	-
S In Slope	-0.23ns	ns	-
$CaCO_3$ In Slope	-0.06ns	ns	-
PG+$CaCO_3$ In Slope	0.03ns	ns	-
PG+dolomite In Slope	0.22**	ns	-
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	0.07ns	ns	-
PG_{all} Avg In Slope	0.07ns	ns	-

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), **P≤0.05.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

Table 67. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on in vitro organic matter digestibility (IVOMD) of bahiagrass forage, 1990-1991.

Comparison	Year		
	1990[1]	1991	1992
Statistics:	-------- (P-value)[2] --------------		
AR*GT	0.0591		
AR*GT*FREQUENCY		ns	-
PG vs other amendments:[3]			
PG_{all} vs S	0.0688	ns	-
PG_{all} vs $CaCO_3$	ns	ns	-
PG vs PG+$CaCO_3$	ns	ns	-
PG vs PG+dolomite	0.0261(-)	ns	-
Annual vs initial rates:[3]			
PG An vs In	-	ns	-
S An vs In	-	ns	-
$CaCO_3$ An vs In	-	ns	-
PG+$CaCO_3$ An vs In	-	ns	-
PG+dolomite An vs In	-	ns	-
PG_{all} Avg An vs Avg In	-	ns	-

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

A.2. Amendment Rates, PG Versus Other Amendments, Annual Versus Initial Rates on Soil pH. Calcium. Phosphorus, Potassium, and Magnesium

Soil pH. Table 68 shows the 1990, 1991, and 1992 pH of the top 15 cm of a Florida Spodosol soil, averaged across all rates for each of the group treatments. Figures 45, 45A, and 45B show the trends with the annual and the initial rates.

Table 68. Group treatments and pH of the top 15 cm of a Florida Spodosol soil under bahiagrass which was amended with PG and other S or Ca amendments, averaged across annual and initial rates, 1990-1992.

Group treatments[1]	Year		
	1990	1991	1992
	------------- pH ---------------		
PG	5.45	5.17	5.47
PG+dolomite[2]	5.76	5.43	5.57
PG+$CaCO_3$[2]	5.38	5.27	5.41
PG_{all}[3]	5.53	5.28	5.48
S (elemental)	5.38	4.86	5.19
$CaCO_3$	5.35	5.44	5.75
Control	5.55	5.37	5.50

[1]See Table 70 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. The various PG amendments, whether applied at the annual or the initial rates or as separate or as group treatments showed no significant pH slopes in 1990, 1991, and 1992 and the slopes tended to be negative (Table 69).

Although not significant statistically, elemental S had the highest negative slopes of -0.10 to -0.24 pH unit per Mg PG or unit equivalent rate ha^{-1} (Table 69).

The annual rates of $CaCO_3$ significantly increased soil pH in 1992 by 0.19 pH unit per Mg PG or unit equivalent rate ha^{-1}. The initial rates of $CaCO_3$ showed also positive but non-significant pH slopes in 1991 and 1992 (Table 69).

Except for elemental S, and $CaCO_3$ at the highest rate, the trends in pH with the amendment rates were not consistent in all years (Figures 44, 44A, and 44B).

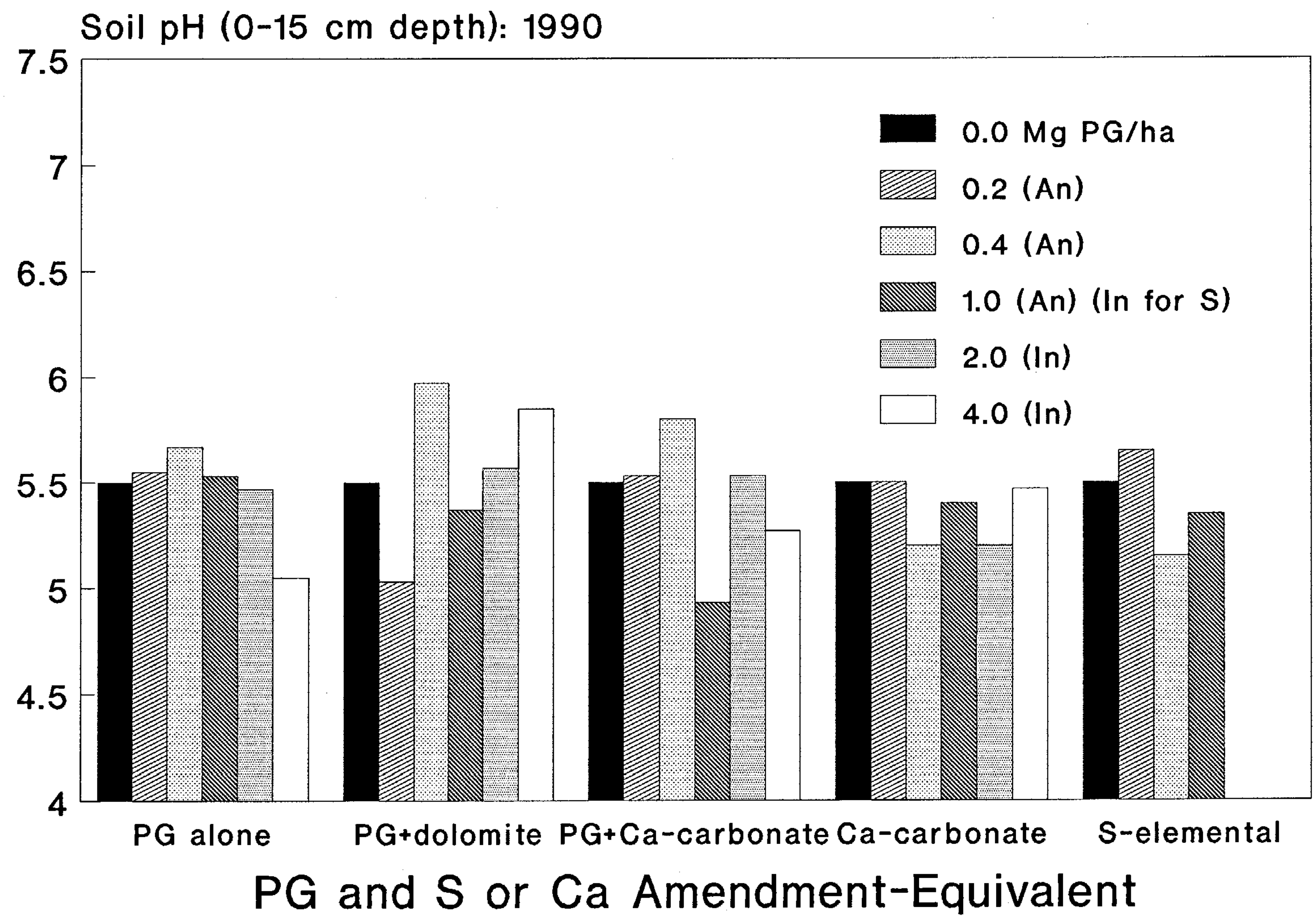


Figure 45. pH of the top 15 cm of a Florida Spodosol soil, 1990, under bahiagrass which was amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or at initial (In) rates, 1990.

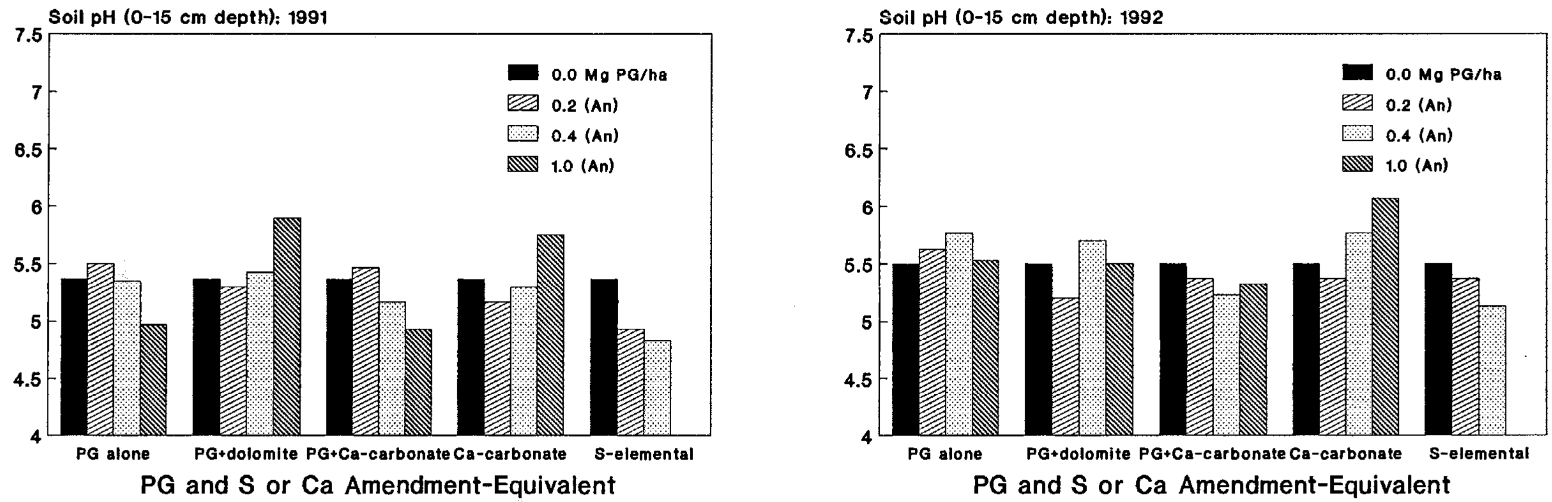


Figure 45A. pH of the top 15 cm of a Florida Spodosol soil, 1991 and 1992, under bahiagrass which was amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

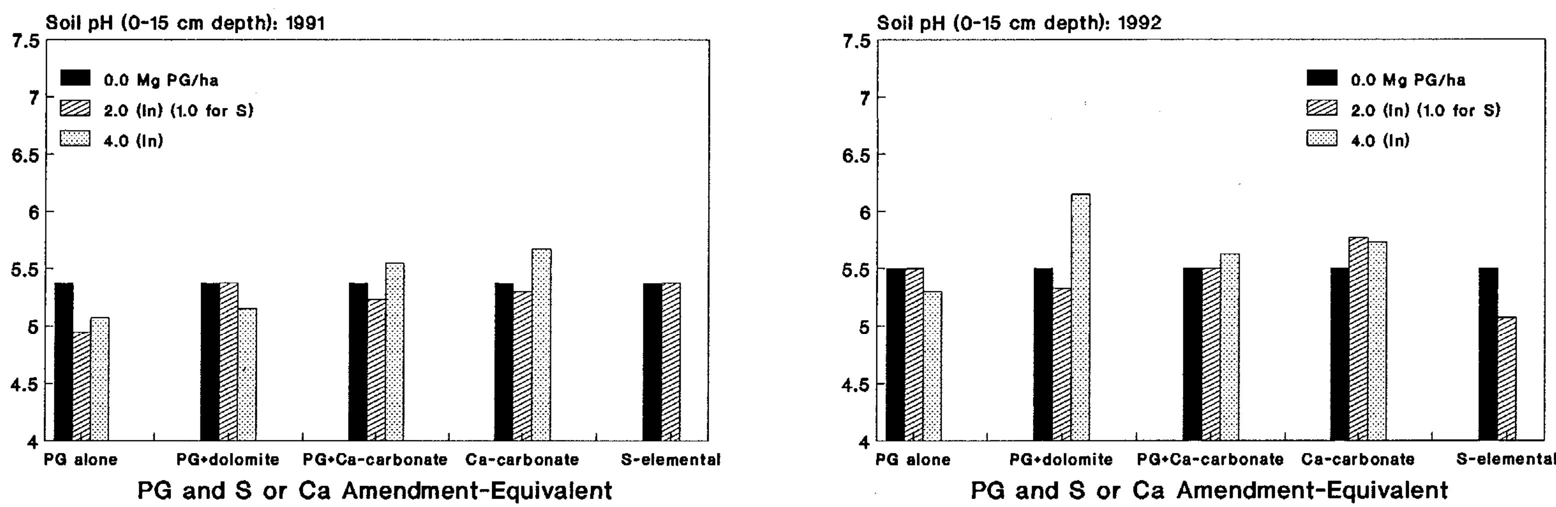


Figure 45B. pH of the top 15 cm of a Florida Spodosol soil, 1991 and 1992, under bahiagrass which was amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

Table 69. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on the pH of the top 15 cm of a Florida Spodosol soil under bahiagrass, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
Intercept	pH		
	5.67	5.31	5.41
	(P-value)[2]		
AR*GT	0.0395		
AR*GT*FREQUENCY[3]		0.0230	0.0360
Slope	pH/Mg PG ha^{-1}		
A. Rates, Annual (An):			
PG An Slope	-0.08*	-0.05ns	0.01ns
S An Slope	-0.10ns	-0.24ns	-0.13ns
$CaCO_3$ An Slope	-0.09ns	0.09ns	0.19**
PG+$CaCO_3$ An Slope	-0.08ns	-0.09ns	-0.05ns
PG+dolomite An Slope	0.05ns	0.15ns	0.10ns
B. Rates, Initial (In):			
PG In Slope	-0.08*	-0.06ns	-0.01ns
S In Slope	-0.10ns	-0.16*	-0.12ns
$CaCO_3$ In Slope	-0.09ns	0.07ns	0.07ns
PG+$CaCO_3$ In Slope	-0.08ns	0.02ns	0.03ns
PG+dolomite In Slope	0.05ns	-0.01ns	0.08*
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	-0.04ns	0.00ns	0.00ns
PG_{all} Avg In Slope	-0.04ns	-0.02ns	0.03ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), *P<0.10 (slightly significant), **P≤0.05.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

PG versus other amendments. The comparative statistics for PG_{all} vs S for soil pH show significant and slightly significant P-values in 1991 and 1992, respectively (Table 70). These indicate that elemental S, when applied at the rate of the S equivalent in 1 Mg of PG ha^{-1}, would more likely make the soil acidic than would the PG amendments.

The comparison PG_{all} vs $CaCO_3$ gave slightly significant and significant P-values in 1991 and 1992, respectively. The negative signs indicated that the average slopes for the various PG amendments (PG_{all}) in 1991 and 1992 were less than the slopes for $CaCO_3$, also averaged across the corresponding rates.

Table 70. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on the pH of the top 15 cm of a Florida Spodosol soil under bahiagrass 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
<u>Statistics:</u>	-------- (P-value)[2] -----------		
AR*GT	0.0395		
AR*GT*FREQUENCY		0.0230	0.0360
<u>PG vs other amendments:</u>[3]			
PG_{all} vs S	ns	0.0193	0.0507
PG_{all} vs $CaCO_3$	ns	0.0693(-)	0.0082(-)
PG vs PG+$CaCO_3$	0.0120(-)	ns	ns
PG vs PG+dolomite	ns	0.0233(-)	ns
<u>Annual vs initial rates:</u>[4]			
PG An vs In	-	ns	ns
S An vs In	-	ns	ns
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	ns	ns
PG+dolomite An vs In	-	0.0914	ns
PG_{all} Avg An vs Avg In	-	ns	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

The results demonstrate the neutral effect of PG on the top soil pH. Using liming materials such as $CaCO_3$ or dolomite, as sources of Ca, are going to increase soil pH whether intended or not. The use of elemental S as a source of S will inevitably make the soil acidic.

The results just noted are important to bahiagrass pasture management. The soil pH recommended by IFAS for bahiagrass is 5.5

(Kidder et al., 1990). Rechcigl et al. (1993) obtained the optimum bahiagrass yields at a soil pH of 5.0. The highest annual or initial application rates of $CaCO_3$ gave soil pH values in 1991 and 1992 which were higher than those of PG and of the control and greater than pH 5.5 (Figures 45A and 45B). This would explain the negative 1991 and 3-year mean forage yield slopes for the initial rates of $CaCO_3$ (Table 43 and Figure 35B) and the significant differences in the 1991 and the 3-year mean slopes of PG_{all} and those of $CaCO_3$ (Tables 44).

The 3-year mean negative forage yield slopes for the annual or the initial rates of elemental S (Table 43 and Figures 35A and 35B) can now be explained on the basis of the soil pH. In 1991, the highest annual and the highest initial rates of elemental S brought the soil pH down to less than 5.0 (Figure 45A and 45B). Note that in 1991 the forage yield slopes for elemental S for both annual and initial rates were very strongly negative (Table 43).

Annual versus initial rates. Table 70 shows no significant P-values for the annual rates versus the initial rates in 1991 and 1992 for the various amendments, indicating similar effects on soil pH.

Calcium. The 1990, 1991, and 1992 soil Ca concentrations at the top 15 cm soil, averaged across all the rates of the various amendments, are given in Table 71. Figures 46, 46A, and 46B show the trends with the annual and the initial rates.

Table 71. Group treatments and Ca concentrations in the top 15 cm of a Florida Spodosol soil under bahiagrass which was amended with PG and other S or Ca amendments, averaged across annual and initial rates, 1990-1992.

Group treatments[1]	Year		
	1990	1991	1992
	------------- mg Ca kg^{-1} ---------		
PG	900.9	733.3	814.9
PG+dolomite[2]	1065.7	826.1	875.3
PG+$CaCO_3$[3]	861.6	692.9	793.3
PG_{all}[3]	942.7	750.8	827.8
S (elemental)	928.9	575.2	711.9
$CaCO_3$	783.7	721.0	896.5
Control	1008.0	701.7	881.7

[1]The comparative statistics showed no significant P-values.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

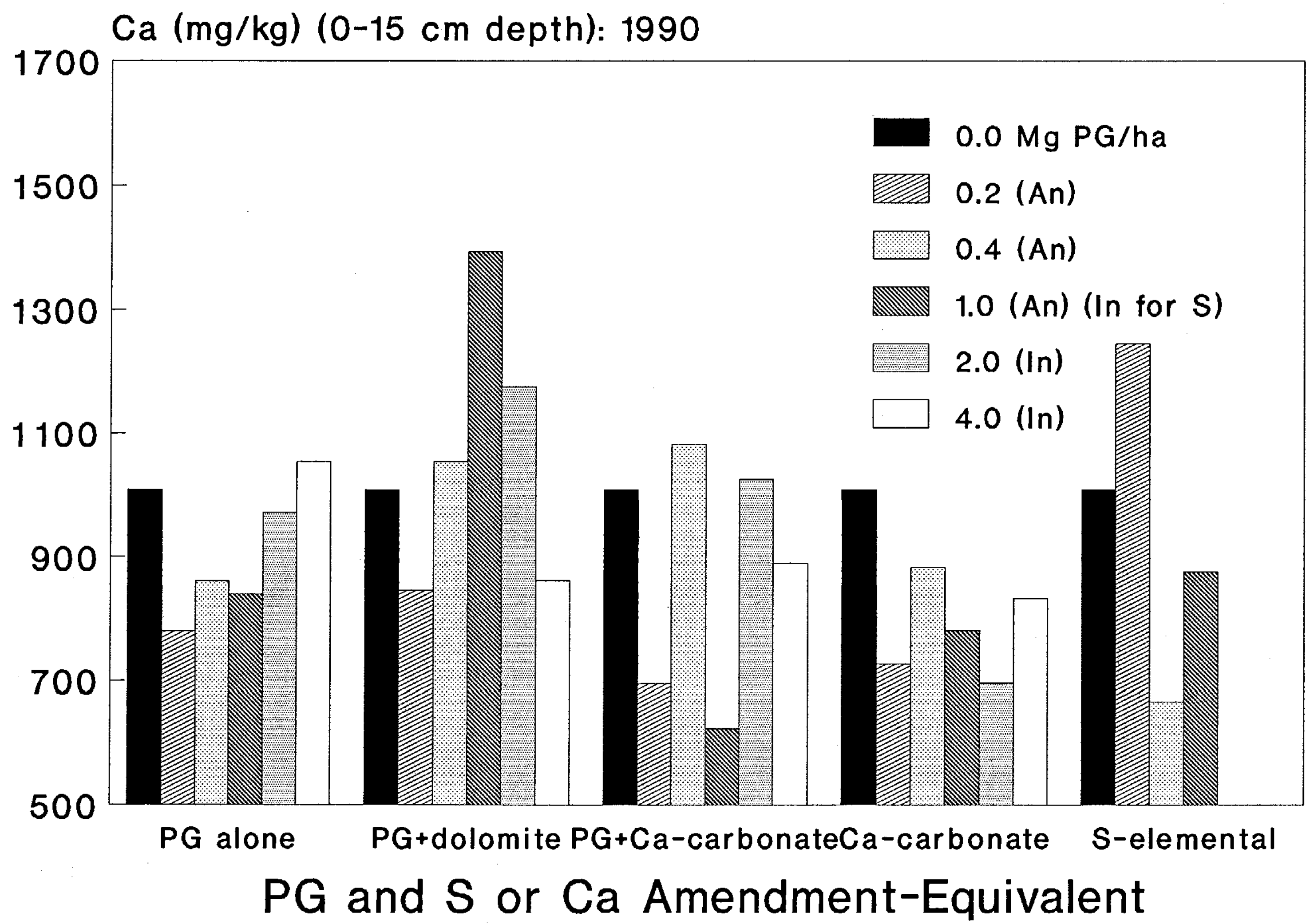


Figure 46. Calcium concentrationsin the top 15 cm of a Florida Spodosol soil, 1990, under bahiagrass which was amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or initial (In) rates, 1990.

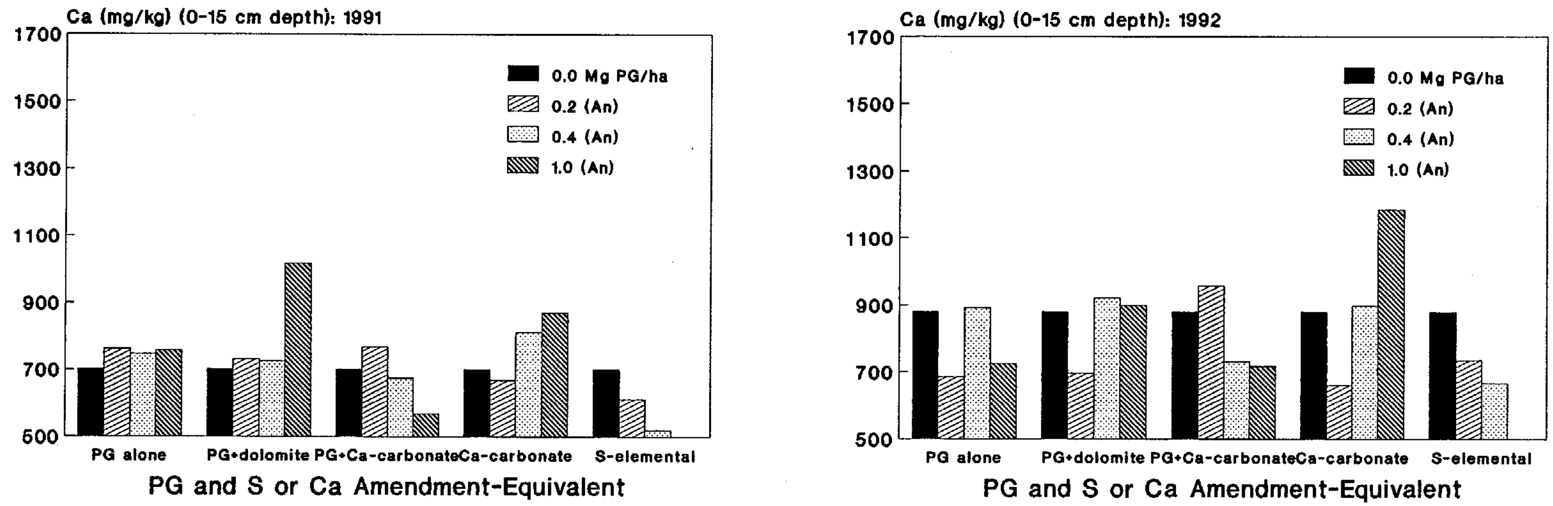


Figure 46A. Calcium concentrations in the top 15 cm of a Florida Spodosol soil, 1991 and 1992, under bahiagrass which was amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

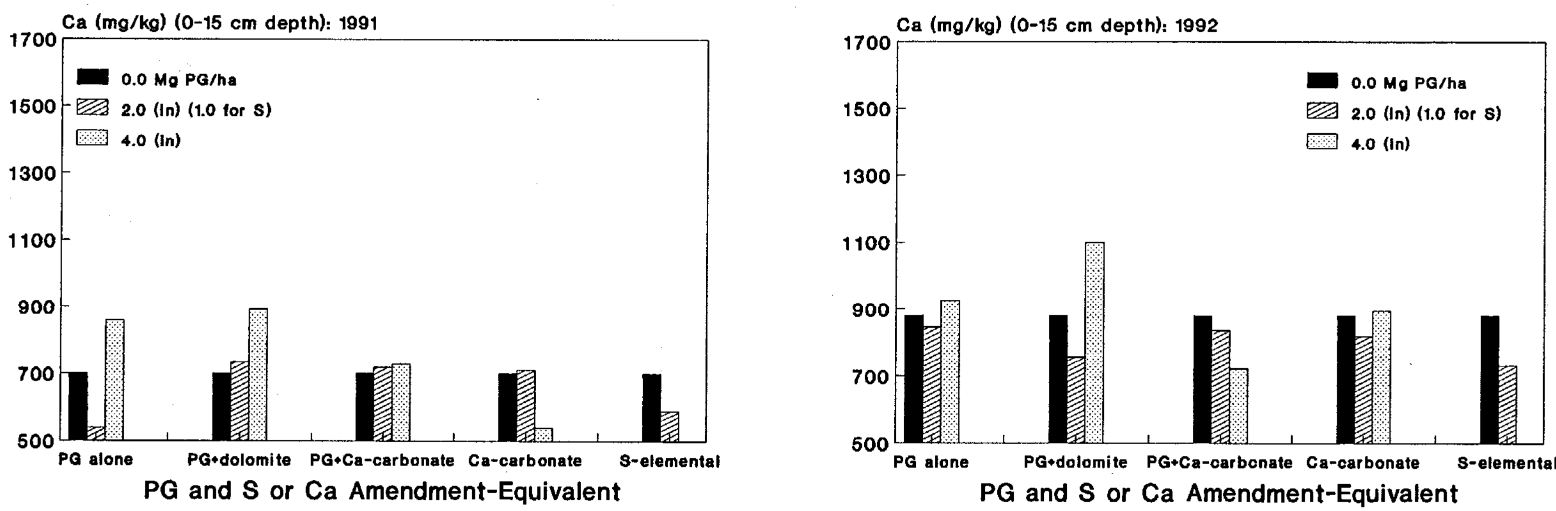


Figure 46B. Calcium concentrationsin the top 15 cm of a Florida Spodosol soil, 1991 and 1992, under bahiagrass which was amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

Effects of rates. No table of slopes is presented since the statistics showed no significant or slightly ($P<0.10$) significant slopes for any of the various amendments.

Figures 46 (1990), 46A (annual rates, 1991 and 1992), and 46B (initial rates, 1991 and 1992) showed no consistent trends, and the topsoil Ca concentrations appeared totally unrelated to the rates of the Ca amendments. The non-significant effects of PG on Ca concentrations in the top 15 cm soil in this experiment were similarly noted in the environmental study (Table 37 and Figure 31). This could be due to the loss of the Ca after a year's time from the highly soluble PG from the topsoil. The $CaCO_3$, which is relatively insoluble, may not have dissolved enough to significantly affect the level of exchangeable Ca in the topsoil.

PG versus other amendments. The comparative statistics showed no significant P-values for the various comparisons for soil Ca.

Annual versus initial rates. There were also no significant P-values for the annual versus the initial rates for soil Ca.

Phosphorus. The 1990, 1991, and 1992 soil P concentrations at the top 15 cm soil, averaged across all the rates of the various amendments, are given in Table 72. Figures 47, 47A, and 47B show the trends with the annual and the initial rates.

Table 72. Group treatments and P concentrations in the top 15 cm of a Florida Spodosol soil under bahiagrass which was amended with PG and other S or Ca amendments, averaged across annual and initial rates, 1990-1992.

Group treatments[1]	Year		
	1990	1991	1992
	------------- mg P kg^{-1} -----------		
PG	12.70	8.73	3.85
PG+dolomite[2]	12.53	8.87	4.49
PG+$CaCO_3$[3]	12.09	8.43	3.39
PG_{all}[3]	12.44	8.68	3.91
S (elemental)	16.32	8.27	3.03
$CaCO_3$	9.89	7.90	4.71
Control	12.80	8.65	4.45

[1]The comparative statistics showed no significant P-values.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

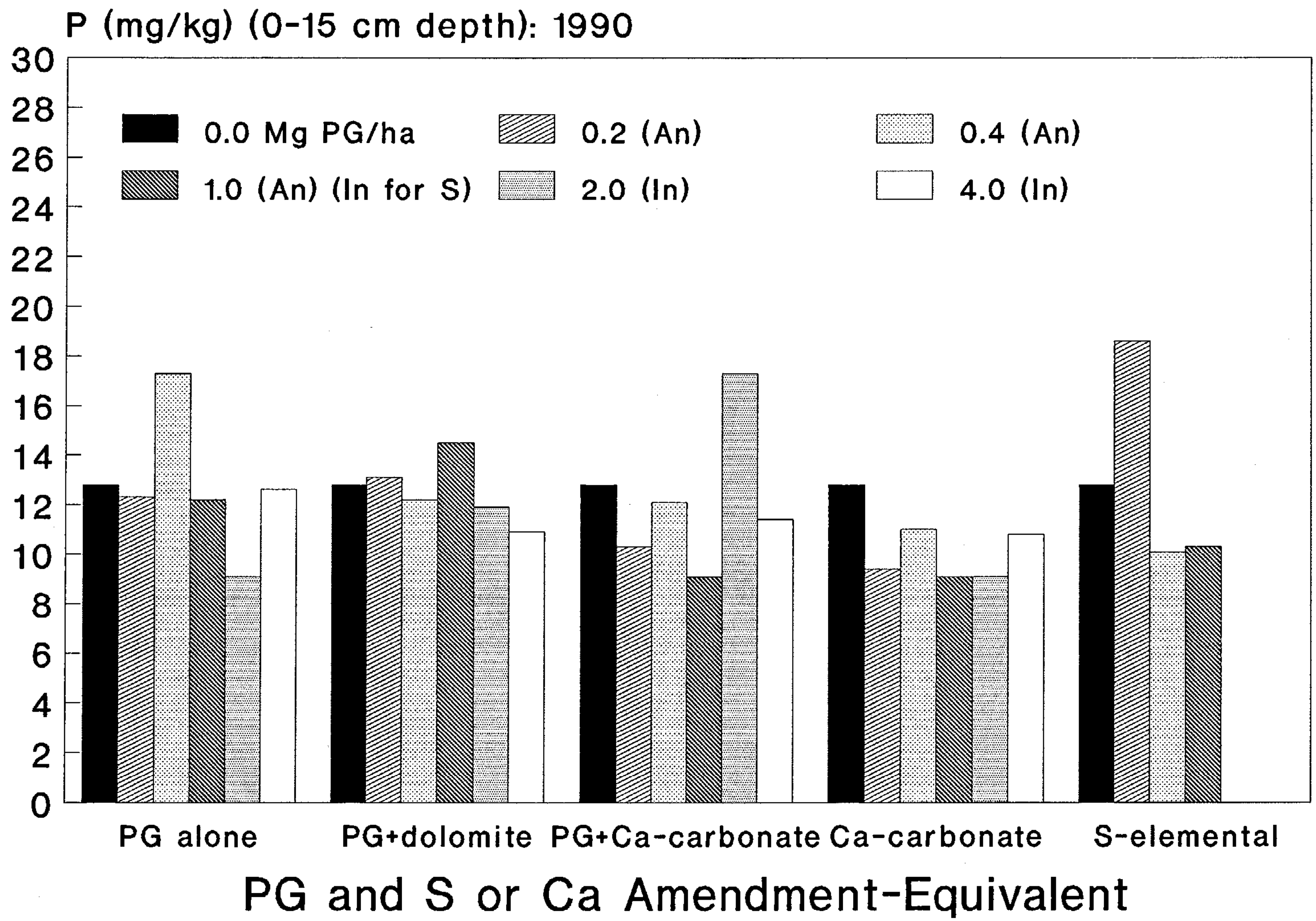


Figure 47. Phosphorus concentrationsin the top 15 cm of a Florida Spodosol soil, 1990, under bahiagrass which was amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or initial (In) rates, 1990.

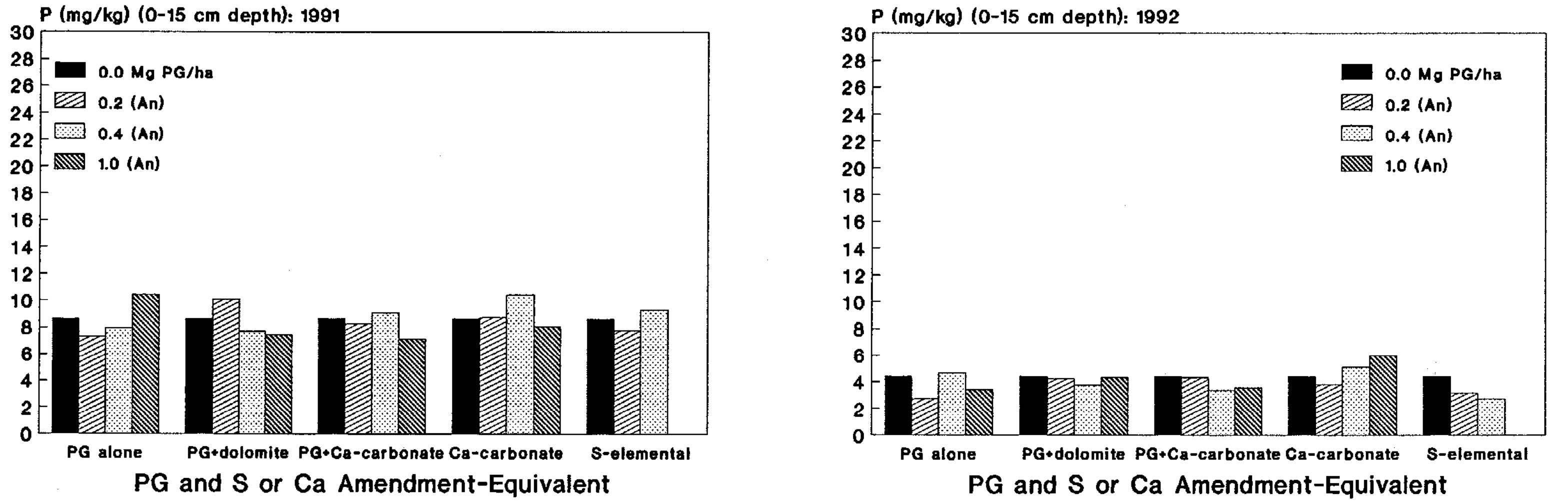


Figure 47A. Phosphorus concentrationsin the top 15 cm of a Florida Spodosol soil, 1991 and 1992, under bahiagrass which was amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

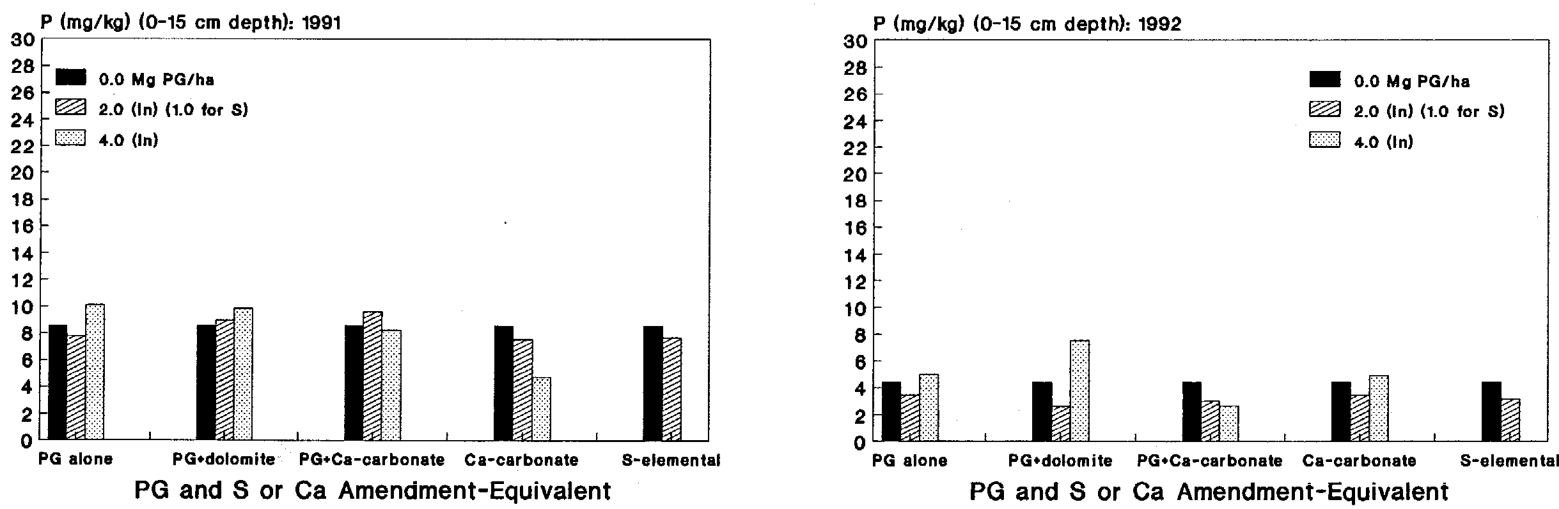


Figure 47B. Phosphorus concentrationsin the top 15 cm of a Florida Spodosol soil, 1991 and 1992, under bahiagrass which was amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

Effects of rates. The statistics for P concentrations in the topsoil showed no significant slopes, positive or negative, for any of the various amendments. Figures 46, 46A, and 46B also showed no consistent trends with the rates of the amendment.

PG versus other amendments. There were also no significant P-values for the various comparisons for soil P.

Annual versus initial rates. There were no significant P-values for the annual versus the initial rates for soil P.

Potassium. The 1990, 1991, and 1992 soil K concentrations at the top 15 cm soil, averaged across all the rates of the various amendments, are given in Table 73. Figures 48, 48A, and 48B show the trends with the annual and the initial rates.

Effects of rates. The PG amendments reduced the topsoil K concentrations significantly by 1.21 to 1.90 mg K kg^{-1} per Mg PG ha^{-1}, but only during the first year (1990) and not thereafter (Table 74). The average reduction in soil K for the PG amendments (PG_{all}) was 1.64 mg kg^{-1} per Mg PG ha^{-1}. Although not significant, the annual rates of PG+$CaCO_3$, PG+dolomite and PG_{all} showed large negative slopes in 1991. Elemental S and $CaCO_3$, at the annual rates, also showed large negative K slopes in 1990, but the slopes did not attain any level of significance. In 1991, the initial rates of $CaCO_3$ reduced soil K by 1.61 mg kg^{-1} per Mg PG or unit equivalent rate ha^{-1} (Table 74).

Table 73. Group treatments and K concentrations in the top 15 cm of a Florida Spodosol soil under bahiagrass which was amended with PG and other S or Ca amendments, averaged across annual and initial rates, 1990-1992.

Group treatments[1]	Year		
	1990	1991	1992
	------------- mg K kg^{-1} -----------		
PG	19.43	18.13	14.77
PG+dolomite[2]	19.73	16.96	13.63
PG+$CaCO_3$[2]	21.57	16.92	15.69
PG_{all}[3]	20.24	17.34	14.64
S (elemental)	21.26	19.47	13.72
$CaCO_3$	23.94	16.19	12.56
Control	21.10	16.93	10.80

[1]See Table 75 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

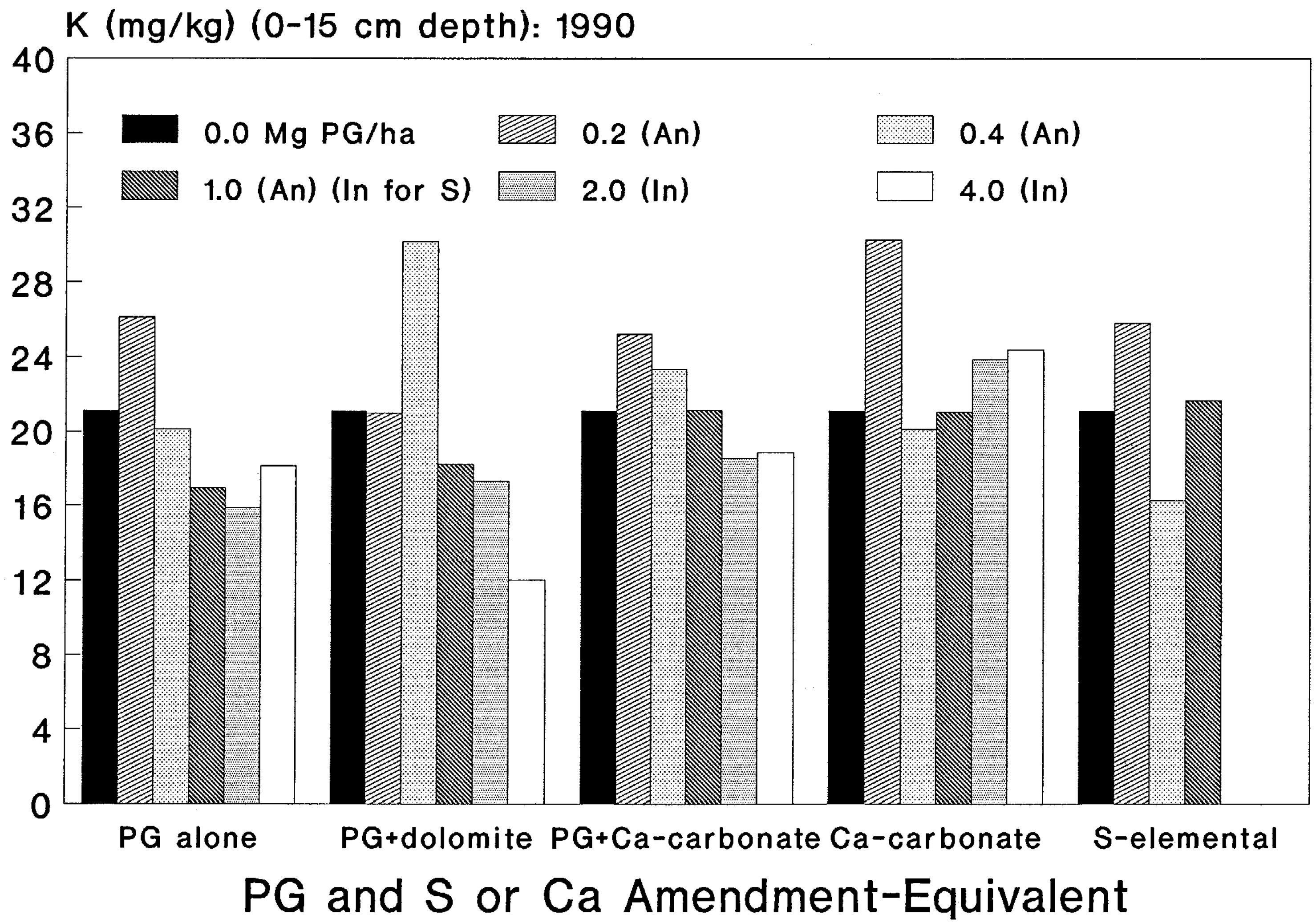


Figure 48. Potassium concentrations in the top 15 cm of a Florida Spodosol soil, 1990, under bahiagrass which was amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or initial (In) rates, 1990.

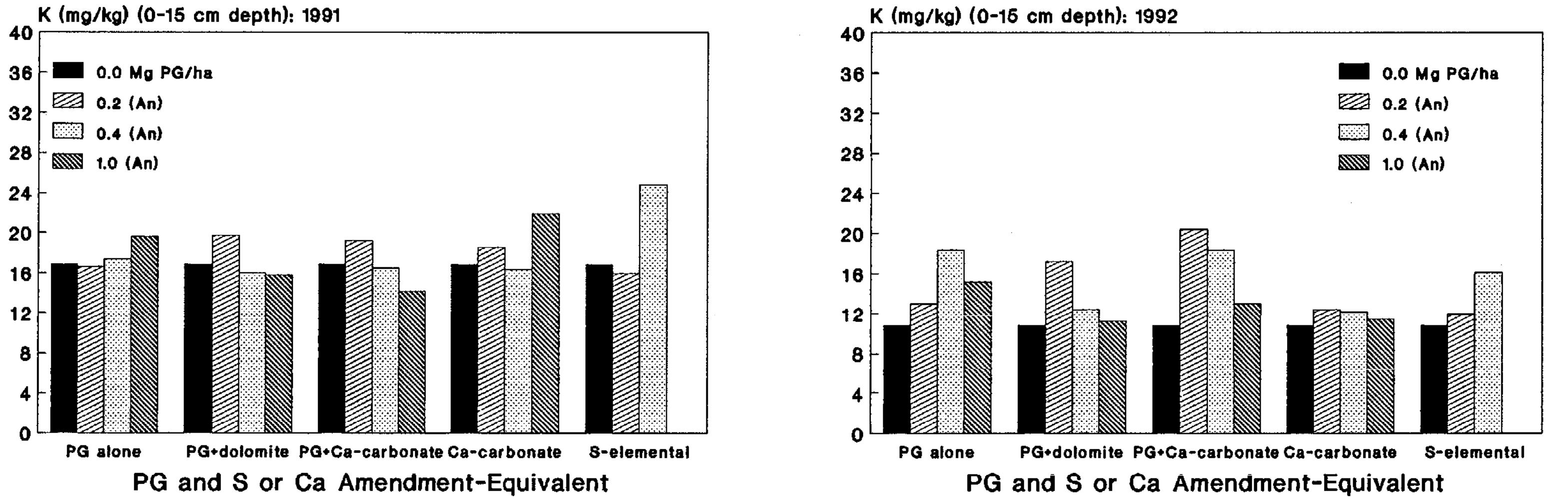


Figure 48A. Potassium concentrationsin the top 15 cm of a Florida Spodosol soil, 1991 and 1992, under bahiagrass which was amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-1992.

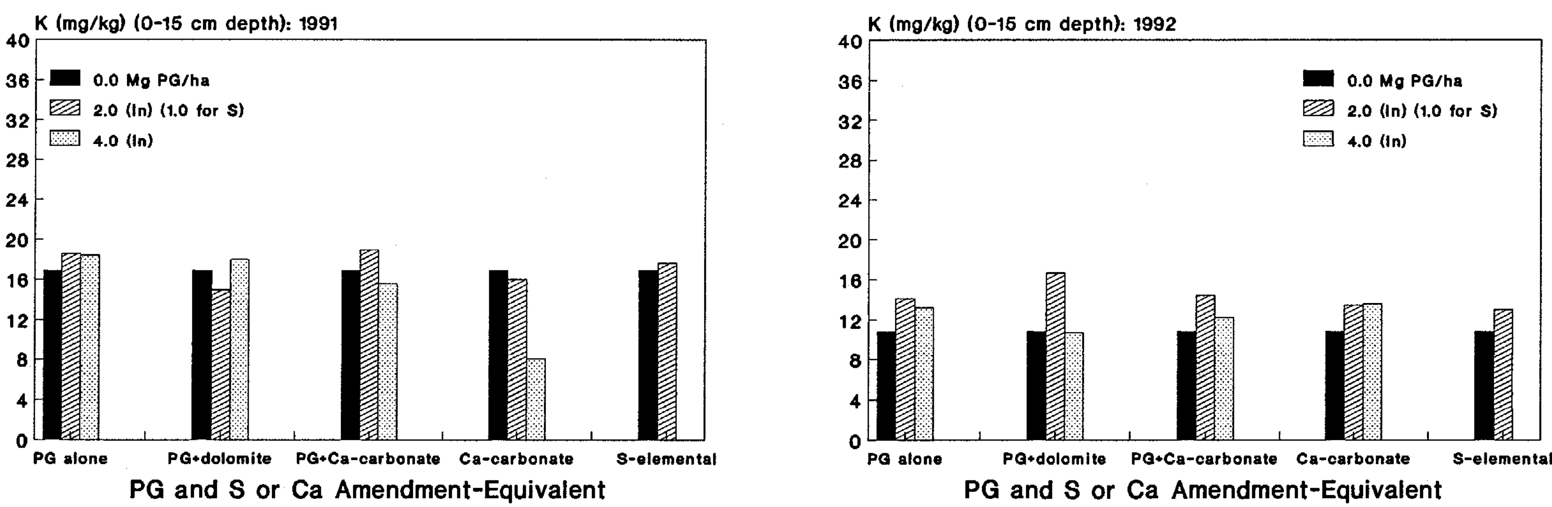


Figure 48B. Potassium concentrationsin the top 15 cm of a Florida Spodosol soil, 1991 and 1992, under bahiagrass which was amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

Table 74. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on K concentrations in the top 15 cm of a Florida Spodosol soil under bahiagrass, 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
Intercept	----------- $mg\ K\ kg^{-1}$ --------		
	24.66	17.51	14.91
	--------- (P-value)[2] ---------		
AR*GT	0.0353		
AR*GT*FREQUENCY[3]		0.0882	ns
Slope	------- $mg\ kg^{-1}/Mg\ PG\ ha^{-1}$ ----		
A. Rates, Annual (An):			
PG An Slope	-1.79^{***}	0.40ns	ns
S An Slope	-1.67ns	1.53ns	ns
$CaCO_3$ An Slope	-0.46ns	0.88ns	ns
PG+$CaCO_3$ An Slope	-1.21^{*}	-0.71ns	ns
PG+dolomite An Slope	-1.90^{***}	-0.29ns	ns
B. Rates, Initial (In):			
PG In Slope	-1.79^{***}	0.21ns	ns
S In Slope	-1.67ns	0.05ns	ns
$CaCO_3$ In Slope	-0.46ns	-1.61^{***}	ns
PG+$CaCO_3$ In Slope	-1.21^{*}	-0.09ns	ns
PG+dolomite In Slope	1.90^{***}	-0.18ns	ns
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	-1.64^{***}	-0.20ns	ns
PG_{all} Avg In Slope	-1.64^{***}	-0.02ns	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), $^{*}P<0.10$ (slightly significant), $^{***}P\leq0.01$.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

PG versus other amendments. The comparative statistics (Table 75) showed a significant P-value for PG_{all} vs $CaCO_3$. The negative sign indicated that PG had a more adverse effect on soil K levels than $CaCO_3$ in 1990. There were no significant differences in the slopes after 1990. The adverse effects of the PG amendments on soil K concentrations were primarily limited to the first year of application.

Table 75. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on K concentrations in the top 15 cm of a Florida Spodosol soil under bahiagrass 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
<u>Statistics:</u>	-------- (P-value)[2] --------------		
AR*GT	0.0353		
AR*GT*FREQUENCY		0.0882	ns
<u>PG vs other amendments:</u>[3]			
PG_{all} vs S	ns	ns	ns
PG_{all} vs $CaCO_3$	0.0396(-)	ns	ns
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	ns
<u>Annual vs initial rates:</u>[4]			
PG An vs In	-	ns	ns
S An vs In	-	ns	ns
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	ns	ns
PG+dolomite An vs In	-	ns	ns
PG_{all} Avg An vs Avg In	-	ns	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

<u>Annual versus initial rates.</u> There were no significant P-values for the annual versus the initial rates for the various amendments in all three years (Table 75). Hence, the annual and the initial rates of the various amendments had similar effects, adverse or otherwise, on K concentrations in the topsoil.

<u>Magnesium.</u> Soil Mg concentrations in 1990, 1991, and 1992 at the top 15 cm, averaged across all the rates of the various amendments, are given in Table 76. Figures 49, 49A, and 49B show the trends with the annual and the initial rates.

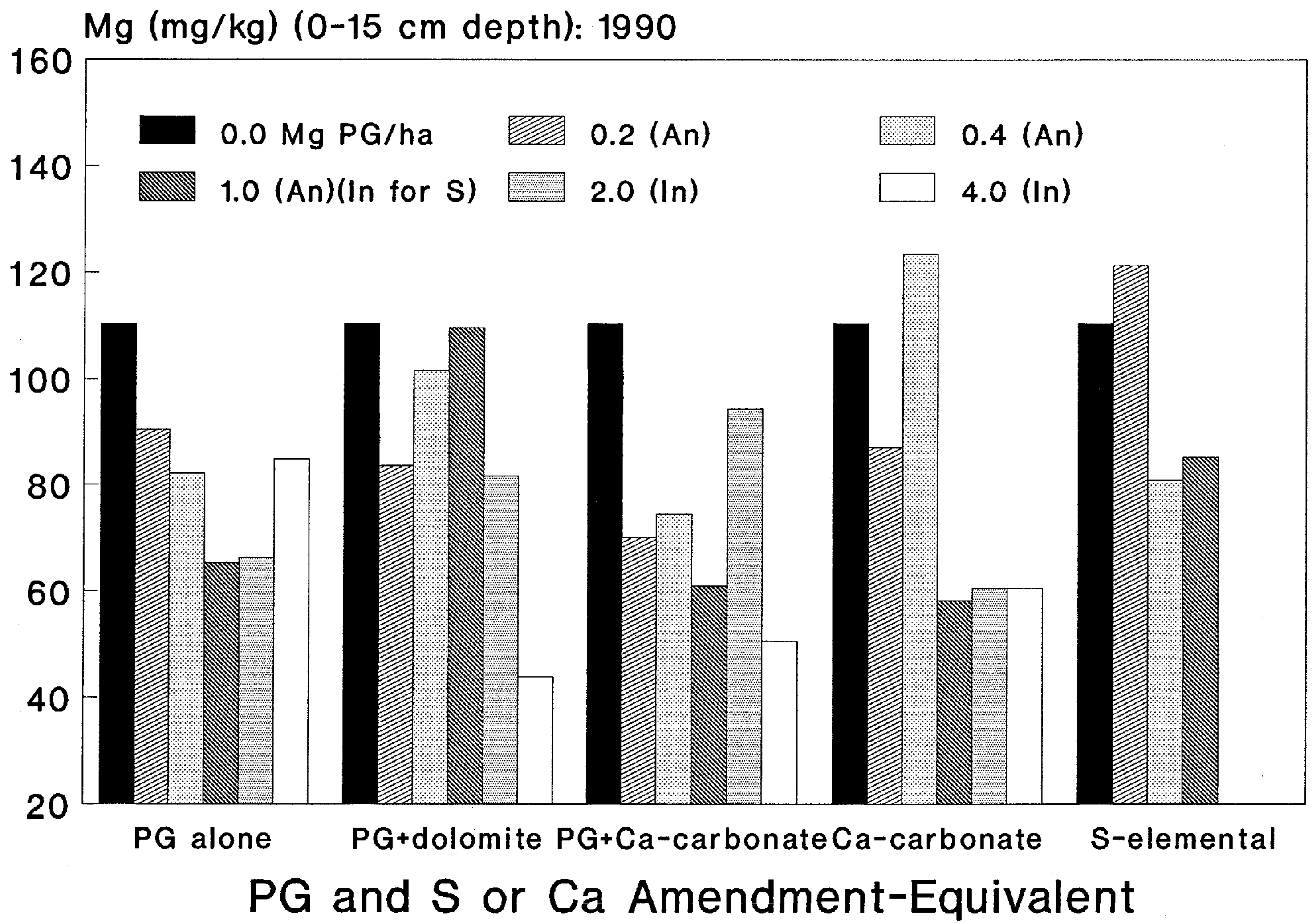


Figure 49. Magnesium concentrations in the top 15 cm of a Florida Spodosol soil, 1990, under bahiagrass which was amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-1992, or initial (In) rates, 1990.

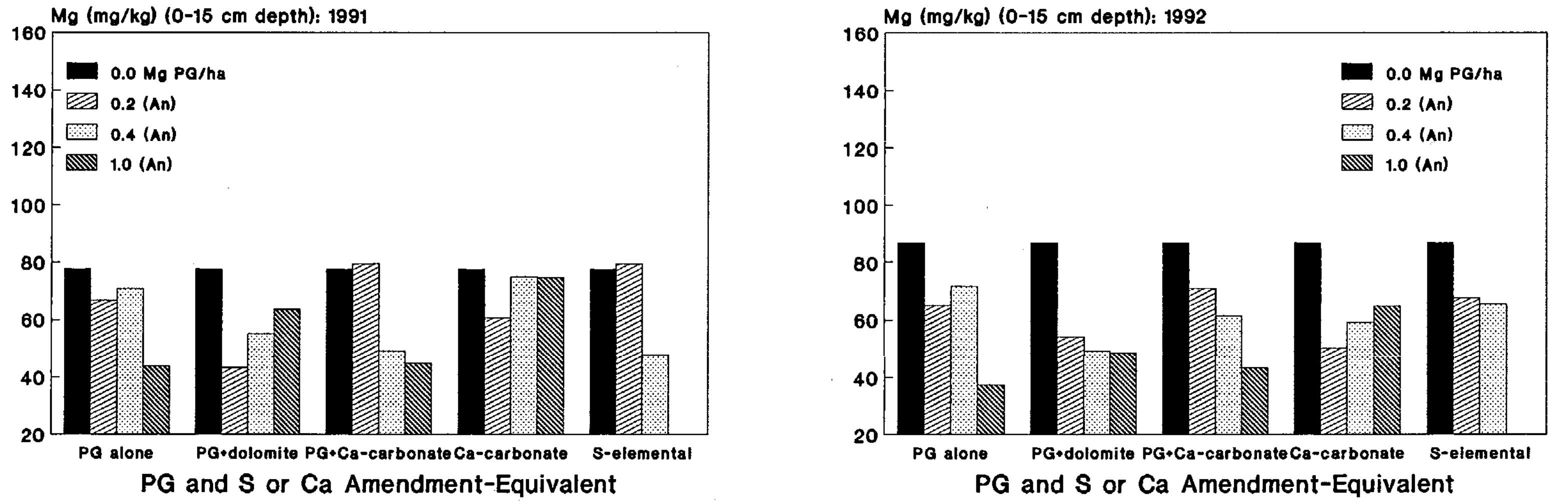


Figure 49A. Magnesium concentrationsin the top 15 cm of a Florida Spodosol soil, 1991 and 1992, under bahiagrass which was amended with PG and other S or Ca amendments applied at the annual(An) rates, 1990-1992.

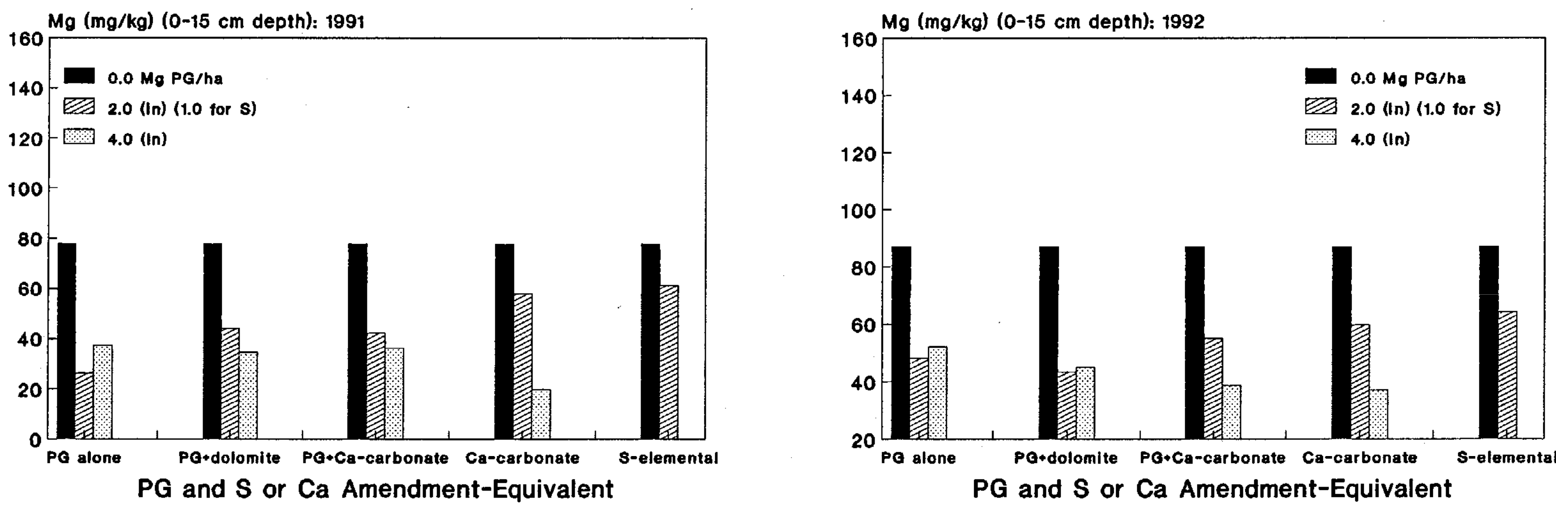


Figure 49B. Magnesium concentrationsin the top 15 cm of a Florida Spodosol soil, 1991 and 1992, under bahiagrass which was amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990.

Table 76. Group treatments and Mg concentrations in the top 15 cm of a Florida Spodosol soil under bahiagrass which was amended with PG and other S or Ca amendments, averaged across annual and initial rates, 1990-1992.

Group treatments[1]	Year		
	1990	1991	1992
	------------- mg Mg kg^{-1} ----------		
PG	77.8	49.1	55.0
PG+dolomite[2]	84.1	47.9	48.1
PG+$CaCO_3$[2]	71.2	50.6	54.4
PG_{all}[3]	77.7	49.2	52.5
S (elemental)	109.2	62.9	65.9
$CaCO_3$	78.2	57.7	53.9
Control	110.5	77.8	87.1

[1]See Table 78 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. In 1990, the individual PG amendments showed slightly ($P<0.10$) significant adverse effects on soil Mg concentrations, reducing extractable Mg by 4.89 to 6.99 mg kg^{-1} per Mg PG ha^{-1} (Table 77) . However, the various PG amendments, averaged across all rates, significantly reduced soil Mg by 5.72 mg kg^{-1} per Mg PG ha^{-1} in 1990. Also in 1990, $CaCO_3$ significantly reduced soil Mg by 7.89 mg kg^{-1} per Mg PG or unit equivalent rate ha^{-1}. Elemental S had also a negative slope, but it was not significant.

In 1991, the slopes for the individual PG amendments at the annual rates of application ranged from -6.59 to -9.39 mg kg^{-1} per Mg PG ha^{-1}, but only the PG+$CaCO_3$ slope (-9.39) was significant. However, the average effect of the various PG amendments at the annual rates (PG_{all} An) significantly reduced soil Mg by 7.75 mg kg^{-1} per Mg PG ha^{-1}. The initial PG rates continued to reduce soil Mg concentrations in 1991 significantly by 7.62 to 9.06 mg kg^{-1} per kg PG ha^{-1} with an average slope of -8.11 mg kg^{-1} per Mg PG ha^{-1} for PG_{all}. Treatment $CaCO_3$ also significantly reduced soil Mg by 7.89 mg kg^{-1} per Mg PG or unit equivalent rate ha^{-1} in 1991. The negative slope for elemental S was not significant (Table 77).

In 1992, the soil Mg slopes for all the treatments were not significant (Table 77). Table 76 shows that soil Mg levels were lowest at the end of 1991 for all treatments including the control and were relatively unchanged at the end of 1992. However, Table 76 also shows that the gaps in soil Mg concentrations between PG_{all} and the control continued to widen from 1990 to 1992.

Table 77. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on Mg concentrations in the top 15 cm of a Florida Spodosol soil under bahiagrass, 1990-1992.

Comparison	Year 1990[1]	1991	1992
Intercept	----------- mg Mg kg^{-1} -------		
	95.37	73.93	62.43
	--------- (P-value)[2] ---------		
AR*GT	0.0805		
AR*GT*FREQUENCY[3]		0.0029	ns
Slope	------- mg kg^{-1}/Mg PG ha^{-1} ----		
A. Rates, Annual (An):			
PG An Slope	-5.28*	-7.28ns	ns
S An Slope	-4.49ns	-7.08ns	ns
$CaCO_3$ An Slope	-7.89***	-0.46ns	ns
PG+$CaCO_3$ An Slope	-6.99*	-9.39**	ns
PG+dolomite An Slope	-4.89*	-6.59ns	ns
B. Rates, Initial (In):			
PG In Slope	-5.28*	-9.06***	ns
S In Slope	-4.49ns	-4.21ns	ns
$CaCO_3$ In Slope	-7.89***	-7.89***	ns
PG+$CaCO_3$ In Slope	-6.99*	-7.62***	ns
PG+dolomite In Slope	-4.89*	-7.66***	ns
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	-5.72**	-7.75**	ns
PG_{all} Avg In Slope	-5.72**	-8.11***	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), *P<0.10 (slightly significant), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

PG versus other amendments. Only PG_{all} vs S showed a slightly (P<0.10) significant P-value, but only in 1991, with the negative sign indicating a more negative slope for PG_{all} than that for elementals S. The comparison PG_{all} vs $CaCO_3$ showed that the effects of the PG amendments (PG_{all}) and those of $CaCO_3$ on soil Mg, averaged across their respective rates, were not different in all three years. No differences Were noted on the effects on soil Mg between PG and PG+$CaCO_3$ or PG and PG+dolomite (Table 78).

Annual versus initial rates. The P-values in 1991 were significant for PG and $CaCO_3$, slightly significant for PG+dolomite, and not significant for PG+$CaCO_3$ (Table 78). However, the P-value for PG_{all} annual versus PG_{all} initial in 1991 was highly significant and, being positive, indicated a less negative slope for the annual rates than for the initial rates. No significant P-values were noted in 1992 for any of the amendments (Table 78). Thus, to minimize the depletion of soil Mg from the topsoil, PG or $CaCO_3$ should be applied annually at the low rates rather than once every three years at the much higher rates.

Table 78. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on Mg concentrations in the top 15 cm of a Florida Spodosol soil under bahiagrass 1990-1992.

Comparison	Year		
	1990[1]	1991	1992
Statistics:	-------- (P-value)[2]	-------------	
AR*GT	0.0805		
AR*GT*FREQUENCY		0.0029	ns
PG vs other amendments:[3]			
PG_{all} vs S	ns	0.0978(-)	ns
PG_{all} vs $CaCO_3$	ns	ns	ns
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	ns
Annual vs initial rates:[4]			
PG An vs In	-	0.0359	ns
S An vs In	-	ns	ns
$CaCO_3$ An vs In	-	0.0045	ns
PG+$CaCO_3$ An vs In	-	ns	ns
PG+dolomite An vs In	-	0.0950	ns
PG_{all} Avg An vs Avg In	-	0.0055	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

B. ANNUAL RYEGRASS EXPERIMENT

B.1. Amendment Rates, PG Versus Other Amendments, and Annual Versus Initial Rates on Forage Yields, Percent Dry Matter (DM), Nutrient Contents, and Other Forage Quality Measures

B.1.1. Forage Dry Matter (DM) Yields

The effects of the group treatments on forage yields averaged across the annual and the initial rates are given in Table 79. The trends with the annual and the initial rates are shown in Figures 50, 50A, and 50B.

Table 79. Group treatments and total[1] forage dry matter (DM) yields of annual ryegrass, averaged across annual and initial rates, 1990-91 to 1992-93.

Group treatments[2]	Year			Mean
	1990-91	1991-92	1992-93	
	--------- Mg DM ha^{-1}	-------------		
PG	3.25	8.91	6.20	6.12
PG+dolomite[3]	3.36	9.33	5.90	6.22
PG+$CaCO_3$[3]	3.21	8.75	6.22	6.07
PG_{all}[4]	3.27	9.00	6.11	6.14
S (elemental)	3.01	8.85	6.05	5.97
$CaCO_3$	3.22	8.70	5.81	5.90
Control	3.36	8.50	6.04	5.97

[1]Total of 2 harvests in 1990-91 and 3 in 1991-92 and 1992-93.
[2]The comparative statistics showed no significant P-values.
[3]1% by weight added to bring PG pH in water (1:1) to 5.5.
[4]Average over all treatments containing PG.

Effects of rates. The statistics showed no significant forage yield slopes for the annual ryegrass in 1990-91, 1991-92, and 1992-93. The 1990-91 yields showed no trends or any influence of the various amendments on yield (Figure 50). The experimental site, formerly a virgin saw palmetto land, was cultivated for the first time for the study and limed with dolomite. The rich virgin soil, liming, and the decomposing vegetation may be responsible for the lack of response to the treatments. By 1991-92, at both the annual and the initial rates, non-significant but apparent positive trends were noted, particularly with the PG and the elemental S treatments (Figure 50A). Similar trends were also noted in 1992-93 (Figure 50B).

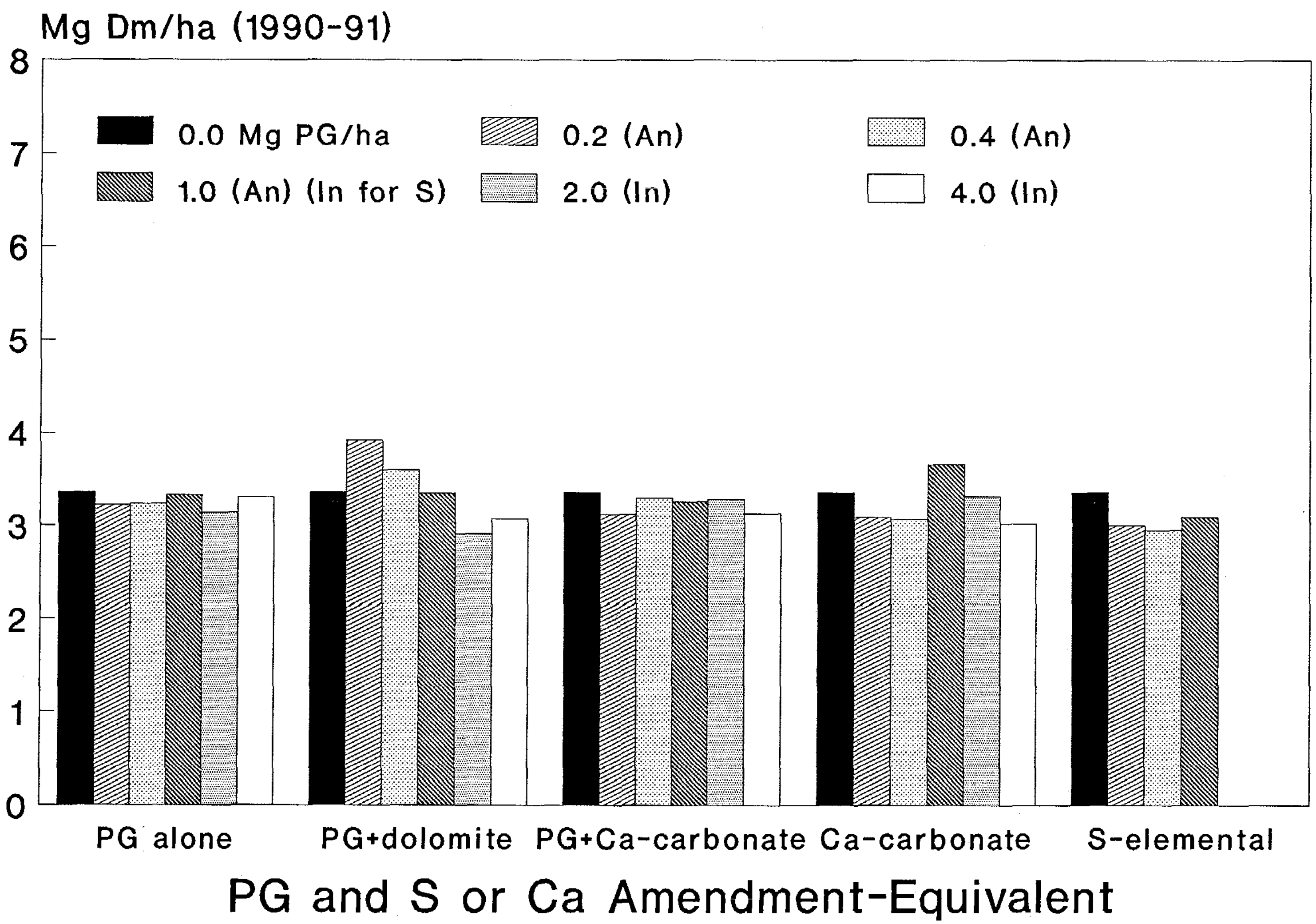


Figure 50. Total regrowth forage dry matter yieldsof annual ryegrass, 1990-91, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

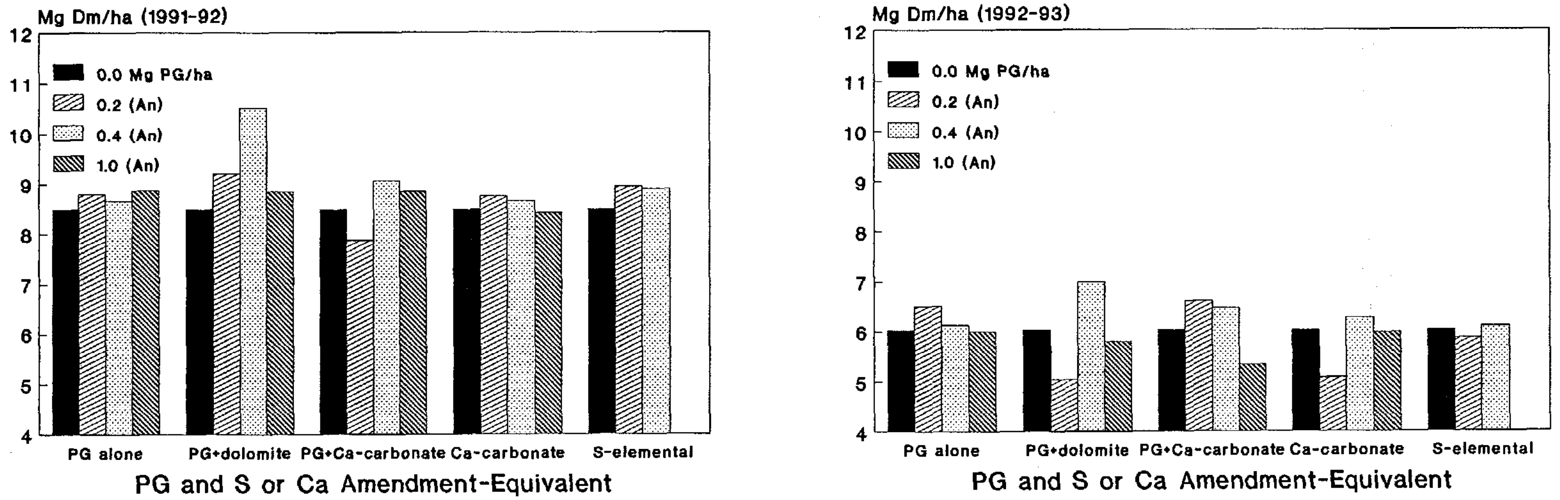


Figure 50A. Total regrowth forage dry matter yieldsof annual ryegrass, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

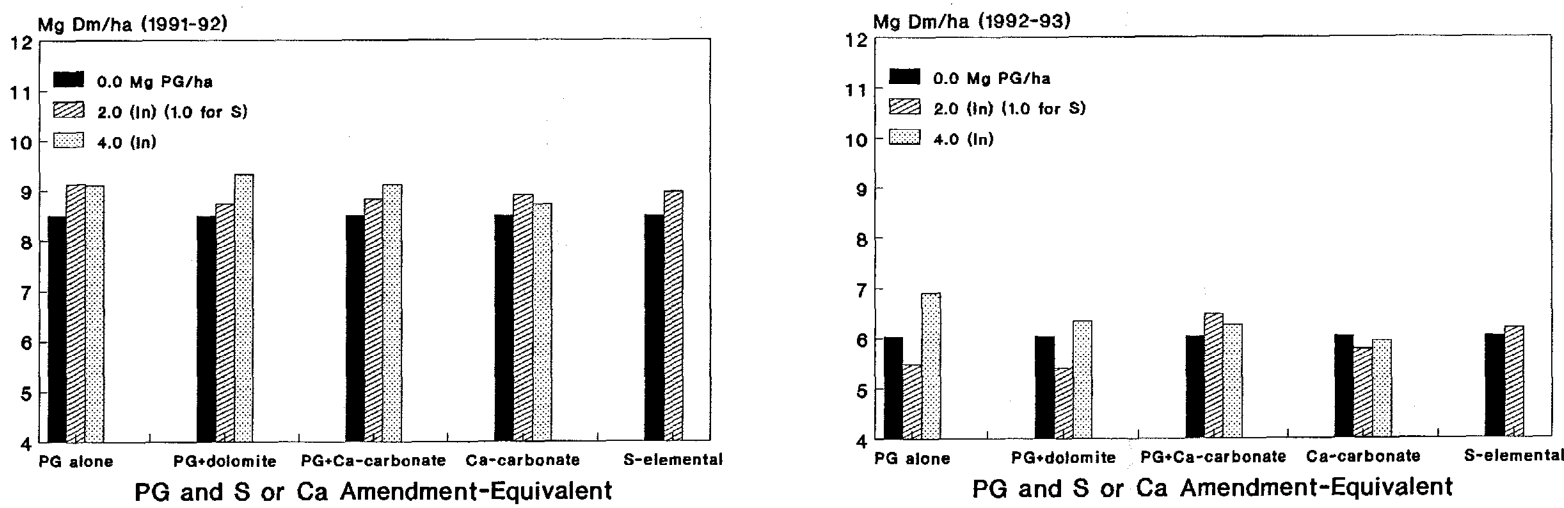


Figure 50B. Total regrowth forage dry matter yieldsof annual ryegrass, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

PG versus other amendments. The statistics showed no significant differences between the effects of the various amendments on the forage yield of annual ryegrass in all thre years.

Annual versus initial rates. The statistics also showed no significant P-values for the annual rates versus initial rates in in all three years.

B.1.2. Percent Dry Matter (%DM)

Table 80 shows the effects of the group treatments on %DM of the annual ryegrass forage averaged across the annual and the initial rates. The trends with the annual and the initial rates are indicated in Figures 51, 51A, and 51B.

Table 80. Group treatments and percent dry matter (%DM) of annual ryegrass forage, averaged across annual and initial rates, 1990-91 to 1992-93.

Group treatments[1]	Year			Mean
	1990-91	1991-92	1992-93	
	%DM			
PG	14.0	20.2	20.3	18.7
PG+dolomite[2]	14.3	20.6	20.3	18.9
PG+$CaCO_3$[2]	14.6	20.4	20.7	19.1
PG_{all}[3]	14.3	20.4	20.4	18.9
S (elemental)	13.3	18.6	20.3	17.9
$CaCO_3$	13.5	19.8	19.4	18.0
Control	13.2	19.3	19.3	18.0

[1]See Table 82 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. The higher the %DM the greater the solids in the freshly harvested forage and the less water in the forage. The various PG amendments significantly increased %DM by 0.26 to 0.30% per Mg PG ha^{-1} in 1990-91 (Table 81). In 1991-92 the annual rates of PG and PG+$CaCO_3$, but not PG+dolomite, increased %DM by 0.68 and 0.66, respectively. The initial rates of PG+dolomite increased %DM by 0.44% per Mg PG ha^{-1}. There were no effects of the various amendments on %DM in the 1992-93 harvests. When averaged over the 3-year period and the rates, both PG_{all} annual and PG_{all} initial increased %DM by 0.22% per Mg PG ha^{-1}.

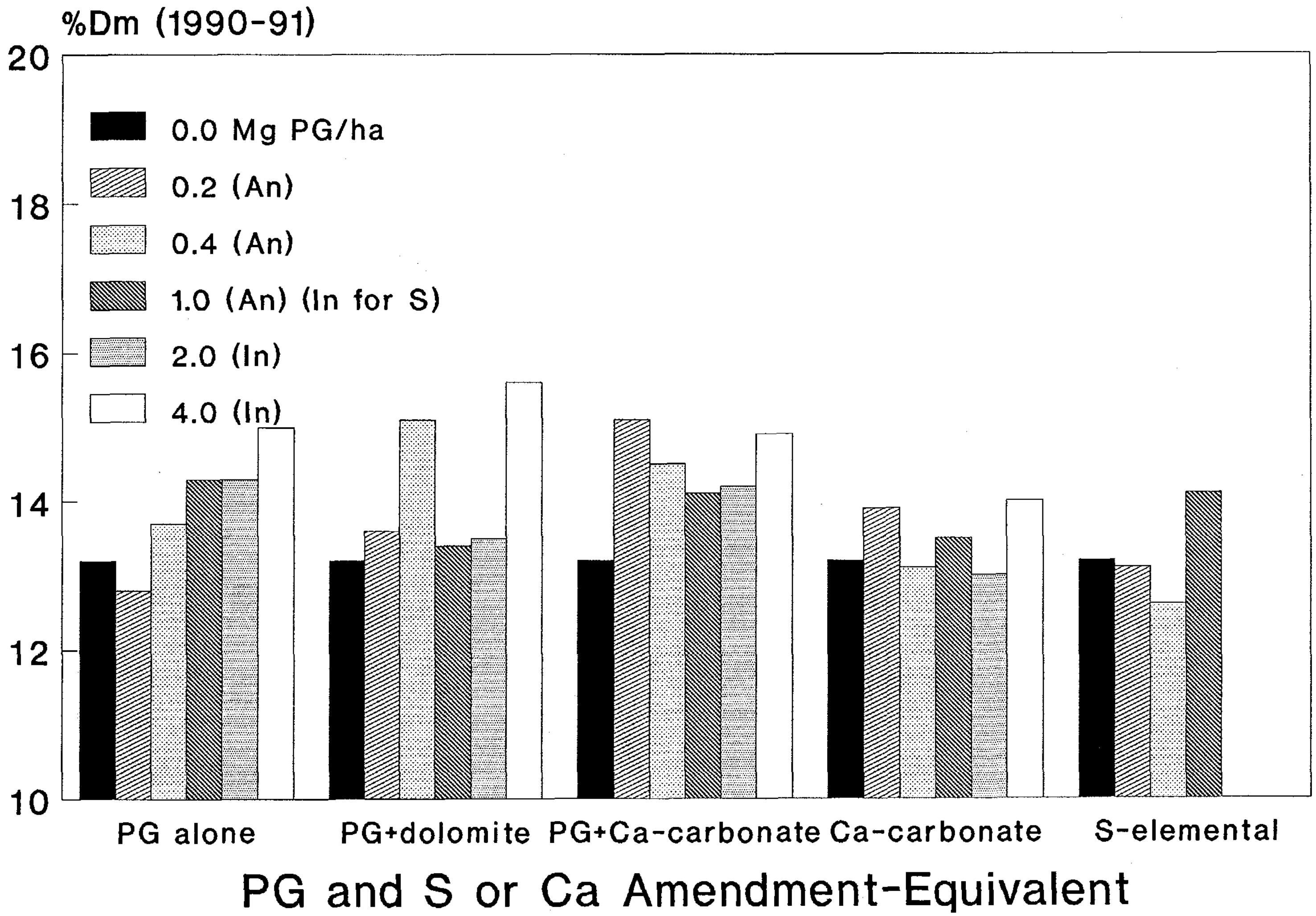


Figure 51. Percent dry matter (%DM) of annual ryegrass regrowth forage, 1990-91, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In), 1990-91.

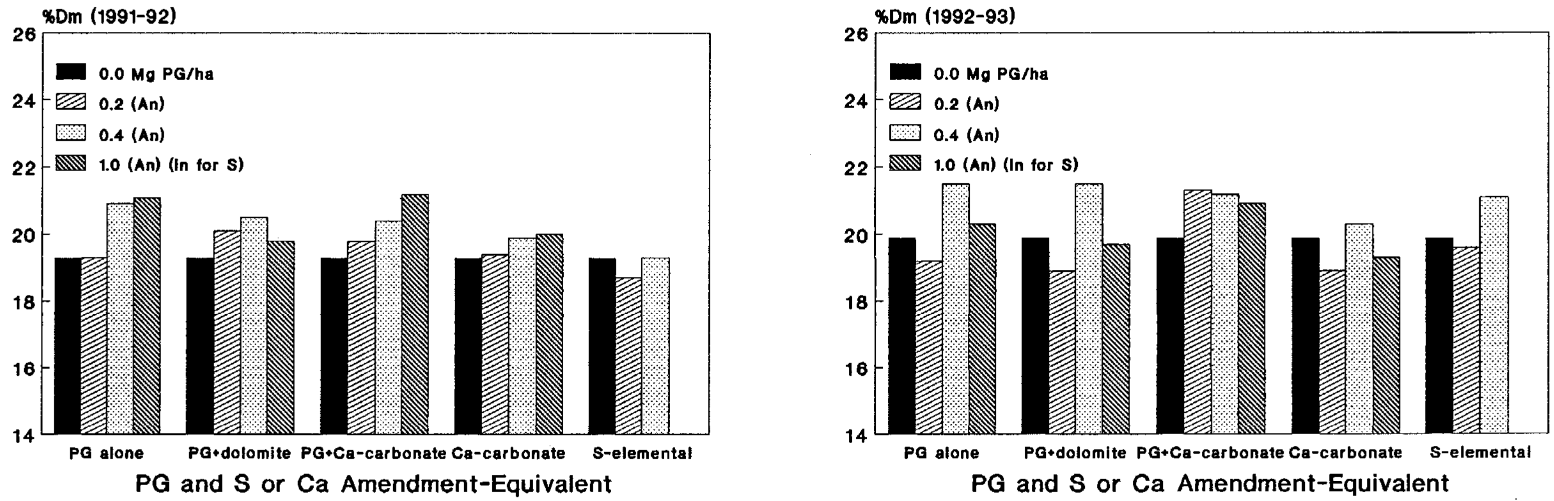


Figure 51A. Percent dry matter (%DM) of annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

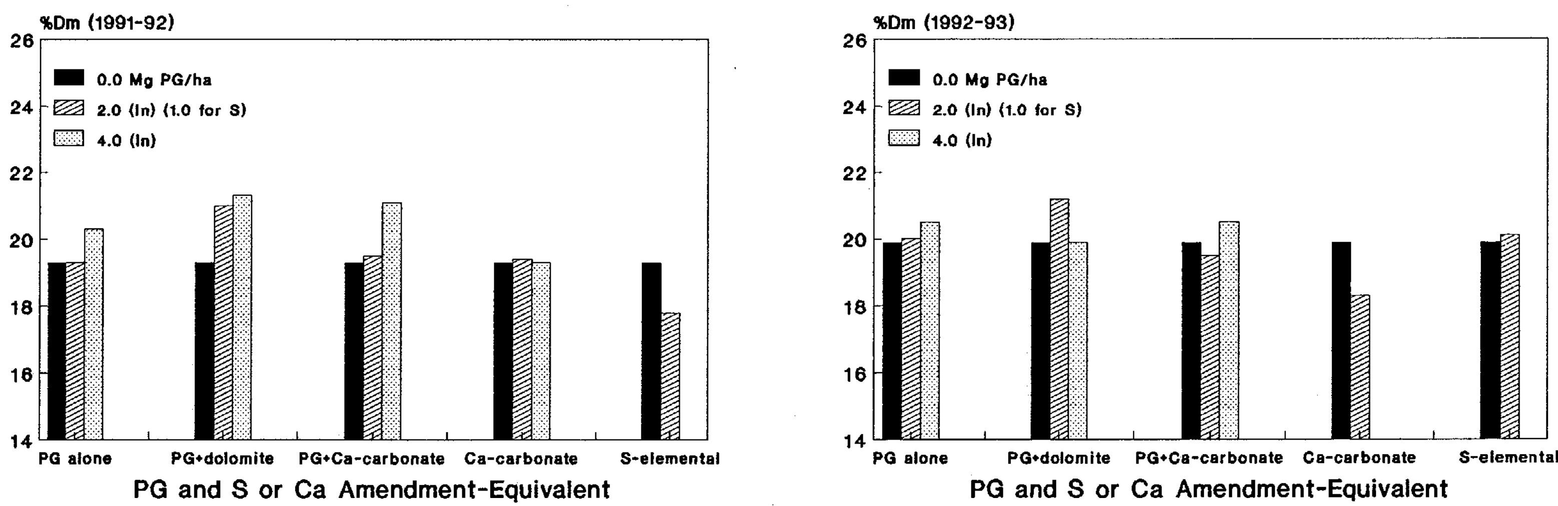


Figure 51B. Percent dry matter (%DM) of annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

Table 81. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on percent dry matter (%DM) of annual ryegrass, 1990-91 to 1992-93.

Treatment	Year			Mean
	1990-91[1]	1991-92	1992-93	
<u>Intercept</u>	----------- %DM ---------------			
	13.41	19.15	19.72	17.47
<u>Statistics:</u>	-------- (P-value)[2] -----------			
AR*GT	0.0044			
AR*GT*FREQUENCY[3]		0.0066	ns	
AR*GT*FREQUENCY*YEAR				0.0370
<u>Slope</u>	----------- %DM/Mg PG ha^{-1} ------			
<u>A. Rates, Annual (An):</u>				
PG An Slope	0.26^{**}	0.68^{**}	ns	0.20^{*}
S An Slope	0.01ns	-0.03ns	ns	0.09ns
$CaCO_3$ An Slope	0.02ns	0.31ns	ns	0.03ns
PG+$CaCO_3$ An Slope	0.30^{***}	0.66^{**}	ns	0.31^{***}
PG+dolomite An Slope	0.27^{***}	0.40ns	ns	0.16ns
<u>B. Rates, Initial (In):</u>				
PG In Slope	0.26^{**}	0.15ns	ns	0.18^{*}
S In Slope	0.01ns	-0.45ns	ns	0.05ns
$CaCO_3$ In Slope	0.02ns	0.12ns	ns	0.01ns
PG+$CaCO_3$ In Slope	0.30^{***}	0.28^{*}	ns	0.19^{**}
PG+dolomite In Slope	0.27^{***}	0.44^{***}		ns
0.29^{***}				
<u>C. Rates, Avg Annual and Avg Initial:</u>				
PG_{all} Avg An Slope	0.28^{***}	0.58^{***}	ns	0.22^{**}
PG_{all} Avg In Slope	0.28^{***}	0.29^{**}	ns	0.22^{***}

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant ($P>0.05$), $^{*}P$ $^{**}P\leq0.05$, $^{***}P\leq0.01$.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

<u>PG versus other amendments.</u> The comparisons for PG_{all} vs S in 1991-92 and over the 3-year period were significant indicating greater slopes for the various PG amendments, averaged across all rates, than those for elemental S, also averaged over all the corresponding rates. The comparisons for PG_{all} vs $CaCO_3$ in 1990-91, 1991-92 and over the 3-year period were significant indicating higher %DM slopes for the PG amendments than those for $CaCO_3$.

Table 82. Comparisons between the slopes (effects of rates) of PG and other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on percent dry matter (%DM) of annual ryegrass, 1990-91 to 1992-93.

Comparisons	Year			Mean
	1990-91[1]	1991-92	1992-93	
<u>Statistics:</u>	-------- (P-value)[2]	--------------		
AR*GT	0.0044			
AR*GT*FREQUENCY		0.0066	ns	
AR*GT*FREQUENCY*YEAR				0.0370
<u>PG vs other amendments:</u>[3]				
PG_{all} vs S	ns	0.0030	ns	0.0097
PG_{all} vs $CaCO_3$	0.0048	0.0936	ns	0.0009
PG vs PG+$CaCO_3$	ns	ns	ns	ns
PG vs PG+dolomite	ns	ns	ns	ns
<u>Annual vs Initial rates:</u>[4]				
PG An vs In	-	ns	ns	ns
S An vs In	-	ns	ns	ns
$CaCO_3$ An vs In	-	ns	ns	ns
PG+$CaCO_3$ An vs In	-	ns	ns	ns
PG+dolomite An vs In	-	ns	ns	ns
PG_{all} Avg An vs Avg In	-	ns	ns	ns

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

<u>**Annual versus initial rates.**</u> Table 82 shows no significant differences between the effects of the annual rates and the initial rates of the various amendments on %DM of annual ryegrass.

Overall, the data on %DM showed that PG, at the annual rates or at the initial rates, increased the solid contents of annual ryegrass regrowth forage, and consequently reduced the water contents in the forage, but this effect did not result in increased forage yield. The fresh PG-fertilized regrowth forages had more solids, hence less water, than forages fertilized with elemental S or $CaCO_3$.

B.1.3. Nutrients in Forage and Other Qualitv Measures

Sulfur content. The %S, averaged over all rates, in annual ryegrass forage are given in Table 83 for the various amendments. Figures 52 and 52A show the trends with the annual and the initial rates.

Table 83. Group treatments and S concentrations in annual ryegrass forage, averaged across annual and initial application rates, 1990-91 to 1992-93.

Group treatments[1]	Year		
	1990-91	1991-92[a]	1992-93
	------------- %S ----------------		
PG	0.27	-	0.21
PG+dolomite[2]	0.27	-	0.20
$PG+CaCO_3$[2]	0.25	-	0.22
PG_{all}[3]	0.26	-	0.21
S (elemental)	0.26	-	0.21
$CaCO_3$	0.22	-	0.16
Control	0.27	-	0.16

[1]See Table 85 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.
[a]No analysis was done.

Table 83 shows similar values in %S for the control and the group treatments in 1990-91 indicating sufficient supply of S in the soil during the first year of the experiment.

Effects of rates. Treatments PG and PG+dolomite increased %S in ryegrass forage in 1990-91 by 0.011 and 0.013% S per Mg PG ha^{-1}, respectively (Table 84). Elemental S and $PG+CaCO_3$ showed no significant slopes in 1990-91. The effect of the PG amendments, averaged over all treatments containing PG and across all rates (PG_{all}), increased %S by 0.010% per Mg PG ha^{-1} in 1990-91.

In the 1992-93 harvests, the annual rates of PG, $PG+CaCO_3$, PG+dolomite, and elemental S increased %S in the forage by 0.024 to 0.029% per Mg PG or unit equivalent rate ha^{-1}. Treatment PG_{all} annual increased %S by 0.028% per Mg PG ha^{-1}. The initial rates of the PG amendments applied in 1990 had lost much of their effect on %S in the 1992-93 harvests (Table 84). Elemental S applied at the initial rate in 1990-91 continued to increase %S in ryegrass in 1992-93 but with a much reduced slope (Table 84).

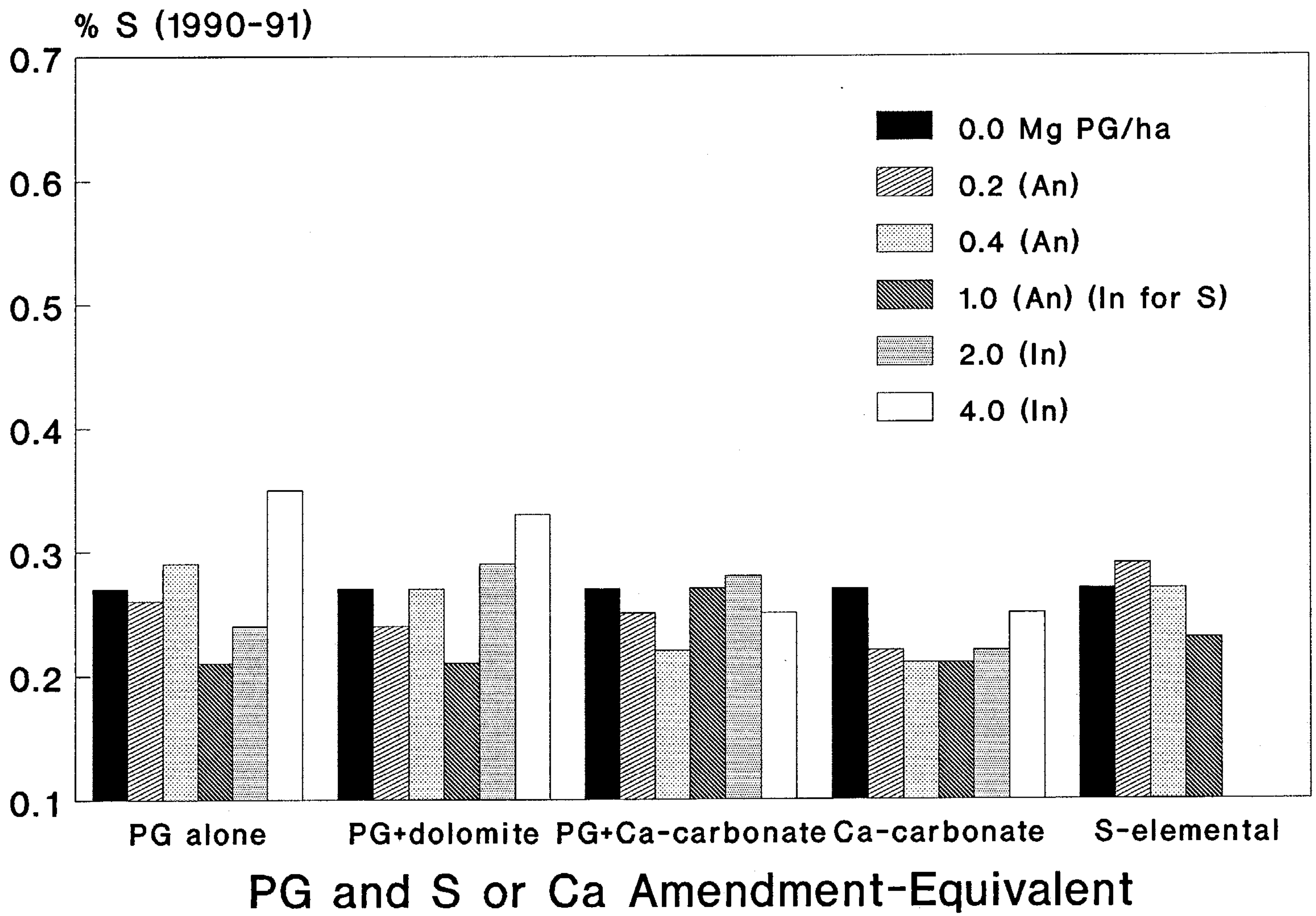


Figure 52. Sulfur concentrations in annual ryegrass regrowth forage, 1990-91, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

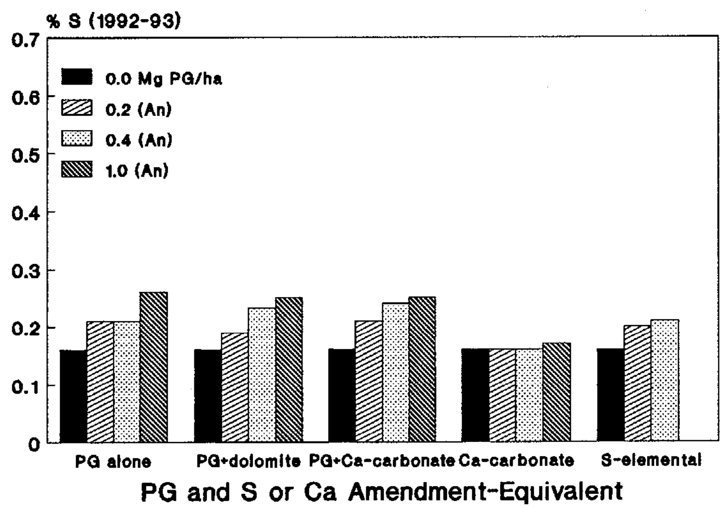


Figure 52A. Sulfur concentrations in annual ryegrass forage, 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

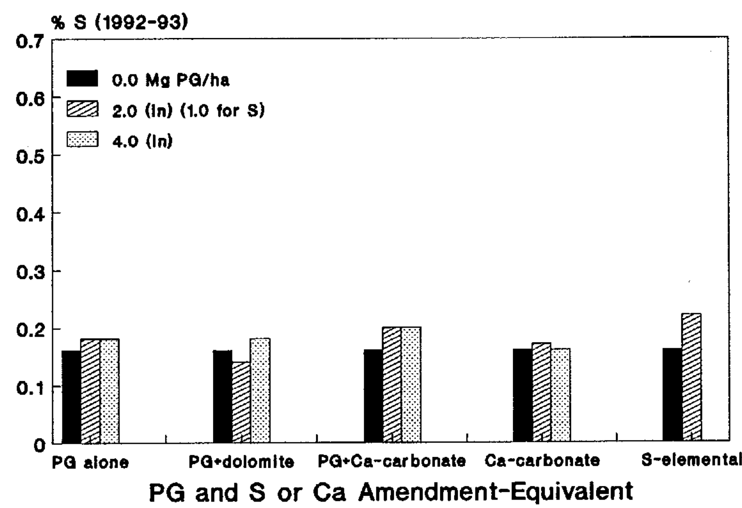


Figure 52B. Sulfur concentrations in annual ryegrass forage, 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

The %S intercepts are the computed %S concentrations in annual ryegrass forage at the zero rates of the various amendments. The much lower 1992-93 %S intercepts compared to the 1990-91 intercepts indicated that the initial soil S had been reduced considerably in 1992-93. Hence, the occurrence of larger %S slopes for the various S amendments in 1992-93 than in 1990-91, especially for the annual rates.

Table 84. Effects of annual (An) and/or initial (In) rates (slopes) of annual and initial rates of PG and other S and Ca amendments on S concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Treatment	Year		
	1990-91[1]	1991-92	1992-93
Intercept	------------ %S ---------------		
	0.237	-	0.167
	----------- (P-value)[2] --------		
AR*GT	0.0203		
AR*GT*FREQUENCY[3]		-	0.0001
Slope	------------ %S/Mg PG ha^{-1} ----		
A. Rates, Annual (An):			
PG An Slope	0.011**	-	0.029***
S An Slope	0.007ns	-	0.024***
$CaCO_3$ An Slope	0.002ns	-	0.001ns
PG+$CaCO_3$ An Slope	0.005ns	-	0.028***
PG+dolomite An Slope	0.013**	-	0.028***
B. Rates, Initial (In):			
PG In Slope	0.011**	-	0.001ns
S In Slope	0.007ns	-	0.016***
$CaCO_3$ In Slope	0.002ns	-	0.001ns
PG+$CaCO_3$ In Slope	0.005ns	-	0.005***
PG+dolomite In Slope	0.013**	-	0.001ns
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	0.010**	-	0.028***
PG_{all} Avg In Slope	0.010**	-	0.002ns

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

Referring back to the forage yield data, the non-significant but apparent positive trends in forage yields in 1991-92 and 1992-93 for the S amendments mentioned earlier could become significant with continuous cropping of these plots with annual ryegrass.

PG versus other amendments. The comparative statistics (Table 85) showed no differences between the effects of PG,, and elemental S, averaged across their equivalent rates, on %S in ryegrass forage. The comparisons between the PG amendments showed no differences in %S slopes. Understandably, the comparisons for PG_{all} vs $CaCO_3$ were significant in 1990-91 and 1992-93, $CaCO_3$ not being an S source.

Table 85. Comparisons between the slopes (effects of rates) of PG and other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on S concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
Statistics:	-------- (P-value)[2]	--------	--------
AR*GT	0.0203		
AR*GT*FREQUENCY		-	0.0001
PG vs other amendments:[3]			
PG_{all} vs S	ns	-	ns
PG_{all} vs $CaCO_3$	0.0046	-	0.0001
PG vs PG+$CaCO_3$	ns	-	ns
PG vs PG+dolomite	ns	-	ns
Annual vs initial rates:[4]			
PG An vs In	-	-	0.0002
S An vs In	-	-	0.0478(-)
$CaCO_3$ An vs In	-	-	ns
PG+$CaCO_3$ An vs In	-	-	0.0287
PG+dolomite An vs In	-	-	0.0001
PG_{all} Avg An vs Avg In	-	-	0.0001

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05).
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

Annual versus initial rates. In 1992-93, the annual rates of PG, $PG+CaCO_3$, and PG+dolomite, or as PG_{all} An, showed greater %S slopes than the initial rates as indicated by the P-values (Table 85). Hence, it is more effective to apply PG at the low rates annually than at the higher rates once in three years. The P-value with negative sign for elemental S annual rates versus the initial rate indicates that elemental S applied at 165 S kg ha^{-1} once in three years is more effective in raising S contents in ryegrass forage per unit rate than the lower rates applied annually.

Calcium content. The Ca contents in ryegrass forage for the various group treatments are given in Table 86 which shows similar %Ca among the various group treatments including the control in 1990-91 and 1991-92. The effects of the various Ca sources became apparent in 1992-93. The trends on the effects of the annual and the initial rates of the amendments on %Ca in ryegrass are shown in Figures 53, 53A, and 53B.

Table 86. Group treatments and Ca concentrations in annual ryegrass forage, averaged across annual and initial application rates, 1990-91 to 1992-93.

Group treatments[1]	Year		
	1990-91	1991-92	1992-93
	%Ca		
PG	0.36	0.57	0.71
PG+dolomite[2]	0.35	0.58	0.70
$PG+CaCO_3$[2]	0.34	0.56	0.72
PG_{all}[3]	0.35	0.57	0.71
S (elemental)	0.32	0.54	0.66
$CaCO_3$	0.36	0.54	0.70
Control	0.36	0.53	0.64

[1]See Table 88 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. The PG amendments showed significant %Ca slopes in 1990-91, ranging from 0.014 to 0.015% per Mg PG ha^{-1} (Table 87). In 1991-92, the annual rates of the individual PG amendments increased %Ca in ryegrass forage by 0.019 to 0.041% with an average of 0.032% per Mg PG ha^{-1} for PG_{all} annual.

In 1992-93, the increases in %Ca for the annual PG rates ranged from 0.040 to 0.045% for the individual amendments with an average (PG_{all} An) of 0.043% per Mg PG ha^{-1}.

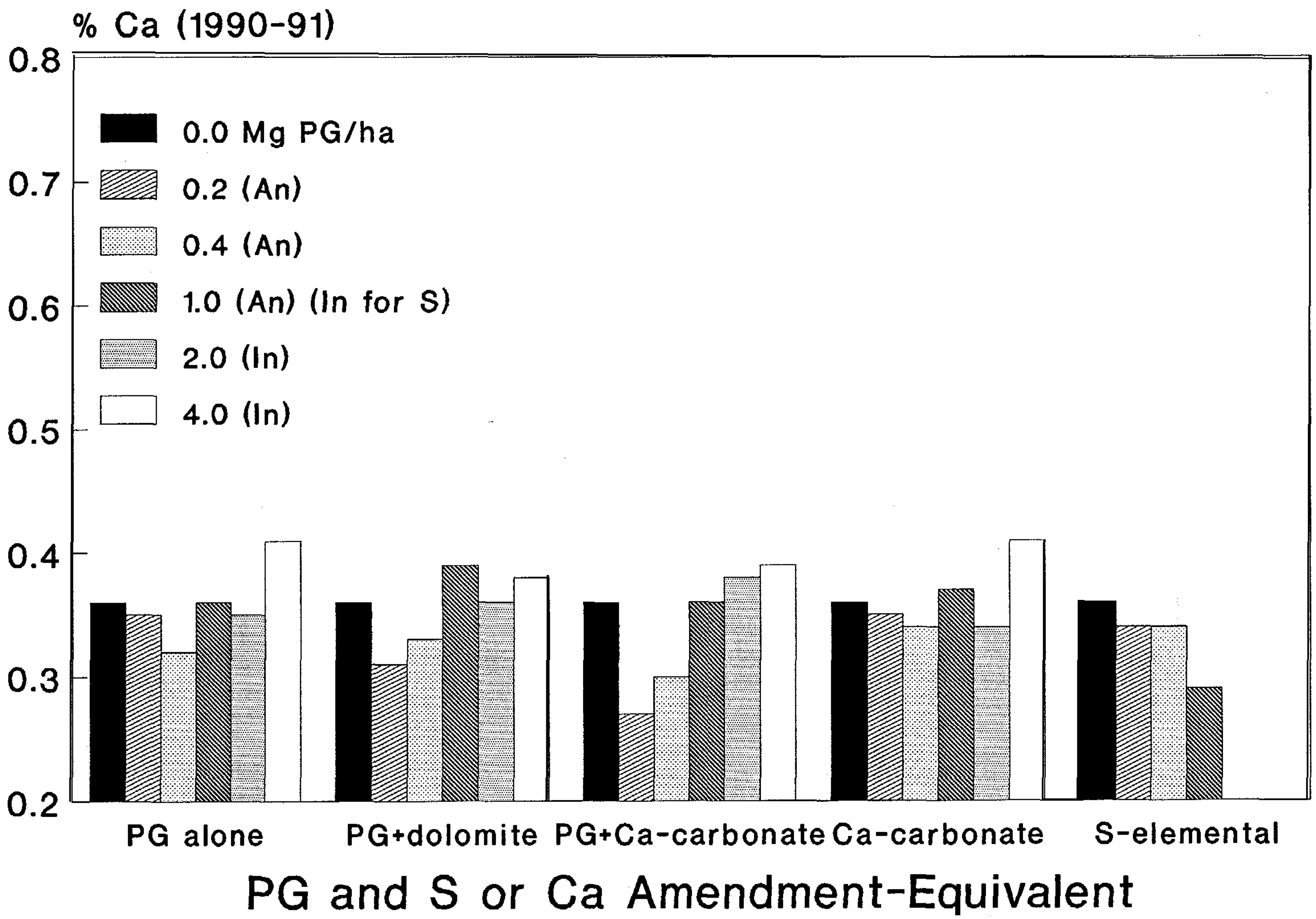


Figure 53. Calcium concentrations in annual ryegrass regrowth forage, 1990-91, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

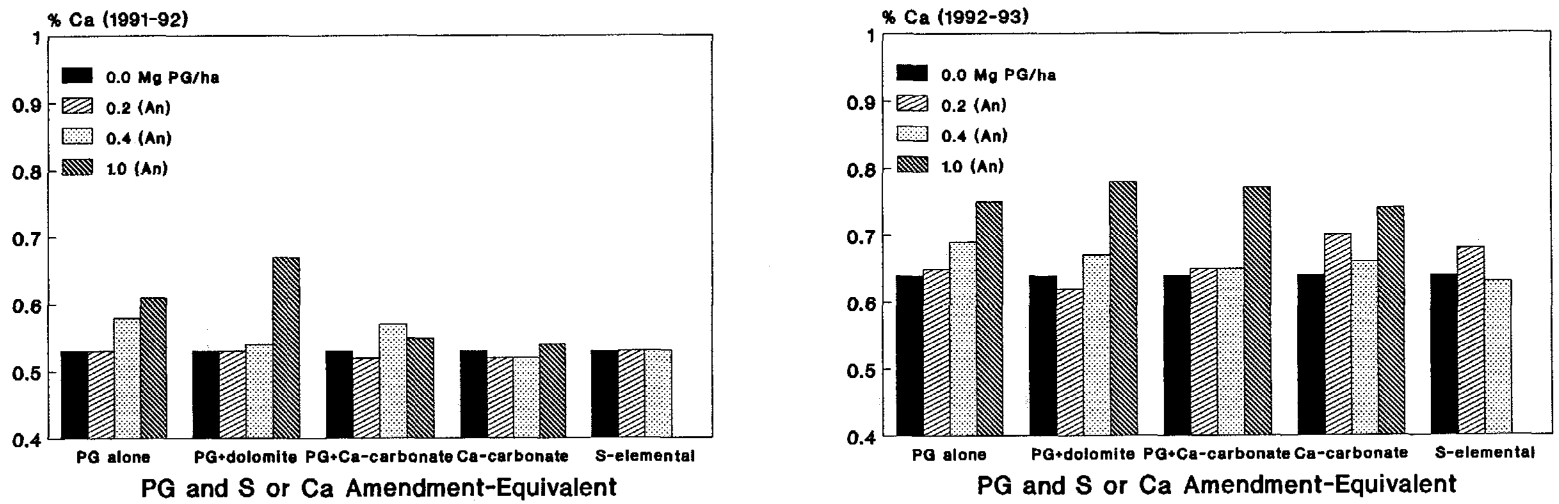


Figure 53A. Calcium concentrations in annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

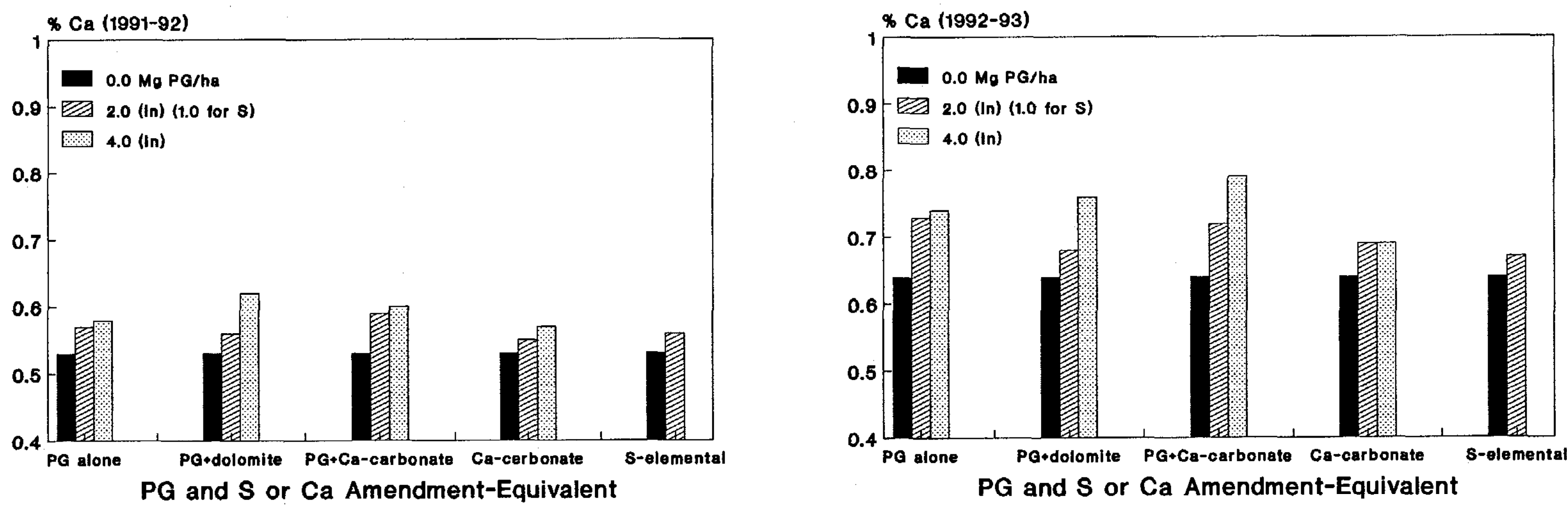


Figure 53B. Calcium concentrations in annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the initial (An) rates in 1990-91.

The initial rates of the individual PG amendments and as a group treatment, PG_{all} In, increased %Ca in ryegrass forage in all three years but at lesser percentages than did the annual rates (Table 87).

Table 87. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on Ca concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
Intercept	------------	%Ca	--------------
	0.415	0.504	0.615
	-----------	(P-value)[2]	--------
AR*GT	0.0001		
AR*GT*FREQUENCY[3]		0.0001	0.0001
Slope	----------	%Ca/Mg PG ha^{-1}	----
A. Rates, Annual (An):			
PG An Slope	0.014***	0.036***	0.045***
S An Slope	0.001ns	0.015ns	0.019ns
$CaCO_3$ An Slope	0.015***	0.011ns	0.041***
PG+$CaCO_3$ An Slope	0.013***	0.019***	0.040**
PG+dolomite An Slope	0.014***	0.041***	0.043**
B. Rates, Initial (In):			
PG In Slope	0.014***	0.016***	0.027***
S In Slope	0.001ns	0.018**	0.018ns
$CaCO_3$ In Slope	0.015***	0.013***	0.016***
PG+$CaCO_3$ In Slope	0.013***	0.019***	0.032***
PG+dolomite In Slope	0.014***	0.020***	0.024***
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	0.014***	0.032***	0.043**
PG_{all} Avg In Slope	0.014***	0.018***	0.027***

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

Treatment $CaCO_3$ at the annual rates increased %Ca in 1990-91 and 1992-93, while the initial rates increased %Ca in all three years.

PG versus other amendments. Despite the dolomite applied earlier to the experimental plots, the comparison for PG_{all} vs $CaCO_3$ indicated significantly higher %Ca slopes for the PG amendments than for $CaCO_3$ in 1991-92 (Table 88). This indicated that the supply of Ca from PG remained important to annual ryegrass despite the Ca from $CaCO_3$ and dolomite. There were no significant P-values for the comparisons between the various PG amendments in all three years. The P-values for PG_{all} vs S showed levels of significance in 1990-91 and 1992-93, elemental S not being a Ca source (Table 88).

Table 88. Comparisons between the slopes (effects of rates) of PG and other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on Ca concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
Statistics:	-------- (P-value)[2]	--------------	
AR*GT	0.0001		
AR*GT*FREQUENCY		0.0001	0.0001
PG vs other amendments:[3]			
PG_{all} vs S	0.0252	ns	0.0570
PG_{all} vs $CaCO_3$	ns	0.0013	ns
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	ns
Annual vs initial rates:[4]			
PG An vs In	-	ns	0.0313(-)
S An vs In	-	ns	ns
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	0.0395(-)	0.0007(-)
PG+dolomite An vs In	-	ns	0.0876(-)
PG_{all} Avg An vs Avg In	-	ns	0.0001(-)

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

Annual versus initial rates. The 1992-93 comparison between the annual rates versus the initial rates for PG+dolomite was slightly significant (Table 88). The comparisons for PG, PG+$CaCO_3$, and PG_{all} were all significant. The negative signs after the P-values indicated that the initial PG rates applied in 1990-91 effectively supplied ryegrass with Ca and even showed a greater slope than the annual rates in the 1992-93 crop based on the actual amounts of PG applied by 1992-93 (Table 88). However, when computed on the basis of the treatment rates, the annual rates slopes were actually greater than the initial rates slopes for all the PG amendments not only in 1992-93 but also in 1991-92 as shown in Table 87.

Based on the results with %Ca in ryegrass forage, PG, as a source of Ca for crops, should be applied to tilled Spodosol land at the low rates annually rather than at the higher initial rates once in three years.

Nitrogen content. The %N in annual ryegrass for the various group treatments, averaged across all rates, are given in Table 89. The trends for the annual and the initial rates are shown in Figures 54, 54A, and 54B.

Table 89. Group treatments and N concentrations in annual ryegrass forage, averaged across annual and initial application rates, 1990-91 to 1992-93.

Group treatments[1]	Year		
	1990-91[1]	1991-92	1992-93
	%N		
PG	2.97	2.75	2.73
PG+dolomite[2]	2.95	2.68	2.59
PG+$CaCO_3$[2]	2.98	2.78	2.73
PG_{all}[3]	2.97	2.74	2.68
S (elemental)	3.03	2.85	2.74
$CaCO_3$	3.11	2.74	2.74
Control	2.77	2.80	2.67

[1]See Table 91 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. In 1990-91, all the amendments at the annual and/or the initial rates showed no significant %N slopes (Table 90). However, Figure 54 showed very apparent positive effects of the various amendments on %N in annual ryegrass forage.

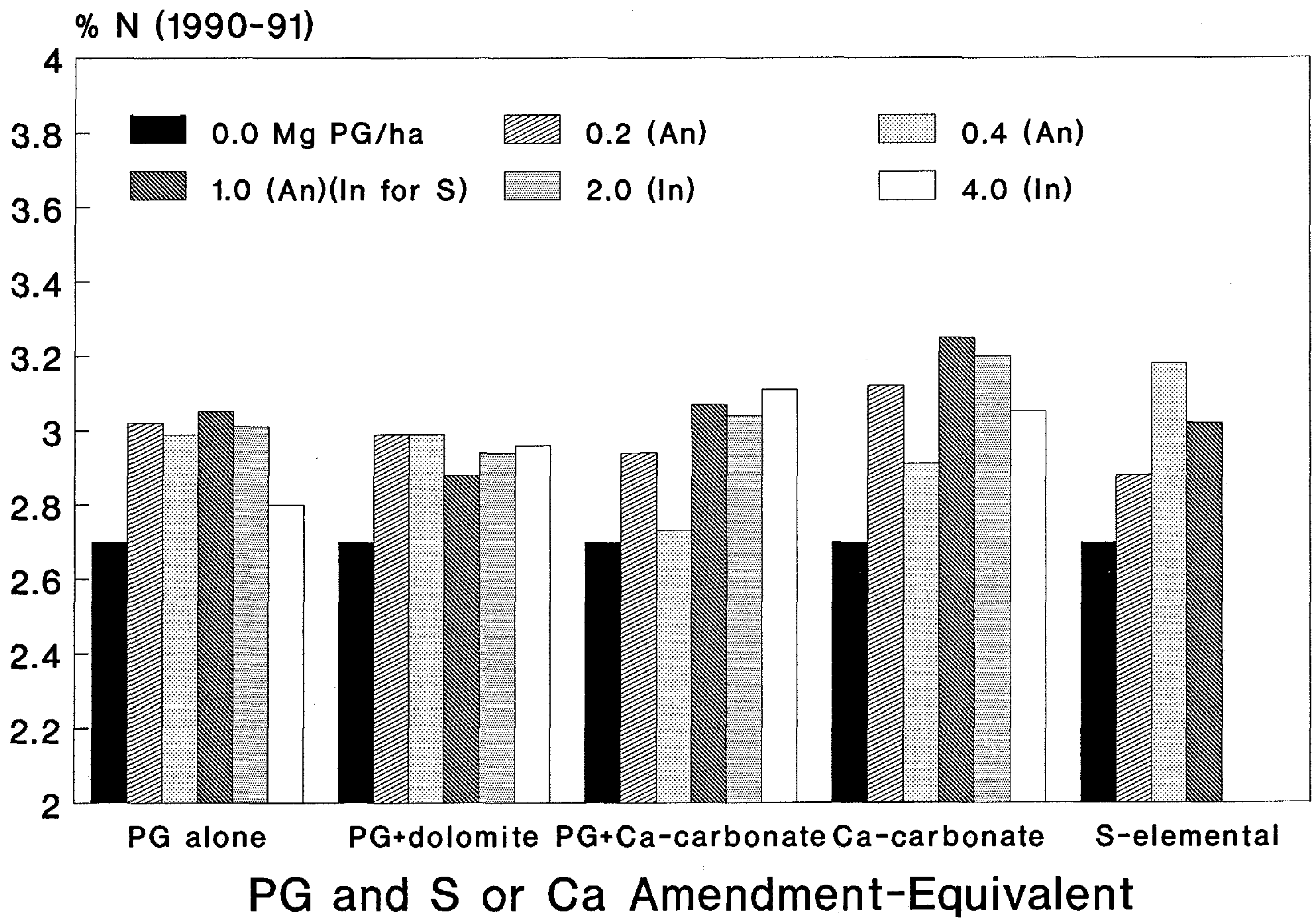


Figure 54. Nitrogen concentrations in annual ryegrass regrowth forage, 1990-91, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

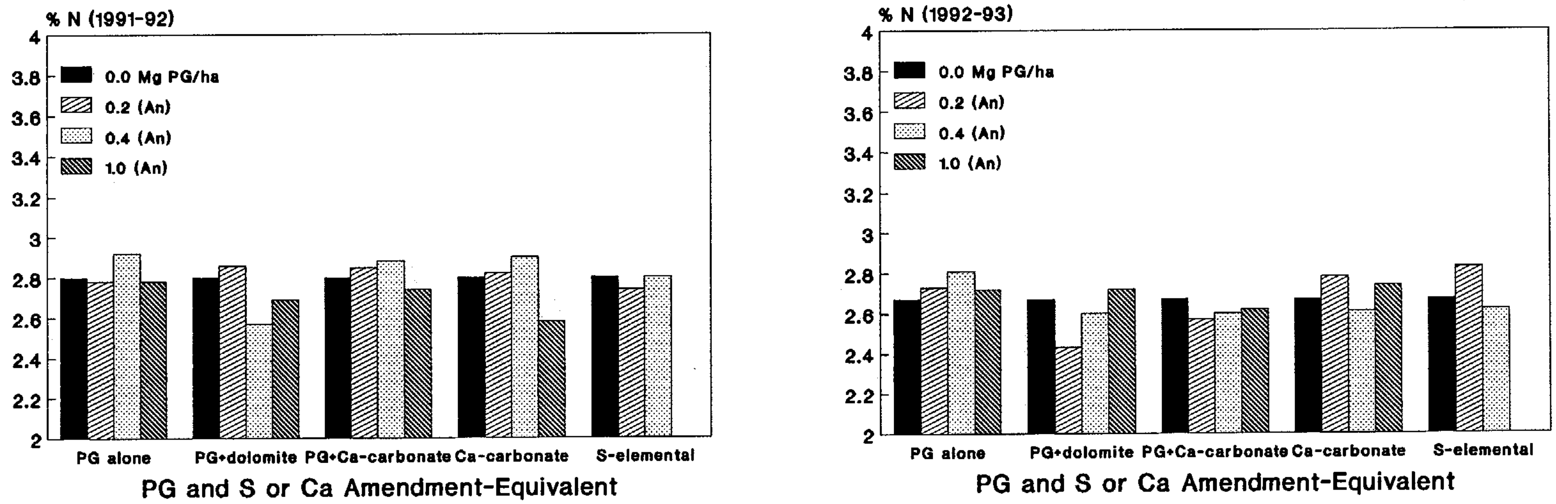


Figure 54A. Nitrogen concentrations in annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

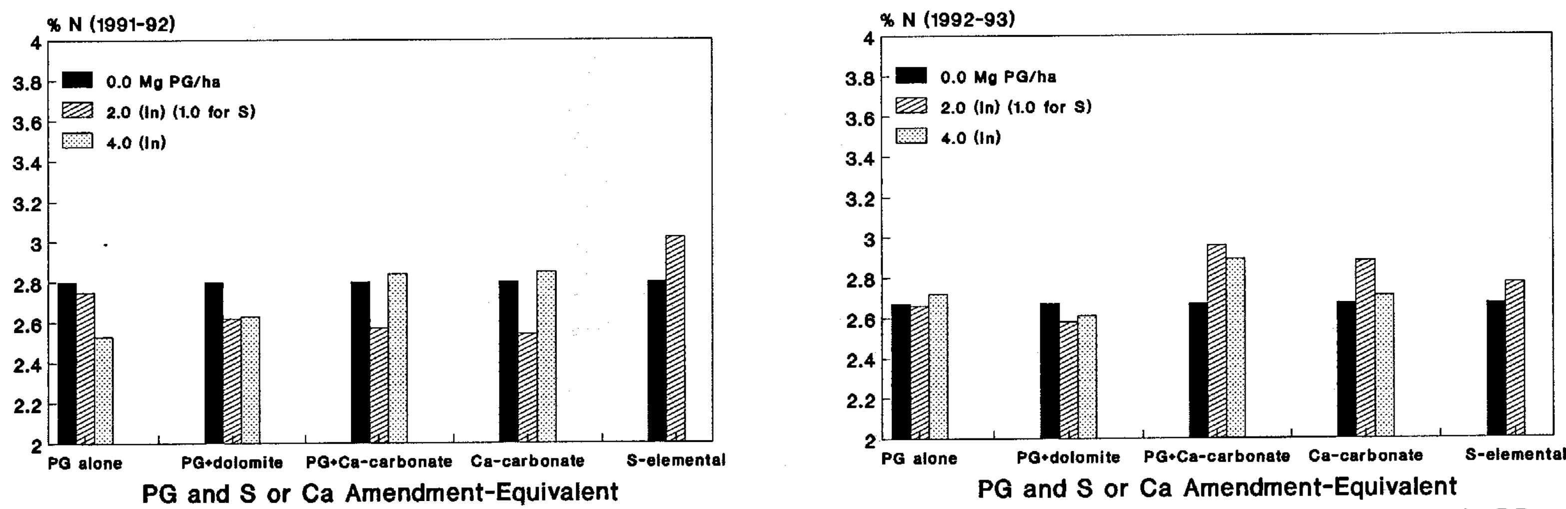


Figure 54B. Nitrogen concentrations in annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

Table 90. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on N concentration in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
Intercept	------------	%N	---------------
	2.922	2.859	2.678
	-----------	(P-value)[2]	--------
AR*GT	ns		
AR*GT*FREQUENCY[3]		0.0792	0.0693
Slope	----------	$\%N/Mg\ PG\ ha^{-1}$	-----
A. Rates, Annual (An):			
PG An Slope	ns	-0.030ns	0.045ns
S An Slope	ns	-0.042ns	0.009ns
$CaCO_3$ An Slope	ns	-0.027ns	0.025ns
PG+$CaCO_3$ An Slope	ns	0.014ns	-0.015ns
PG+dolomite An Slope	ns	-0.055ns	-0.017ns
B. Rates, Initial (In):			
PG In Slope	ns	-0.042*	0.015ns
S In Slope	ns	0.058ns	0.035ns
$CaCO_3$ In Slope	ns	-0.026ns	0.014ns
PG+$CaCO_3$ In Slope	ns	-0.015ns	0.056***
PG+dolomite In Slope	ns	-0.050**	-0.011ns
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	ns	-0.023ns	0.004ns
PG_{all} Avg In Slope	ns	-0.036**	0.020ns

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant ($P>0.05$), *$P<0.10$ (slightly significant), **$P\leq0.05$, ***$P\leq0.01$.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

The %N slopes in 1991-92, with a slightly ($P<0.10$) significant global test AR*GT*FREQUENCY, were mostly negative for the various amendments, with PG_{all} initial reducing %N by 0.036% per Mg PG ha^{-1} (Tabble 90). In 1992-93, PG+$CaCO_3$ increased %N by 0.056% per Mg PG ha^{-1}, but PG_{all} annual or initial had no effect on %N. The somewhat conflicting results indicated that PG had little or no effect on %N in annual ryegrass forage under the conditions of the experiment.

PG versus other amendments. With only slightly significant global tests, it is concluded that the effects of the various amendments on %N in annual ryegrass were not different. However, the comparison PG vs PG+dolomite indicated that there was no advantage in adding dolomite to PG (Table 91).

Table 91. Comparisons between the slopes (effects of rates) of PG and other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on N concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
<u>Statistics:</u>	(P-value)[2]		
AR*GT	ns		
AR*GT*FREQUENCY		0.0792	0.0693
<u>PG vs other amendments:</u>[3]			
PG_{all} vs S	ns	ns	ns
PG_{all} vs $CaCO_3$	ns	ns	ns
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	0.0378
<u>Annual vs initial rates:</u>[4]			
PG An vs In	-	ns	ns
S An vs In	-	0.0595(-)	ns
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	ns	0.0007(-)
PG+dolomite An vs In	-	ns	ns
PG_{all} Avg An vs Avg In	-	0.0686	0.0931(-)

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

Annual versus initial rates. The effects of the annual rates and the initial rates of PG, PG+dolomite, and $CaCO_3$ were not different. With the conflicting 1991-92 and 1992-93 results with PG_{all}, the only conclusion is that the effects of the annual rates an% the initial rates for the various amendments on %N in ryegrass were not different (Table 91).

Phosphorus content. The P contents in annual ryegrass with the group treatments, averaged across all rates, are given in Table 92. The trends for the annual and the initial rates are shown in Figures 55, 55A, and 55B.

Table 92. Group treatments and P concentrations in annual ryegrass forage, averaged across annual and initial application rates, 1990-91 to 1992-93.

Group treatments[1]	Year		
	1990-91	1991-92	1992-93
	------------- %P -----------------		
PG	0.30	0.29	0.51
PG+dolomite[2]	0.28	0.28	0.49
PG+$CaCO_3$[2]	0.28	0.29	0.48
PG_{all}[3]	0.29	0.29	0.49
S (elemental)	0.29	0.32	0.50
$CaCO_3$	0.26	0.27	0.48
Control	0.29	0.31	0.47

[1]See Table 94 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. Table 93 shows that in 1990-91, PG and PG+$CaCO_3$ increased %P in annual ryegrass forage by 0.008 and 0.007% per Mg PG ha^{-1}, respectively, while PG_{all} showed a %P increase of 0.006% per Mg PG ha^{-1}. There was slight evidence that elemental S at the annual rates also increased P content in annual ryegrass forage.

In 1991-92 the annual rates of PG+dolomite and $CaCO_3$ reduced %P by 0.015% and 0.019% per Mg PG or unit equivalent rate ha^{-1}, respectively. The PG_{all} annual rates reduced %P by 0.009% per Mg PG ha^{-1} (Table 93).

The 1992-93 harvests indicated a slight evidence that the initial rate of elemental S increased %P in annual ryegrass. All the other amendments including PG_{all} at the initial rates showed no significant slopes (Table 93).

There were no significant slopes for any of the amendments in 1992-93 (Table 93).

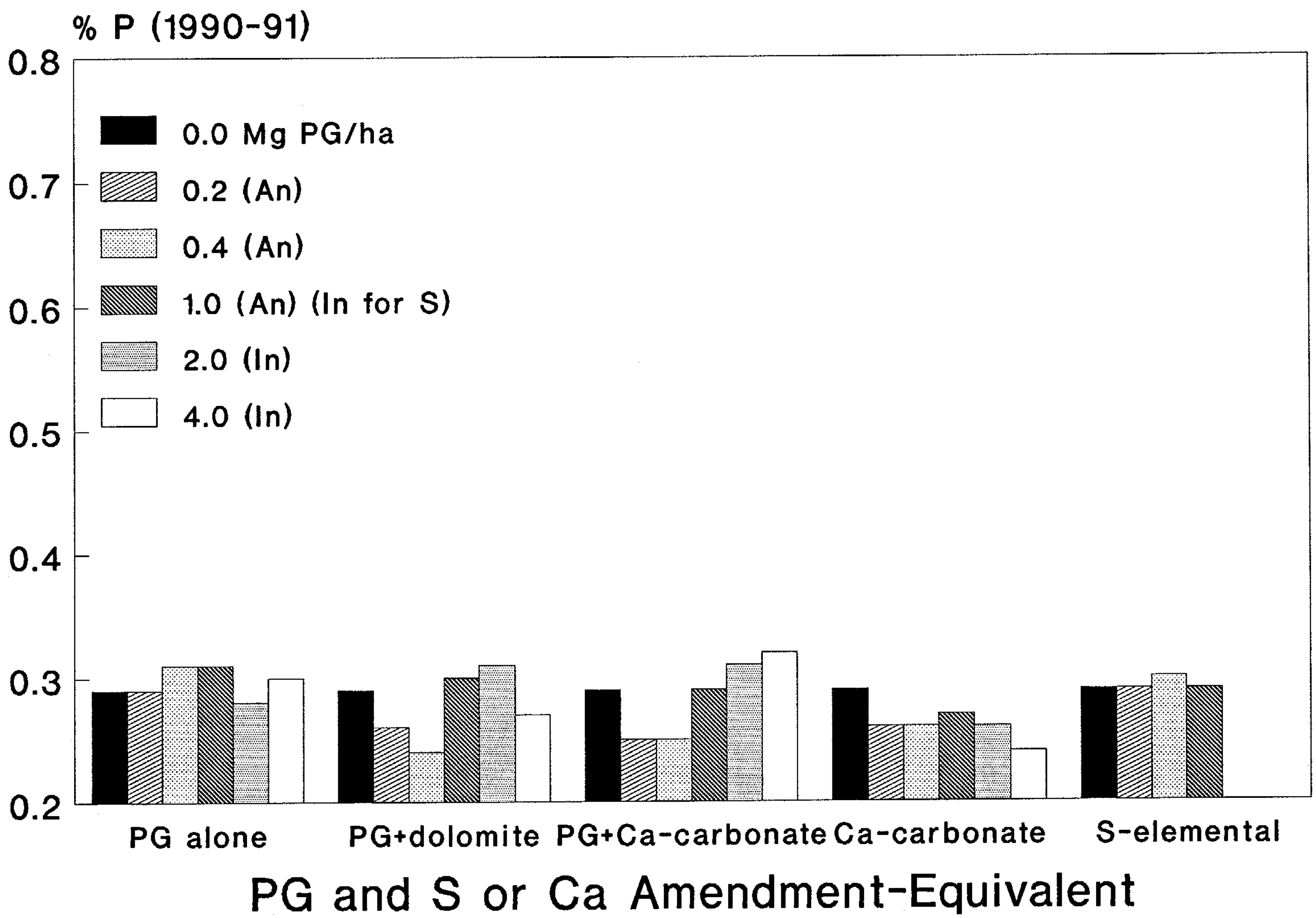


Figure 55. Phosphorus concentrations in annual ryegrass regrowth forage, 1990-91, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

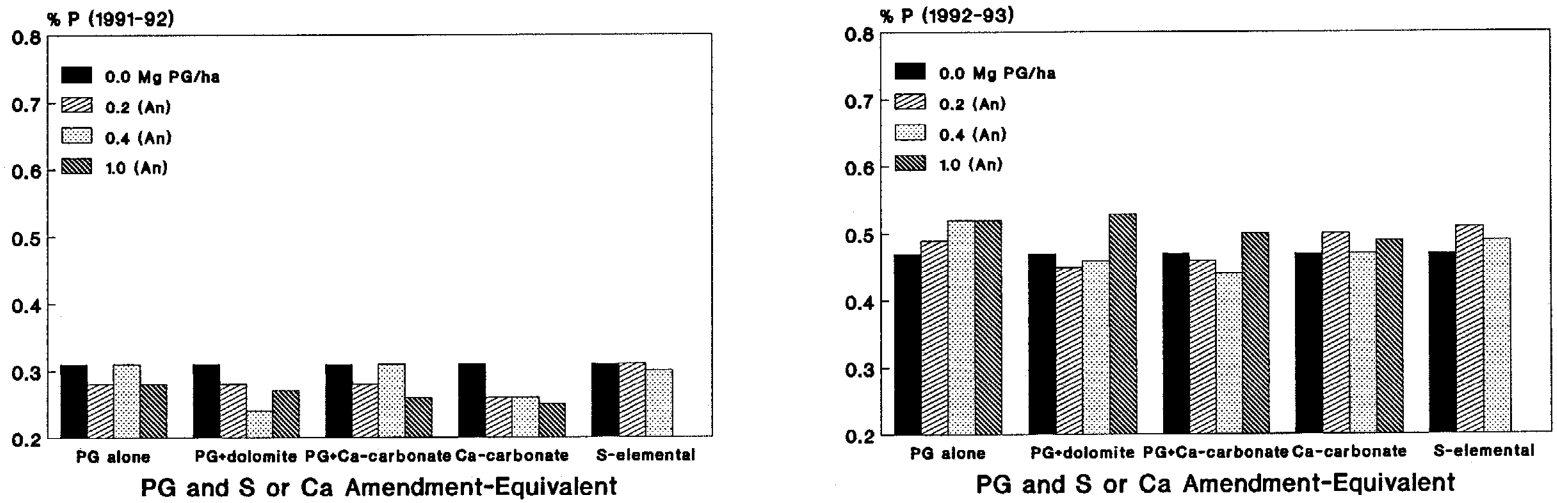


Figure 55A. Phosphorus concentrations in annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

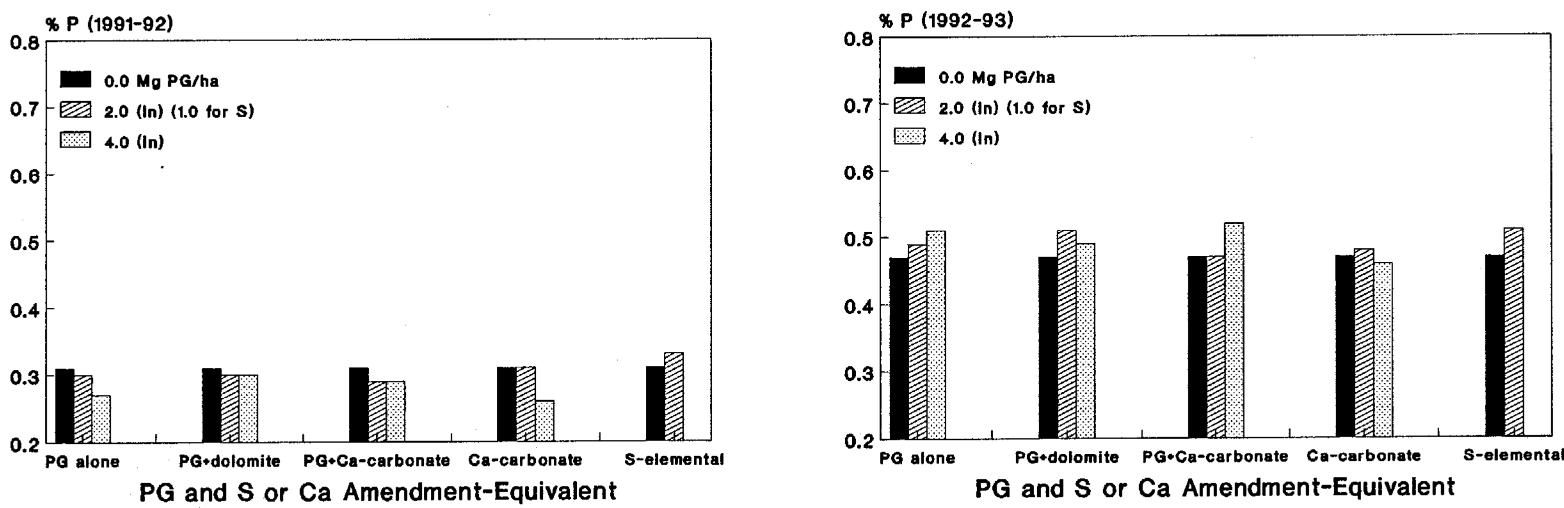


Figure 55B. Phosphorus concentrations in annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

Table 93. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on P concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
<u>Intercept</u>	------------ %P ---------------		
	0.269	0.299	0.460
	----------- (P-value)[2] --------		
<u>AR*GT</u>	0.0014		
<u>AR*GT*FREQUENCY</u>[3]		0.0013	ns
<u>Slope</u>	------------ %P/Mg PG ha^{-1} ----		
<u>A.</u> <u>Rates, Annual (An):</u>			
PG An Slope	0.008**	-0.003ns	ns
S An Slope	0.011*	0.005ns	ns
$CaCO_3$ Slope	-0.004ns	-0.019***	ns
PG+$CaCO_3$ An Slope	0.007**	-0.007ns	ns
PG+dolomite An Slope	0.003ns	-0.015**	ns
<u>B.</u> <u>Rates, Initial (In):</u>			
PG In Slope	0.008**	-0.003ns	ns
S In Slope	0.011*	0.011*	ns
$CaCO_3$ In Slope	-0.004ns	-0.004ns	ns
PG+$CaCO_3$ In Slope	0.007**	-0.002ns	ns
PG+dolomite In Slope	0.003ns	0.001ns	ns
<u>C.</u> <u>Rates, Avg Annual and Avg Initial:</u>			
PG_{all} Avg An Slope	0.006**	-0.009*	ns
PG_{all} Avg In Slope	0.006**	-0.001ns	ns

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), *P<0.10 (slightly significant), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

<u>PG versus other amendments.</u> The comparison PG vs S indicated in 1991-92 that the PG amendments (PG_{all}) enhanced P uptake by annual ryegrass less than did elemental S (Table 94). On the other hand, the comparisons for PG_{all} vs $CaCO_3$ in 1990-91 and 1991-92 showed that the PG amendments had more positive effects on P uptake by annual ryegrass than $CaCO_3$ (Table 94).

Table 94. Comparisons between the slopes (effects of rates) of PG and other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on P concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
Statistics:	-------- (P-value)[2]	--------------	
AR*GT	0.0014		
AR*GT*FREQUENCY		0.0013	ns
PG vs other amendments:[3]			
PG_{all} vs S	ns	0.0091(-)	ns
PG_{all} vs $CaCO_3$	0.0002	0.0233	ns
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	ns
Annual vs initial rates:[4]			
PG An vs In	-	ns	ns
S An vs In	-	ns	ns
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	ns	ns
PG+dolomite An vs In	-	ns	ns
PG_{all} Avg An vs Avg In	-	0.0172(-)	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05).
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

Annual versus initial rates. The effects of the annual rates and the initial rates for the various amendments analyzed individually were not different. In 1991-92 there was evidence that the PG amendments (PG_{all}) applied at the annual rates had less positive effect on %P in annual ryegrass than the PG amendments applied at the initial rates (Table 94).

Potassium content. The %K in annual ryegrass for the various group treatments, averaged across all rates, are given in Table 95. The 1990-91 and 1991-92 data show that the control forage had apparently higher %K than the amended forage. The trends for the annual and the initial rates are shown in Figures 56, 56A, and 56B.

Table 95. Group treatments and K concentrations in annual ryegrass forage, averaged across annual and initial application rates, 1990-91 to 1992-93.

Group treatments[1]	Year		
	1990-91[1]	1991-92	1992-93
	%K		
PG	1.09	1.02	1.63
PG+dolomite[2]	1.01	1.01	1.58
PG+$CaCO_3$[2]	1.00	1.04	1.61
PG_{all}[3]	1.03	1.02	1.61
S (elemental)	1.10	1.12	1.65
$CaCO_3$	1.03	1.05	1.67
Control	1.30	1.28	1.58

[1]See Table 97 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. There were no significant slopes in 1990-91 and 1992-93 for the various amendments (Table 96).

In 1991-92 all the amendments at the annual rates showed negative %K slopes. The annual rates of the various PG amendments and $CaCO_3$ reduced K contents in ryegrass forage by 0.055 to 0.074% per Mg PG or unit equivalent rate ha^{-1}. The replacement of K by Ca in the exchange complex in the soil and the eventual loss of K from the main roots zones may have adversely affected K uptake by the ryegrass. On the average, the PG amendments at the annual rates (PG_{all} An) reduced %K in the forage by 0.063%. There was also slight evidence that elemental S at the annual rates also reduced S contents in ryegrass (Table 96).

The initial rates of the various PG amendments also reduced K contents in annual ryegrass in 1991-92, but to a much lesser degree than did the annual rates. On the average, the PG amendments at the initial rates (PG_{all} In) reduced %K by 0.038% per Mg PG ha^{-1}.

The effects of elemental S and $CaCO_3$ at the initial rates in 1991-92 on K contents in ryegrass were not significant.

PG versus other amendments. The P-values for the various comparisons were not significant in all three years (Table 97) indicating similar magnitudes in the adverse effects of the various amendments on K contents in ryegrass.

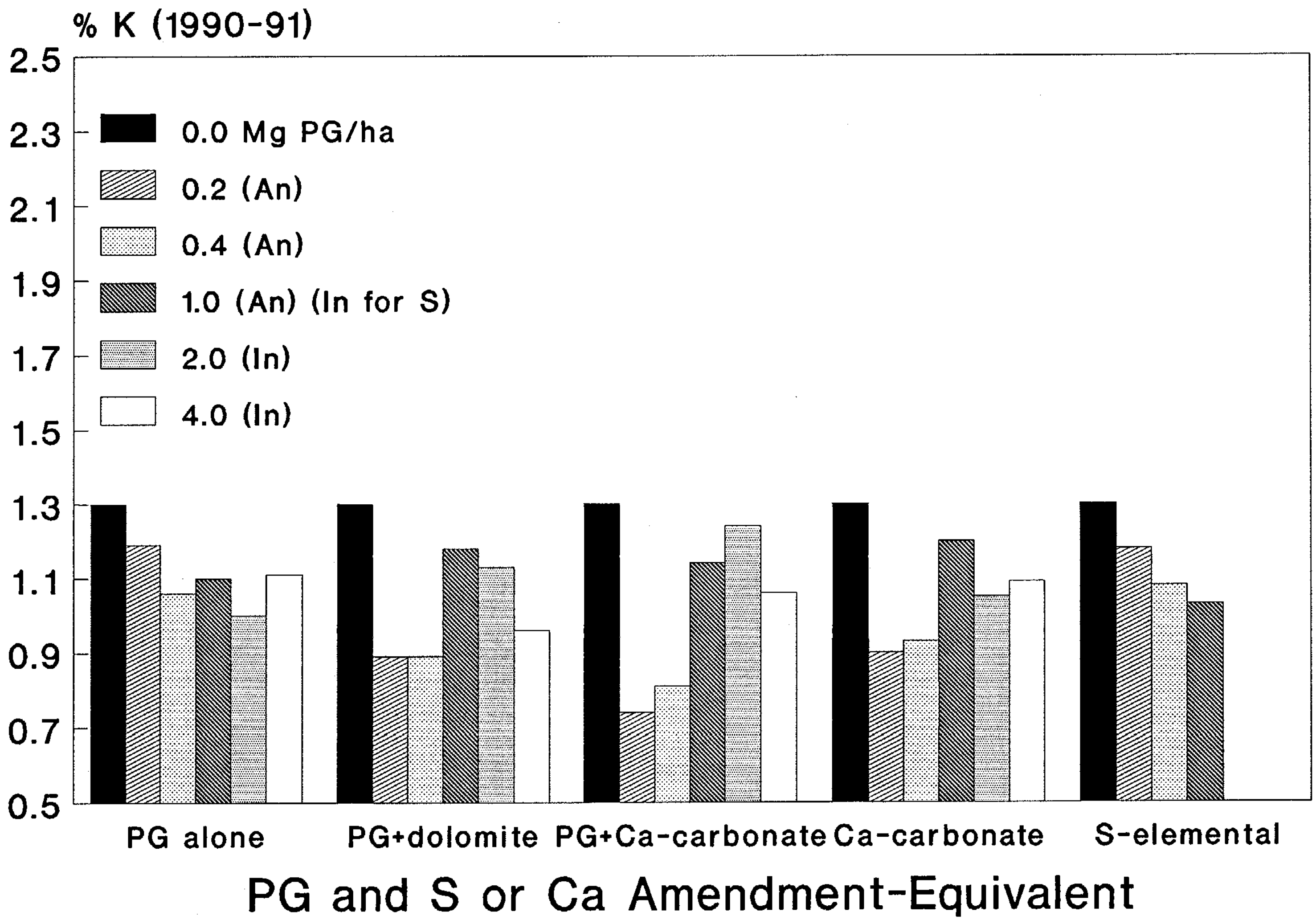


Figure 56. Potassium concentrations in annual ryegrass regrowth forage, 1990-91, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

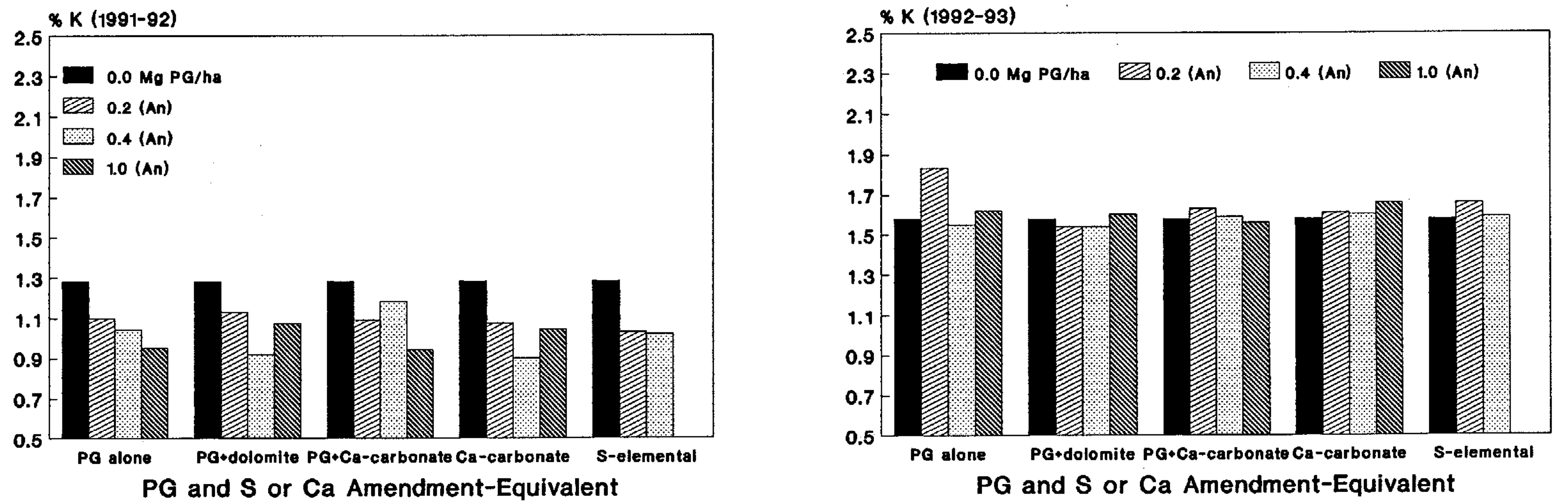


Figure 56A. Potassium concentrations in annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

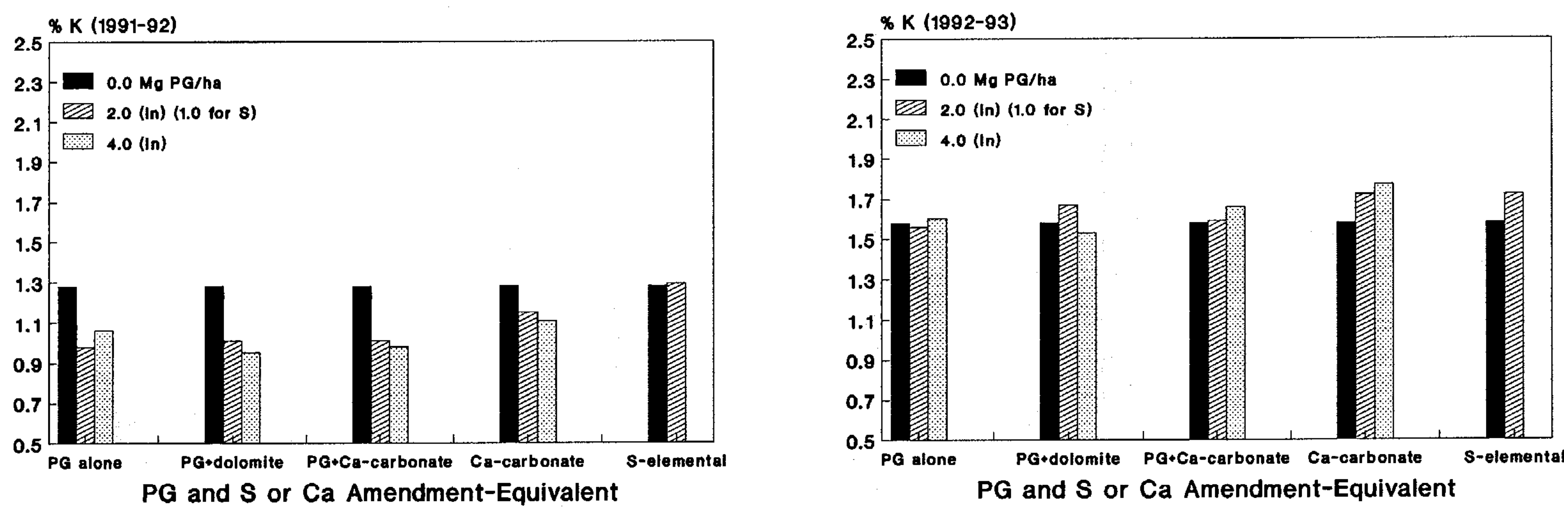


Figure 56B. Potassium concentrations in annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments

Table 96. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on K concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
Intercept	------------ %K ---------------		
	1.005	1.171	1.633
	----------- (P-value)[2] --------		
AR*GT	ns		
AR*GT*FREQUENCY[3]		0.0101	ns
Slope	------------ %K/Mg PG ha^{-1} ----		
A. Rates, Annual (An):			
PG An Slope	ns	-0.072**	ns
S An Slope	ns	-0.087*	ns
$CaCO_3$ An Slope	ns	-0.074**	ns
PG+$CaCO_3$ An Slope	ns	-0.055*	ns
PG+dolomite An Slope	ns	-0.062**	ns
B. Rates, Initial (In):			
PG In Slope	ns	-0.033**	ns
S In Slope	ns	0.041ns	ns
$CaCO_3$ In Slope	ns	-0.008ns	ns
PG+$CaCO_3$ In Slope	ns	-0.039**	ns
PG+dolomite In Slope	ns	-0.042***	ns
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	ns	-0.063***	ns
PG_{all} Avg In Slope	ns	-0.038***	ns

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), *P<0.10 (slightly significant), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

Annual versus initial rates. With slopes computed on the basis of the actual amounts of amendments applied, the comparisons for the various PG amendments and PG_{all} showed no significant differences in the effects of the annual rates and the initial rates on K contents in ryegrass in 1991-92 and 1992-93 (Table 97). The comparison for elemental S in 1991-92 indicated that the annual rates and the initial rate slopes in Table 96 were significantly different, with the annual rates causing greater adverse effects on K contents in ryegrass than the initial rates. There was also an indication that the annual rates of $CaCO_3$ had a more adverse effect on K content in ryegrass than the initial rates.

Table 97. Comparisons between the slopes (effects of rates) of PG and other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on K concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
Statistics:	(P-value)[2]		
AR*GT	ns		
AR*GT*FREQUENCY		0.0101	ns
PG vs other amendments:[3]			
PG_{all} vs S	ns	ns	ns
PG_{all} vs $CaCO_3$	ns	ns	ns
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	ns
Annual vs initial rates:[4]			
PG An vs In	-	ns	ns
S An vs In	-	0.0081(-)	ns
$CaCO_3$ An vs In	-	0.0819(-)	ns
PG+$CaCO_3$ An vs In	-	ns	ns
PG+dolomite An vs In	-	ns	ns
PG_{all} Avg An vs Avg In	-	ns	ns

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P-values <0.10 are also given and referred to as "slightly significant for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

Magnesium. The %Mg in annual ryegrass for the various group treatments, averaged across all rates, are given in Table 98. The trends for the annual and the initial rates are shown in Figures 57, 57A, and 57B.

Table 98. Group treatments and Mg concentrations in annual ryegrass forage, averaged across annual and initial application rates, 1990-91 to 1992-93.

Group treatments[1]	Year		
	1990-91[1]	1991-92	1992-93
	------------- %Mg ----------------		
PG	0.33	0.43	0.47
PG+dolomite[2]	0.35	0.45	0.46
PG+$CaCO_3$[3]	0.32	0.43	0.47
PG_{all}[3]	0.33	0.44	0.47
S (elemental)	0.35	0.49	0.52
$CaCO_3$	0.37	0.45	0.50
Control	0.38	0.48	0.52

[1]See Table 100 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. In 1990-91, PG and PG+$CaCO_3$, but not PG+dolomite, significantly reduced %Mg in ryegrass forage by 0.009% to 0.010% per Mg PG ha^{-1}. Probably because of PG+dolomite, PG_{all} annual only slightly significantly reduced Mg contents by 0.006 per Mg PG ha^{-1}. The slopes for elemental S and $CaCO_3$ were not significant (Table 99).

In 1991-92, the annual rates of PG and PG+$CaCO_3$, but not PG+dolomite, reduced tissue Mg by 0.016 to 0.018% per Mg PG ha^{-1}. Again, because of the less adverse effects of PG+dolomite on %Mg, PG_{all} annual only slightly significantly reduced Mg contents by 0.010 per Mg PG ha^{-1}. By 1992-93, all PG amendments, including PG+dolomite, reduced tissue Mg significantly by 0.015 to 0.020% per Mg PG ha^{-1}, with PG_{all} annual also significantly reducing Mg in forage 0.018% per Mg PG ha^{-1} (Table 99).

The initial rates of PG, PG+$CaCO_3$, and PG+dolomite reduced %Mg in 1991-92 by 0.014 to 0.017% per Mg PG ha^{-1}. On the average, PG_{all} initial reduced Mg contents in ryegrass by 0.016% per Mg PG ha^{-1}. The adverse effects of the initial rates of the PG amendments on tissue Mg were much less in 1992-93 than they were in 1991-92 (Table 99).

The %Mg slopes of the annual rates of $CaCO_3$ and the initial rates of elemental S were slightly significant in 1991-92, but not in the other years (Table 99). These indicate that $CaCO_3$ and elemental S may also adversely affect Mg uptake by annual ryegrass.

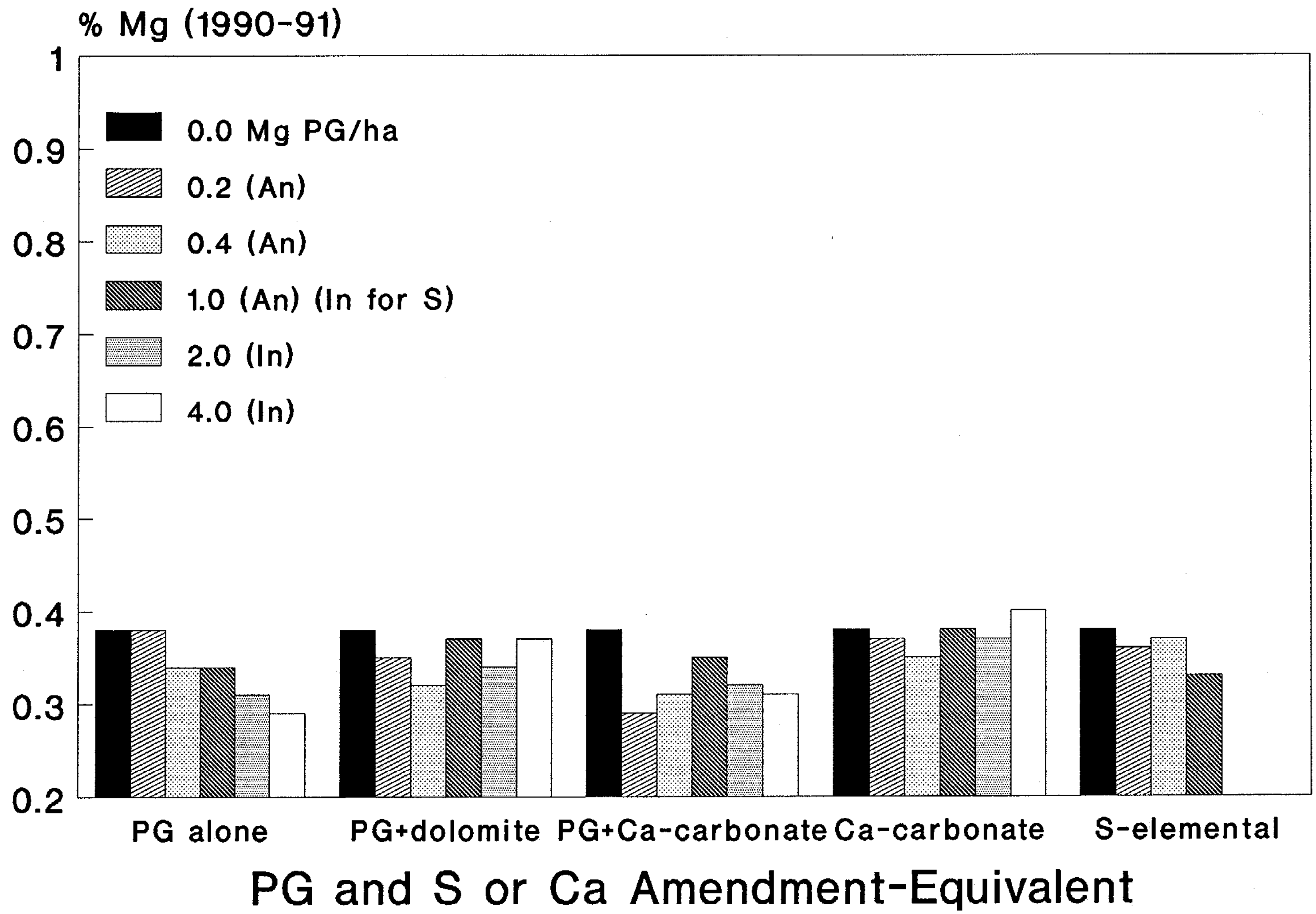


Figure 57. Magnesiun concentrations in annual ryegrass regrowth forage, 1990-91, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

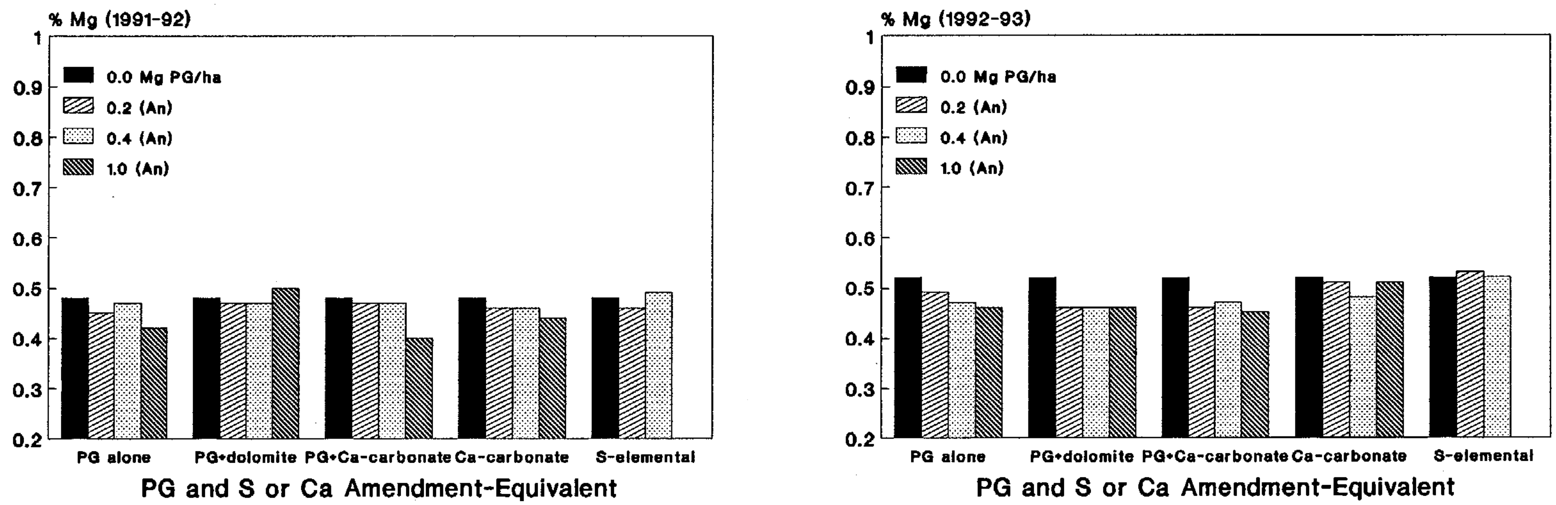


Figure 57A. Magnesium concentrations in annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

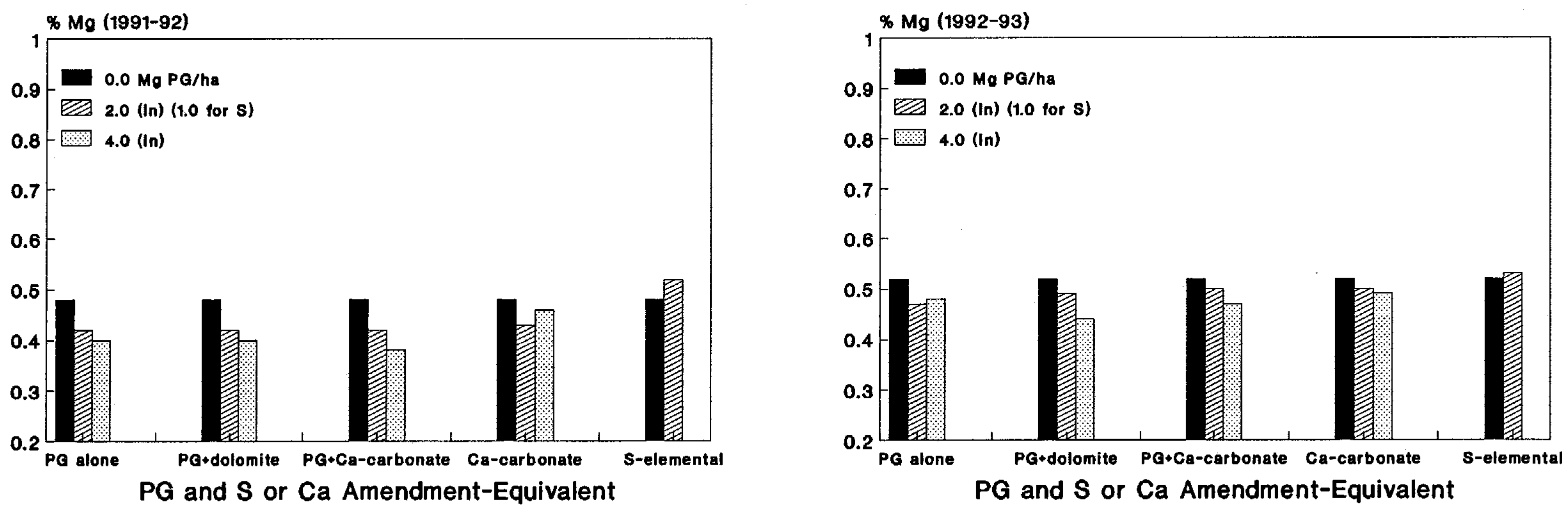


Figure 57B. Magnesium concentrations in annual ryegrass regrowth forage, 1991-92 and 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

Table 99. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on Mg concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
<u>Intercept</u>	------------ %Mg --------------		
	0.355	0.476	0.503
	----------- (P-value)[2] --------		
<u>AR*GT</u>	0.0026		
<u>AR*GT*FREQUENCY</u>[3]		0.0001	0.0006
<u>Slope</u>	----------- %Mg/Mg PG ha^{-1} ----		
<u>A.</u> <u>Rates, Annual (An):</u>			
PG An Slope	-0.010**	-0.016***	-0.015**
S An Slope	-0.002ns	0.003ns	0.001ns
$CaCO_3$ An Slope	0.006ns	-0.013*	-0.001ns
PG+$CaCO_3$ An Slope	-0.009**	-0.018***	-0.020***
PG+dolomite An Slope	0.000ns	0.003ns	-0.019***
<u>B.</u> <u>Rates, Initial (In):</u>			
PG In Slope	-0.010**	-0.014***	-0.007*
S In Slope	-0.002ns	0.012*	0.010ns
$CaCO_3$ In Slope	0.006ns	-0.006ns	-0.003ns
PG+$CaCO_3$ In Slope	-0.009**	-0.017***	-0.004ns
PG+dolomite In Slope	0.000ns	-0.015***	-0.009**
<u>C.</u> <u>Rates, Avg Annual and Avg Initial:</u>			
PG_{all} Avg An Slope	-0.006*	-0.010*	-0.018***
PG_{all} Avg In Slope	-0.006*	-0.016***	-0.007**

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), *P<0.10 (slightly significant), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

<u>**PG versus other amendments.**</u> The P-values for the comparison PG_{all} vs S in 1991-92 and 1992-93 (Table 100) showed that the slopes for PG_{all} were significantly different from the slopes for elemental S in Table 99. The negative signs indicated that the effects of the PG amendments as a whole on %Mg in ryegrass were more adverse than those of elemental S. Similar results were noted for PG_{all} vs $CaCO_3$.

The P-values for PG vs PG+dolomite in 1990-91 and 1991-92, showed that their slopes were significantly different. Again, the negative signs indicated that PG had a more negative effect on %Mg than PG+dolomite. Thus, the addition of dolomite to PG most likely should mitigated the adverse effects of PG on %Mg in ryegrass.

Table 100. Comparisons between the slopes (effects of rates) of PG and other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on Mg concentrations in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
Statistics:	-------- (P-value)[2] --------------		
AR*GT	0.0026		
AR*GT*FREQUENCY		0.0001	0.0006
PG vs other amendments:[3]			
PG_{all} vs S	ns	0.0003(-)	0.0002(-)
PG_{all} vs $CaCO_3$	0.0010(-)	ns	0.0019(-)
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	0.0250(-)	0.0325(-)	ns
Annual vs initial rates:[4]			
PG An vs In	-	0.0962	ns
S An vs In	-	ns	ns
$CaCO_3$ An vs In	-	ns	ns
PG+$CaCO_3$ An vs In	-	0.0347	ns
PG+dolomite An vs In	-	0.0001	ns
PG_{all} Avg An vs Avg In	-	0.0001	ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

Annual versus initial rates. Only in 1991-92 were there significant differences between the effects of the annual rates and the initial rates on tissue Mg for the individual PG amendments and for PG_{all} (Table 100). The absence of negative signs meant that the initial rates %Mg slopes were more negative than the annual rates slopes computed on the basis of the actual amounts of PG applied by 1991-92. By 1992-93, on the basis of the actual amounts of PG applied by 1992-93, the slopes for the annual and the initial rates were no longer significantly different.

N:S ratio. The N:S ratios in annual ryegrass, averaged across all rates, for the various amendments are given in Table 101.

The trends with the annual and-the initial rates are shown in Figures 58 and 58A. Contrary to the expected effect of the S amendments on the N:S ratios in forage, Figure 58 shows the amended forages with much higher N:S ratios than the control. Referring back to N and S contents in the forage in Figure 51 and Figure 52, respectively, it is seen that the N:S ratios in Figure 58 were due to the higher N contents in the amended forage than in the control forage and to the similar %S in both treated and control forages. By 1992-93, after three applications of the various S amendments at the annual rates, the N:S ratios went down to levels which were within the ideal range of 12:1 to 15:1 for cattle (McDowell et al., 1993) with the control and the $CaCO_3$-treated forages having a N:S ratio of about 17:1 (Table 101).

Table 101. Group treatments and N:S ratios in annual ryegrass forage, averaged across annual and initial application rates, 1990-91 to 1992-93.

Group treatments[1]	Year		
	1990-91[1]	1991-92	1992-93
	N:S		
PG	11.00	-	13.00
PG+dolomite[2]	10.93	-	12.95
PG+$CaCO_3$[2]	11.92	-	12.41
PG_{all}[3]	11.28	-	12.79
S (elemental)	11.65	-	13.05
$CaCO_3$	14.14	-	17.13
Control	10.26	-	16.69

[1]See Table 103 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. Table 102 shows that the N:S slopes for the individual PG amendments in 1990-91 were negative, with PG+dolomite having a significant N:S slope that reduced the N:S ratio by 0.69 unit per Mg PG ha^{-1}. Analyzed as a whole and across all rates, PG_{all} reduced N:S ratio by 0.52 unit per Mg PG ha^{-1}. Elemental S during the first year showed no significant effect on the N:S ratios.

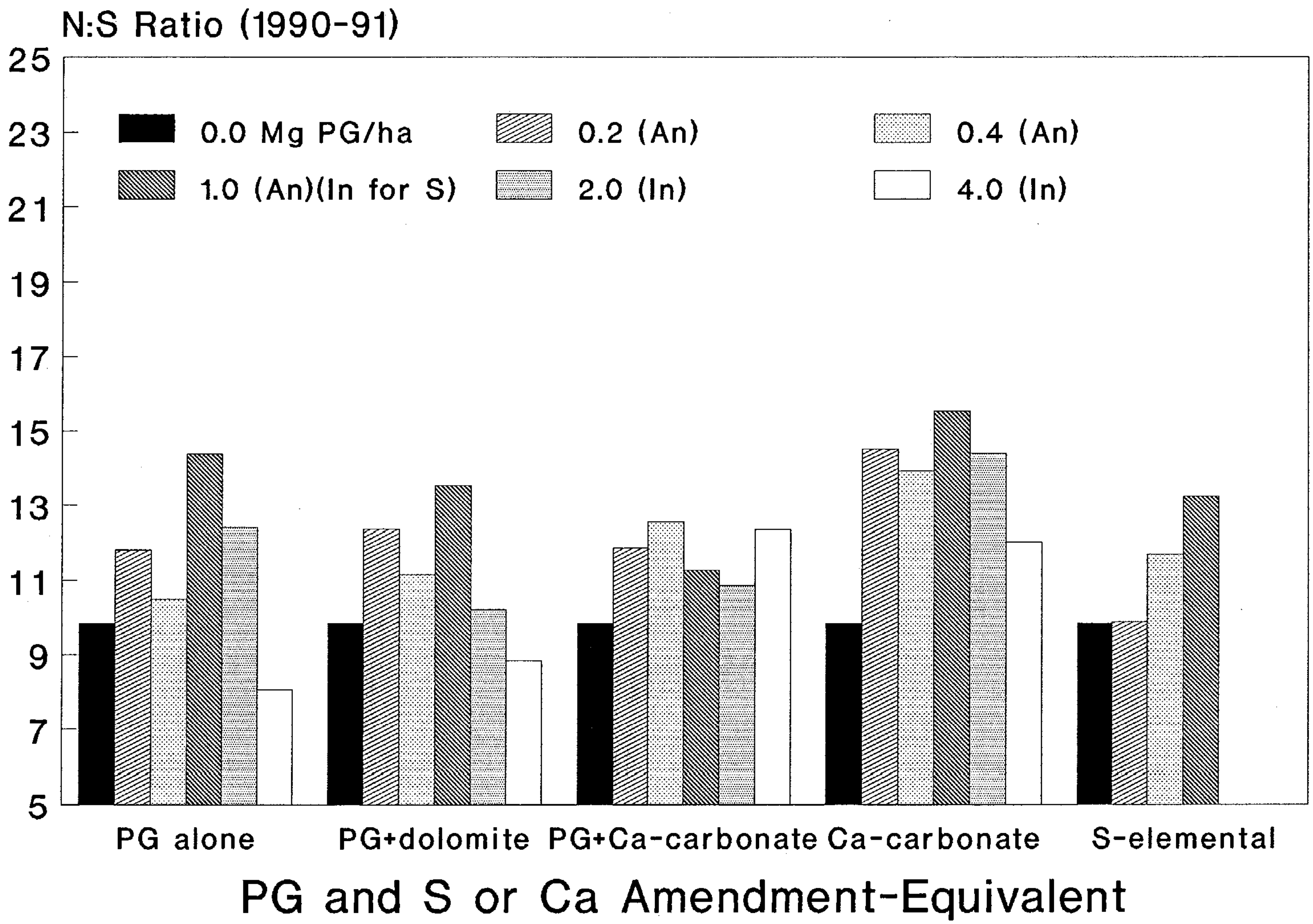


Figure 58. N:S ratios in annual ryegrass regrowth forage, 1990-91, from plots which were amended with PG and S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

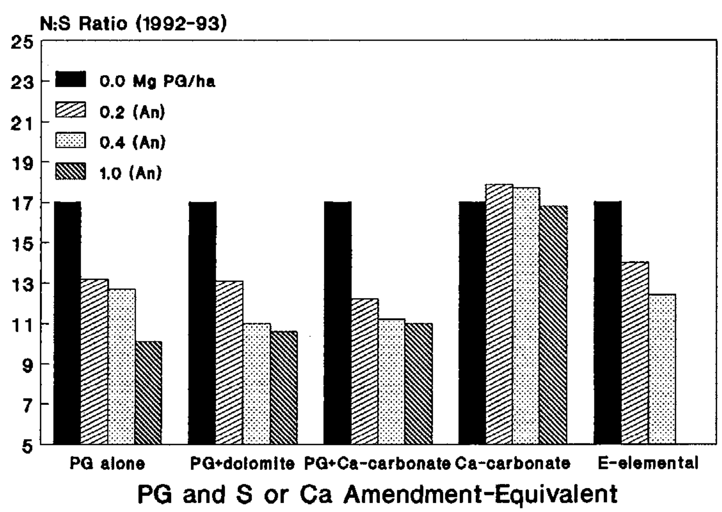


Figure 58A. N:S ratios in annual rye-grass regrowth forage, 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

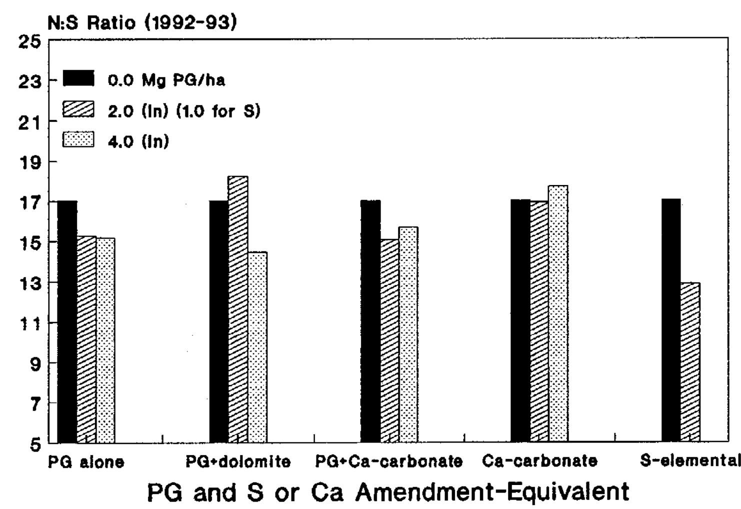


Figure 58B. N:S ratios in annual rye-grass regrowth forage, 1992-93, from plots which were amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

In 1992-93 the PG amendments applied at the annual rates reduced the N:S ratios by a range of 1.90 to 2.05 units per Mg PG ha^{-1}. As a group, PG_{all} annual reduced N:S ratios by 2.00 units per Mg PG ha^{-1}. The initial rates of the various PG amendments applied in 1990-91 lost their effects, individually or as a group, by 1992-93. Elemental S, at the annual or the initial rates, reduced the N:S ratios in ryegrass by 1.80 and 1.09 units per Mg PG or unit equivalent rates ha^{-1} in 1992-93 (Table 102).

Table 102. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on N:S ratios in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
Intercept	------------	N:S	------------
	12.68	-	16.01
	-----------	(P-value)[2]	--------
AR*GT	0.0094		
AR*GT*FREQUENCY[3]		-	0.0003
Slope	------------	N:S/Mg PG ha^{-1}	---
A. Rates, Annual (An):			
PG An Slope	-0.46ns	-	-1.90***
S An Slope	0.08ns	-	-1.80***
$CaCO_3$ An Slope	0.47ns	-	0.60*
PG+$CaCO_3$ An Slope	-0.42ns	-	-2.05***
PG+dolomite An Slope	-0.69**	-	-2.05***
B. Rates, Initial (In):			
PG In Slope	-0.46ns	-	-0.15ns
S In Slope	0.08ns	-	-1.09***
$CaCO_3$ In Slope	0.47ns	-	0.31ns
PG+$CaCO_3$ In Slope	-0.42ns	-	-0.13ns
PG+dolomite In Slope	-0.69**	-	0.03ns
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	-0.52**	-	-2.00***
PG_{all} Avg In Slope	-0.52**	-	-0.08ns

[1]In 1990 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), **P≤0.05, ***P≤0.01.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

PG versus other amendments. Table 103 shows that the effects on N:S ratios in ryegrass of the various PG amendments, separately or as a group, were not different. The comparison PG_{all} vs S shows that PG amendments were as effective as elemental S in reducing the N:S ratio in ryegrass forage. Understandably, PG_{all} vs $CaCO_3$ showed significant P-values in 1990-91 and 1992-93 with negative signs indicating the slopes for PG_{all} to be more negative (or less positive) than those of $CaCO_3$, the latter not being an S source.

Table 103. Comparisons between the slopes (effects of rates) of PG and other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on N:S ratios in annual ryegrass forage, 1990-91 to 1992-93.

Comparison	Year		
	1990-91[1]	1991-92	1992-93
Statistics:	-------- (P-value)[2]	--------------	
AR*GT	0.0001		
AR*GT*FREQUENCY		-	0.0001
PG vs other amendments:[3]			
PG_{all} vs S	ns	-	ns
PG_{all} vs $CaCO_3$	0.0003(-)	-	0.0001(-)
PG vs PG+$CaCO_3$	ns	-	ns
PG vs PG+dolomite	ns	-	ns
Annual vs initial rates:[4]			
PG An vs In	-	-	ns
S An vs In	-	-	0.0072(-)
$CaCO_3$ An vs In	-	-	ns
PG+$CaCO_3$ An vs In	-	-	ns
PG+dolomite An vs In	-	-	ns
PG_{all} Avg An vs Avg In	-	-	0.0001(-)

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05).
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

Annual versus initial rates. The N:S ratio annual rates slopes for the individual PG amendments were not significantly different from the initial rates slopes (Table 103). However, when analyzed as a whole, the N:S average rates slope (PG_{all} An) was significantly more negative than the initial rates slopes. Similarly, the N:S annual rates slope for elemental S was significantly more negative than the initial rates (Table 103).

Thus, the results indicated that the low rates applied annually were more effective in reducing the N:S ratios in annual ryegrass than the higher rates applied once every three years.

In vitro organic matter digestibilitv (IVOMD). The %IVOMD of annual ryegrass, averaged across all rates, for the various amendments are given in Table 104. The trends with the annual and the initial rates in Figure 54 showed apparent positive effects of the various amendments on IVOMD at certain rates of application.

Effects of rates. The statistics gave no significant %IVOMD slopes in 1990-91. No data were obtained from the 1991-91 and 1992-93 harvests.

PG versus other amendments. There were no significant P-values for any of the comparisons.

Annual versus initial rates. There were also no significant P-values for any of the comparisons.

Table 104. Group treatments and in vitro organic matter digestibility (IVOMD) of annual ryegrass forage, averaged across annual and initial application rates, 1990-91 to 1992-93.

Group treatments	Year		
	1990-91[1]	1991-92	1992-93
	%IVOMD		
PG	78.4	-	-
PG+dolomite[1]	77.8	-	-
PG+$CaCO_3$[1]	77.9	-	-
PG_{all}[2]	78.0	-	-
S (elemental)	78.4	-	-
$CaCO_3$	78.3	-	-
Control	76.9	-	-

[1]1% by weight added to bring PG pH in water (1:1) to 5.5.
[2]Average over all treatments containing PG.

The one-year data showed no effects, positive or otherwise, of the various amendments on the in vitro organic matter digestibility (IVOMD) of annual ryegrass forage.

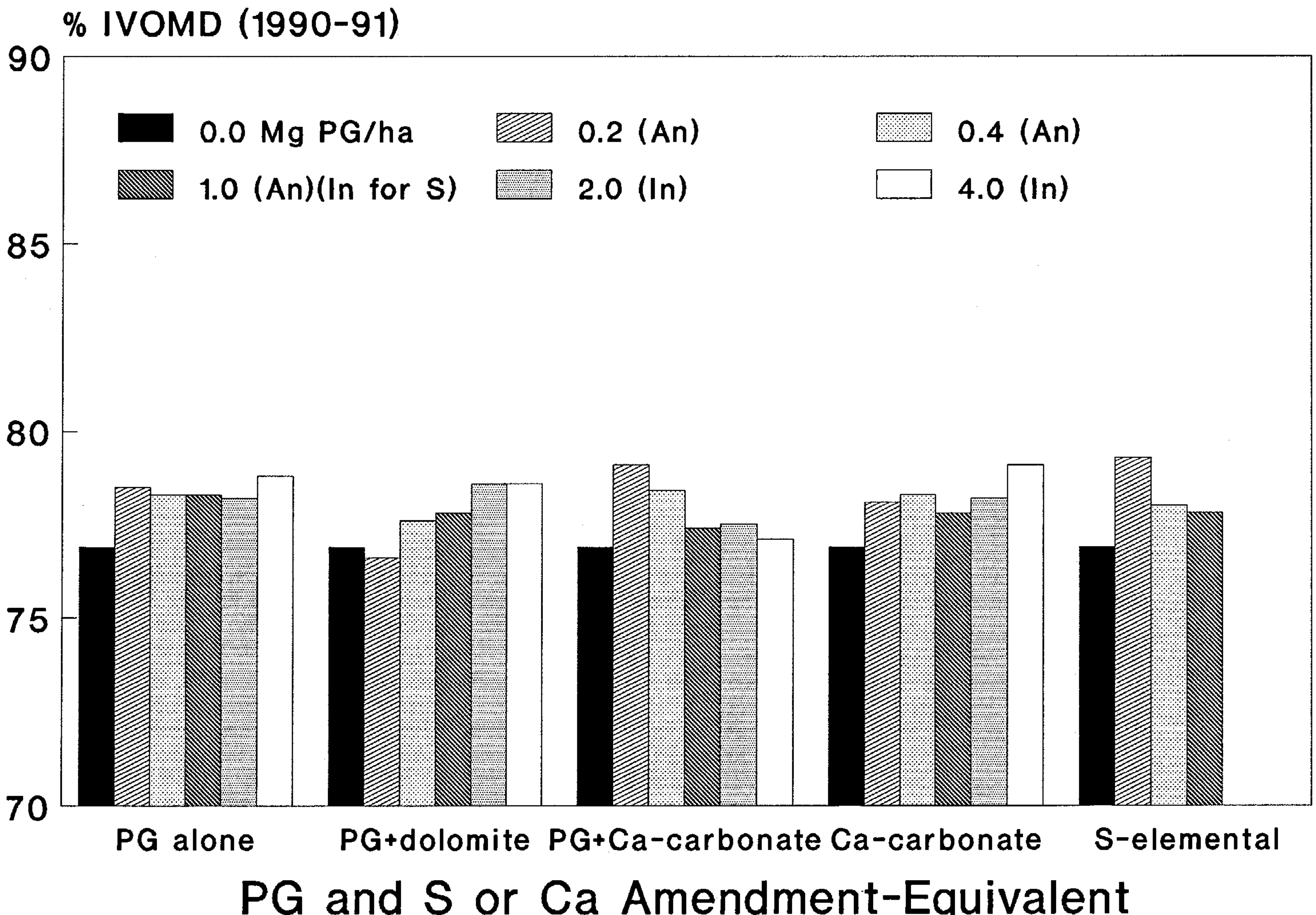


Figure 59. In vitro organic matter digestibility (IVOMD) of annual ryegrass regrowth forage, 1990-91, from plots which were amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

B.2. Amendment Rates, PG Versus Other Amendments, Annual Versus Initial Rates on Soil pH, Calcium. Phosphorus, Potassium, and Magnesium

Soil pH. Soil samples were taken between August and September of 1991, 1992, and 1993 for crop years 1990-91, 1991-92, and 1992-93, respectively. The pH values of the top 15 cm soil samples, averaged across all the rates of the amendments, are given in Table 105. Although PG had the least pH values, they were not much different from those of the other amendments. Figures 60, 60A, and 60B show the pH trends with the annual and the initial rates.

Table 105. Group treatments and pH of the top 15 cm of a Florida Spodosol soil under annual ryegrass which was amended with PG and other S or Ca amendments, averaged across annual and initial rates, 1991 to 1993.

Group treatments[1]	Year		
	1991	1992	1993
	------------- pH ---------------		
PG	5.07	5.52	5.67
PG+dolomite[2]	5.30	5.57	5.75
PG+$CaCO_3$[2]	5.10	5.60	5.69
PG_{all}[3]	5.17	5.56	5.70
S	5.20	5.54	5.70
$CaCO_3$	5.23	5.73	5.71
Control	5.45	5.80	5.77

[1]The comparative statistics showed no significant P-values.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. There were no significant effects of the rates (slopes) of the various amendments in all three years.

PG versus other amendments. The soil pH slopes for the various amendments were not different in all three years.

Annual versus initial rates. The slopes for the annual and the initial rates of the various amendments were not different.

The PG amendments, the $CaCO_3$, and the elemental S applied at several rates to a tilled Spodosol soil which was limed with dolomite and cropped to annual ryegrass for the experiment had no effect on the pH of the top 15 cm of the soil.

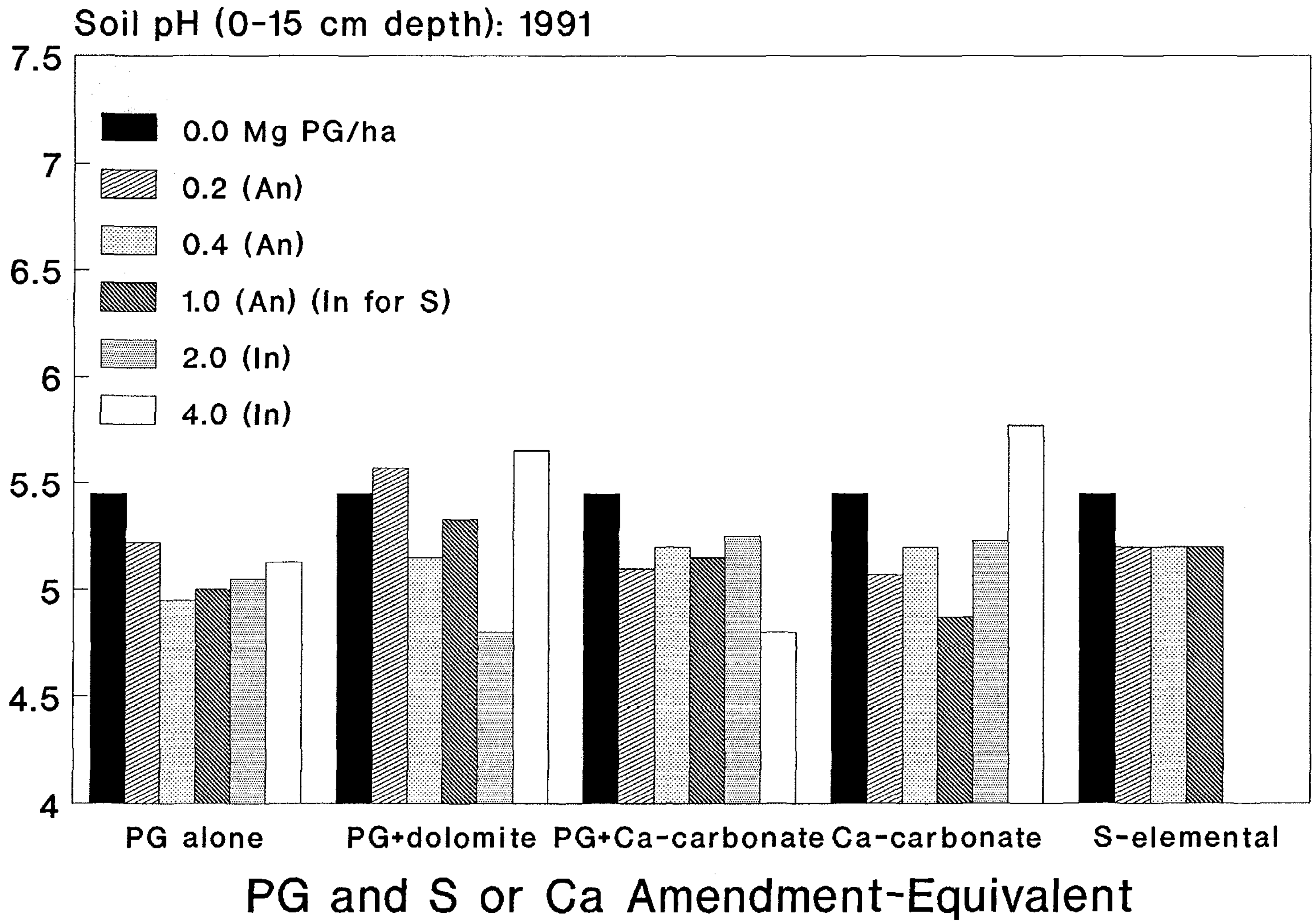


Figure 60. pH of the top 15 cm of a Florida Spodosol soil, 1991, under annual ryegrass which was amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

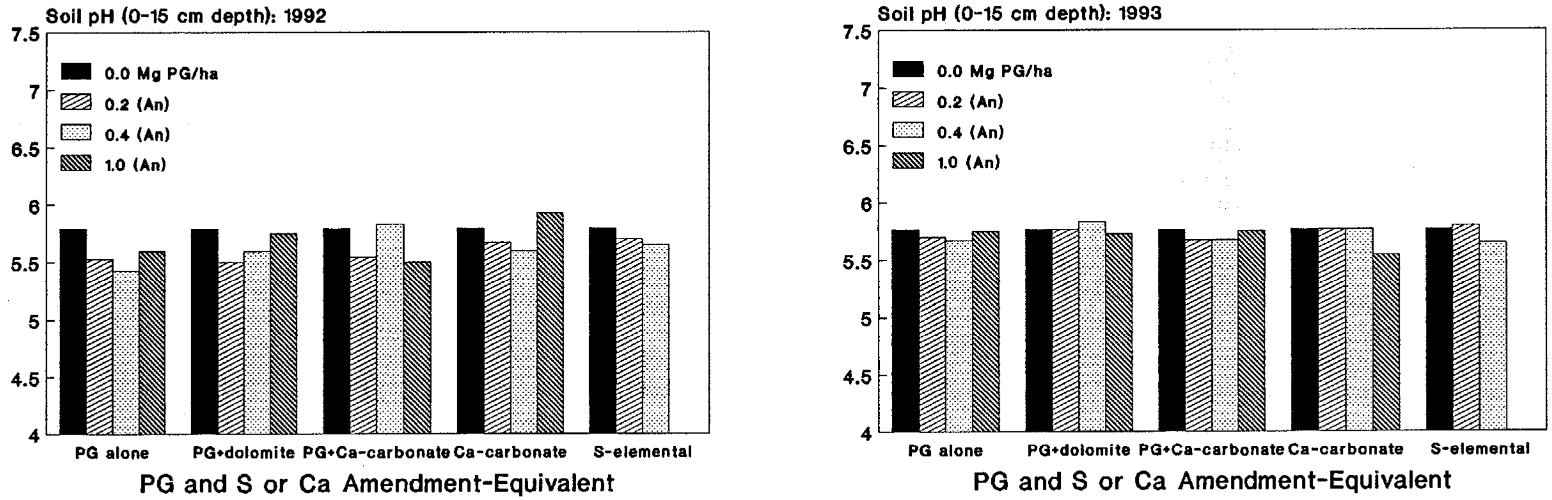


Figure 60A. pH of the top 15 cm of a Florida Spodosol soil, 1992 and 1993, under annual ryegrass which was amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

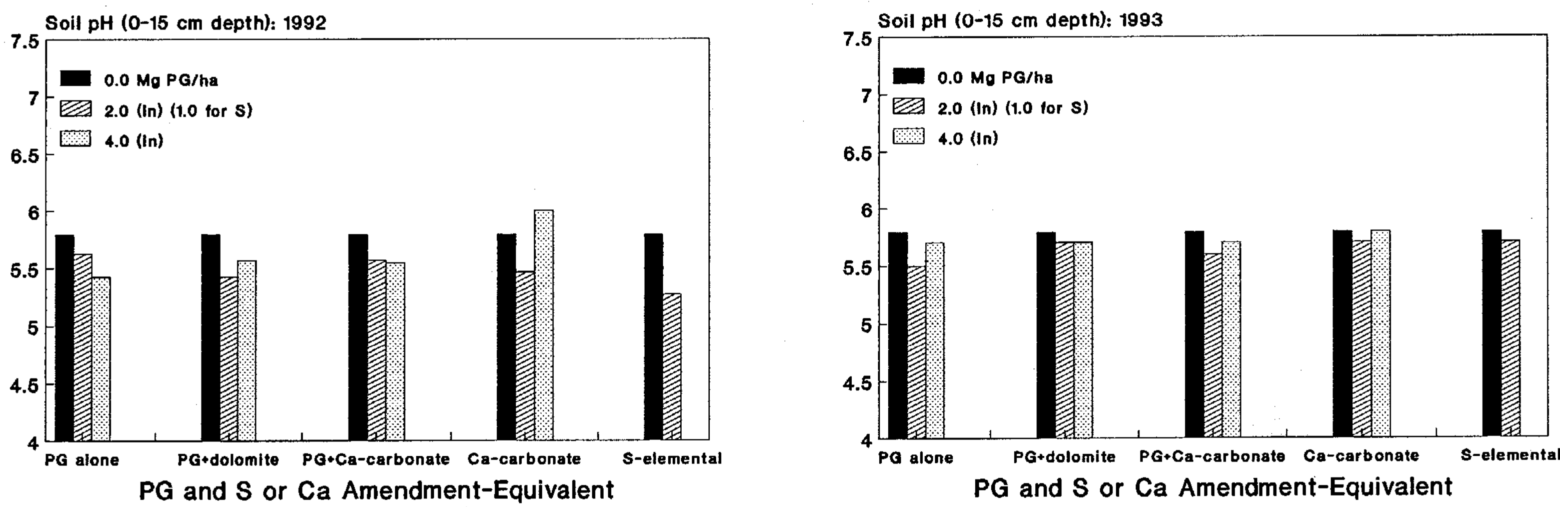


Figure 60B. pH of the top 15 cm of a Florida Spodosol soil, 1992 and 1993, under annual ryegrass which was amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

Calcium. The 1991, 1992, and 1993 Ca concentrations in the top 15 cm soil, averaged across all the rates of the various amendments, are given in Table 106. Figures 61, 61A, and 61B show the trends with the annual and the initial rates.

Table 106. Group treatments and Ca concentrations in the top 15 cm of a Florida Spodosol soil under annual ryegrass which was amended with PG and other S or Ca amendments, averaged across annual and initial rates, 1991 to 1993.

Group treatments[1]	Year		
	1991	1992	1993
	------------- mg Ca kg^{-1} ----------		
PG	557.4	861.1	685.7
PG+dolomite[2]	505.7	711.9	817.6
PG+$CaCO_3$[2]	491.9	779.7	721.5
PG_{all}[3]	518.3	784.2	741.5
S	488.0	781.5	759.1
$CaCO_3$	561.7	745.5	757.5
Control	501.5	935.3	881.0

[1]The comparative statistics showed no significant P-values.
[1]1% by weight added to bring PG pH in water (1:1) to 5.5.
[2]Average over all treatments containing PG.

Effects of rates. Figures 61, 61A, and 61B showed no consistent trends in Ca concentrations with the amendment rates. The statistics showed no significant slopes for any of the amendments in all three years.

PG versus other amendments. The comparisons showed that soil Ca concentration slopes for the various amendments were not significantly different in all three years.

Annual versus initial rates. There were no differences between the effects of the annual rates and the initial rates for any of the amendments in 1991 and 1992.

The 4.0 Mg **ha^{-1}** of PG containing 24% Ca mixed with the top 15 cm soil (2,000,000 kg soil per ha-furrow slice) would have raised topsoil Ca by 480 mg kg^{-1}. That this projected increase in Ca concentration was not detected meant that Ca from PG can be lost from the topsoil of a sandy Florida Spodosol within a year's time. Reeve and Sumner (1972), in a leaching study, found that surface-applied gypsum was completely leached out from the top 10 cm after application of 32 cm of water.

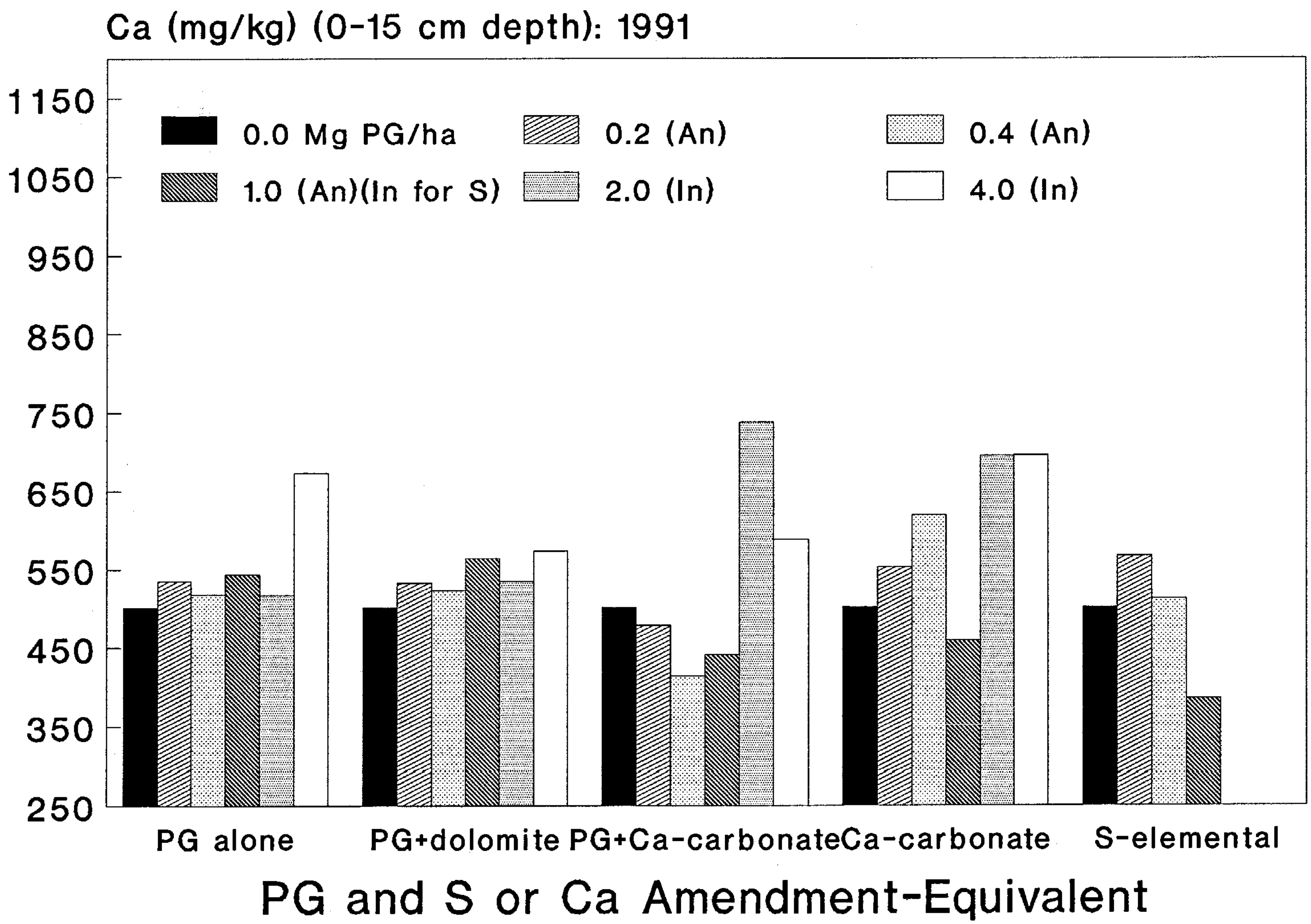


Figure 61. Calcium concentrationsin the top 15 cm of a Florida Spodosol soil, 1991, under annual ryegrass which was amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

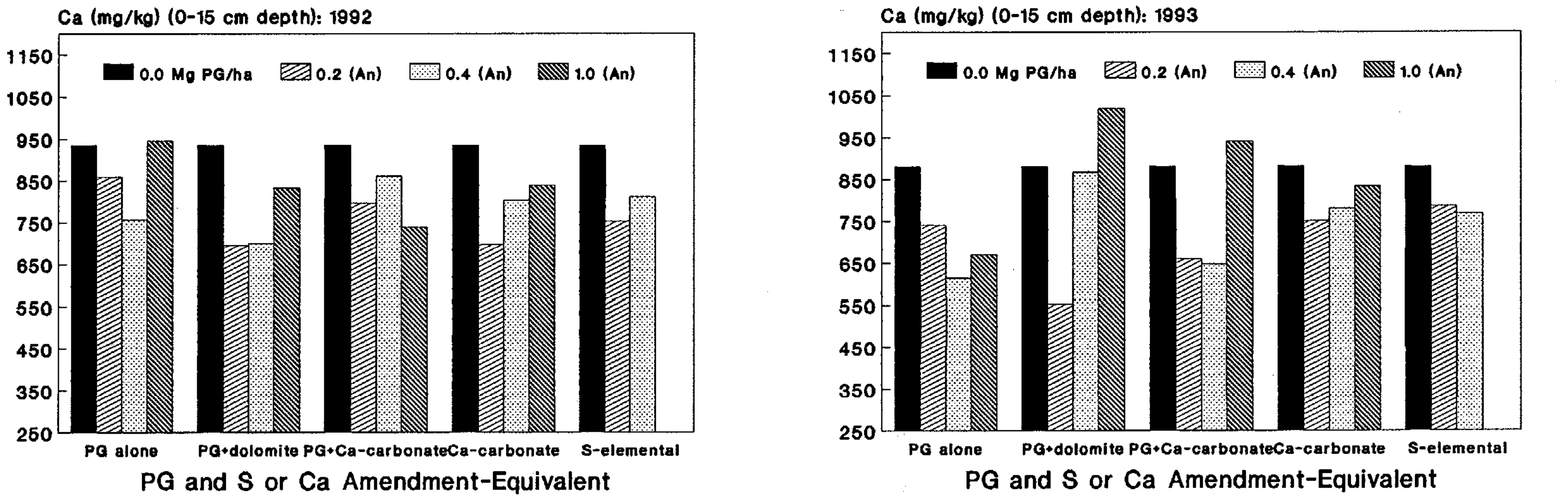


Figure 61A. Calcium concentrationsin the top 15 cm of a Florida Spodosol soil, 1992 and 1993, under annual ryegrass which was amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

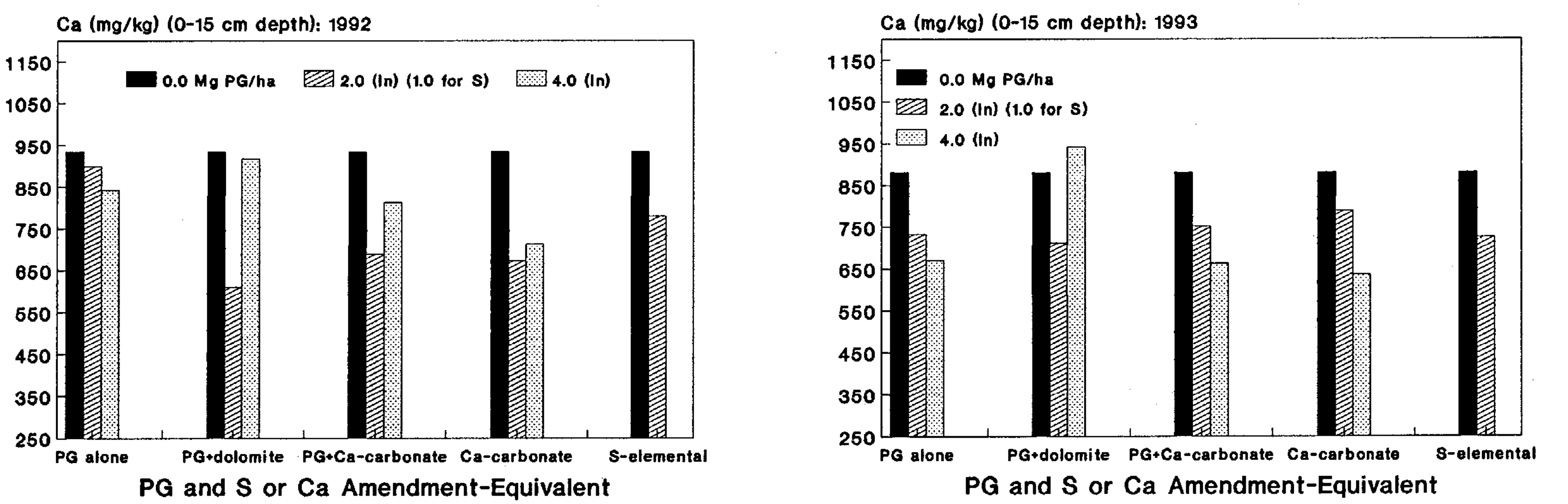


Figure 61B. Calcium concentrationsin the top 15 cm of a Florida Spodosol soil, 1992 and 1993, under annual ryegrass which was amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

Phosphorus. The P concentrations in the top 15 cm soil, averaged across all the rates of the various amendments, are given in Table 107. Figures 62, 62A, and 62B show the trends with the annual and the initial rates.

Table 107. Group treatments and P concentrations in the top 15 cm of a Florida Spodosol soil under annual ryegrass which was amended with PG and other S or Ca amendments, averaged across annual and initial rates, 1991 to 1993.

Group treatments[1]	Year		
	1991	1992	1993
	------------- mg P kg^{-1} ---------		
PG	6.60	7.87	4.69
PG+dolomite[2]	6.50	5.86	6.33
PG+$CaCO_3$[2]	5.72	6.12	5.73
PG_{all}[3]	6.27	6.61	5.58
S	5.85	6.99	5.35
$CaCO_3$	5.59	5.75	5.29
Control	5.70	6.37	8.57

[1]The comparative statistics showed no significant P-values.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Effects of rates. The soil P concentration slopes were not significant for any of the various amendments in all three years.

PG versus other amendments. The soil P slopes of the various amendments were not significantly different.

Annual versus initial rates. There were no significant P-values for the annual versus initial rates for soil P.

Potassium. The K concentrations in the top 15 cm soil, averaged across all the rates of the various amendments, are given in Table 108. Figures 63, 63A, and 63B show the trends with the annual and the initial rates.

Effects of rates. There were no significant slopes for the various amendments in all three years. However, Figures 63A and 63B show very apparent reductions in soil K concentrations with certain rates of the PG amendments in 1992 and 1993.

PG versus other amendments. There were no significant P-values for the comparisons between amendments for soil K.

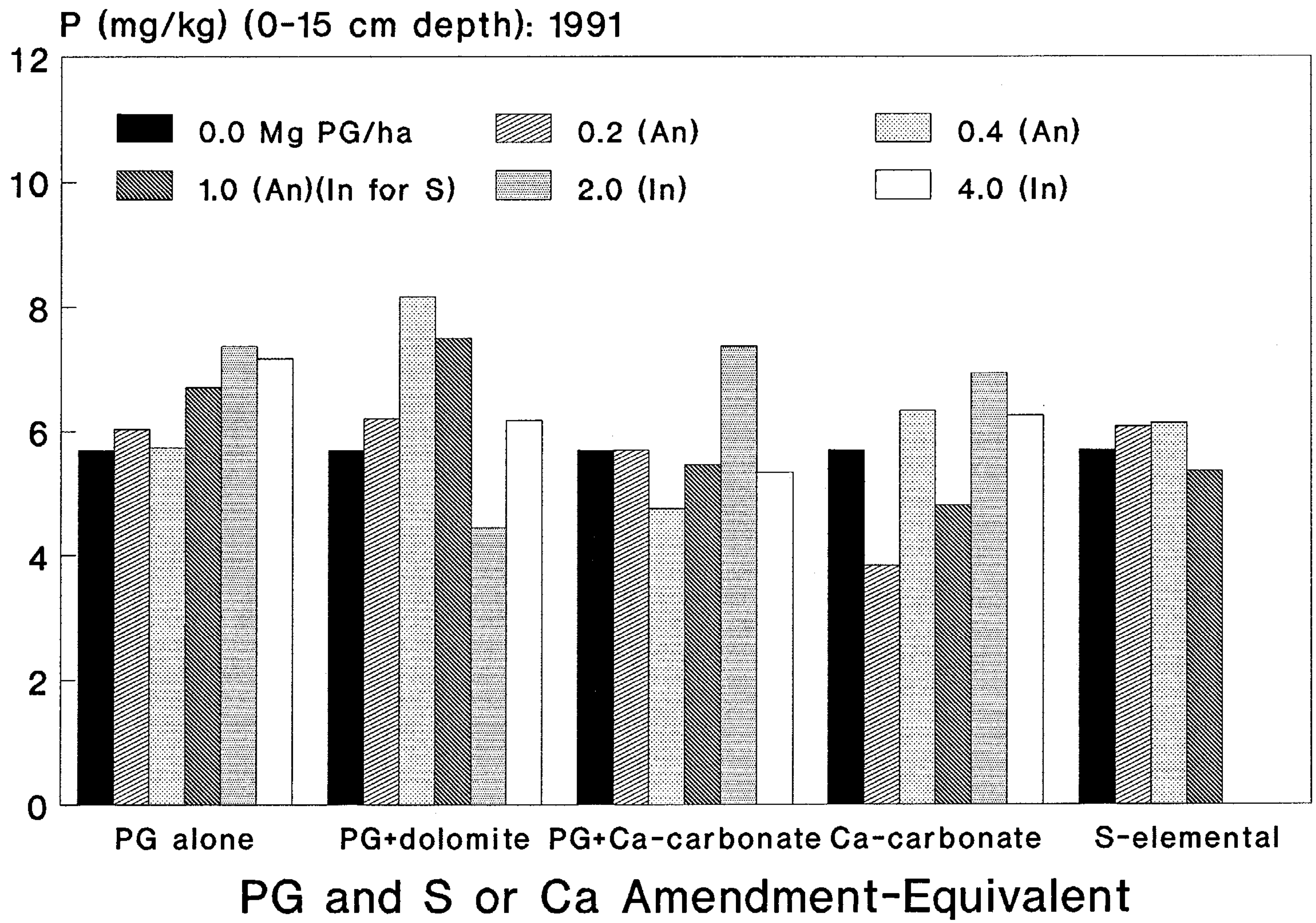


Figure 62. Phosphorus concentrationsin the top 15 cm of a Florida Spodosol soil, 1991, under annual ryegrass which was amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates, 1990-91.

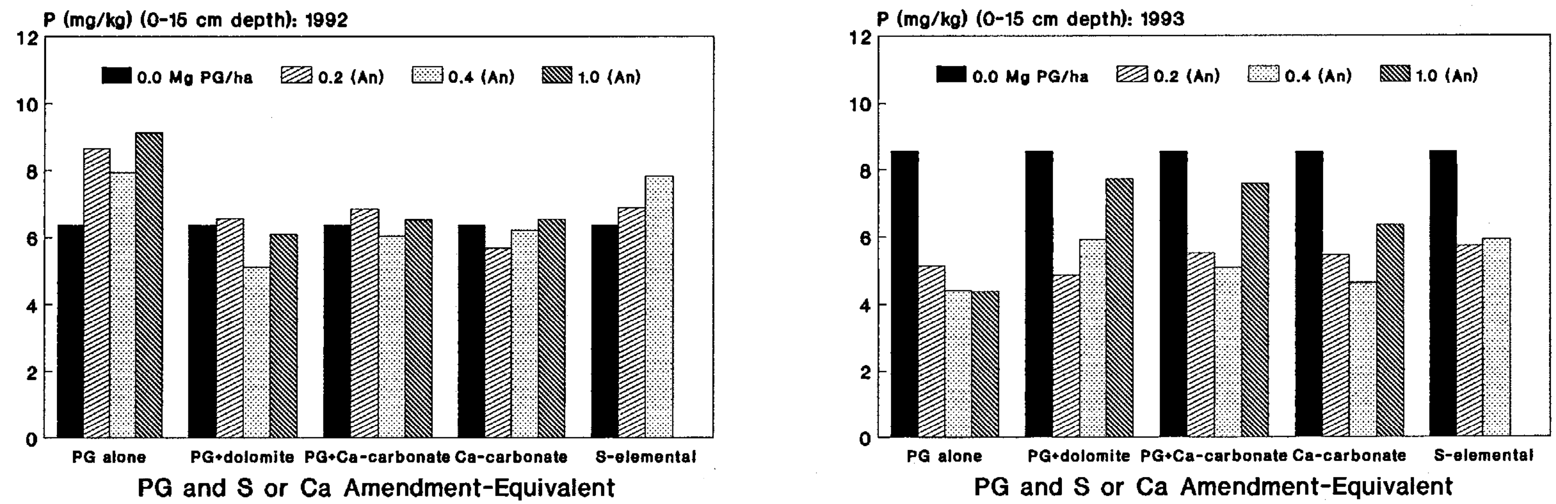


Figure 62A. Phosphorus concentrationsin the top 15 cm of a Florida Spodosol soil, 1992 and 1993, under annual ryegrass which was amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

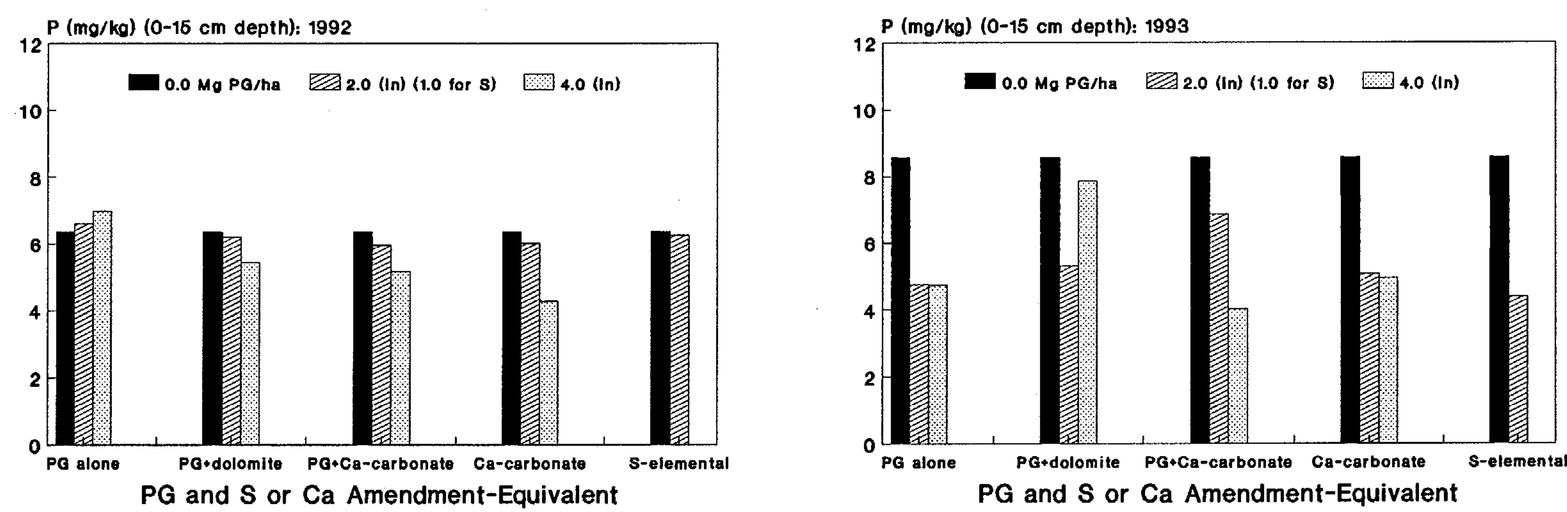


Figure 62B. Phosphorus concentrationsin the top 15 cm of a Florida Spodosol soil, 1992 and 1993, under annual ryegrass which was amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

Table 108. Group treatments and K concentrations in the top 15 cm of a Florida Spodosol soil under annual ryegrass which was amended with PG and other S or Ca amendments, averaged across annual and initial rates, 1991 to 1993.

Group treatments[1]	Year		
	1991	1992	1993
	------------ mg K kg^{-1} ----------		
PG	8.66	14.28	14.90
PG+dolomite[2]	7.44	11.04	13.67
PG+$CaCO_3$[2]	9.37	13.07	17.85
PG_{all}[3]	8.43	12.80	15.47
S	8.93	14.14	13.58
$CaCO_3$	7.44	11.83	18.83
Control	8.05	16.47	20.50

[1]The comparative statistics showed no significant P-values.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

Annual versus initial rates. There were also no significant P-values for the annual versus initial rates for soil K.

Magnesium. Table 109 shows the apparent adverse effects of the PG and the $CaCO_3$ amendments on Mg concentrations in the topsoil in all three years, 1991 to 1993. Figures 64, 64A, and 64B show the trends with the annual and the initial rates.

Effects of rates. Dolomite was applied to the experimental plots in July 1990 which supplied the soil with Mg. This could be the reason for the non-significant slopes in 1991 (Table 110), a year after the various amendments were first applied.

In 1992, PG+$CaCO_3$ and PG+dolomite at the annual rates, with negative slopes at some levels of significance, reduced soil Mg by 24.2 and 29.0 mg kg^{-1} per Mg PG ha^{-1}, respectively. The negative slope of PG did not attain a level of significance. On the average, PG_{all} annual reduced soil Mg by 23.0 mg kg^{-1} per Mg PG ha^{-1}.

In 1993, all the PG amendments at the annual rates continued to affect soil Mg, reducing Mg concentrations by 19.3 to 35.0 mg kg^{-1} per Mg PG ha^{-1}. On the average, PG_{all} annual reduced soil Mg by 26.6 mg kg^{-1} per Mg PG ha^{-1} (Table 110).

Elemental S and $CaCO_3$ at the annual rates also had negative slopes in 1992 and 1993, but they were not significant.

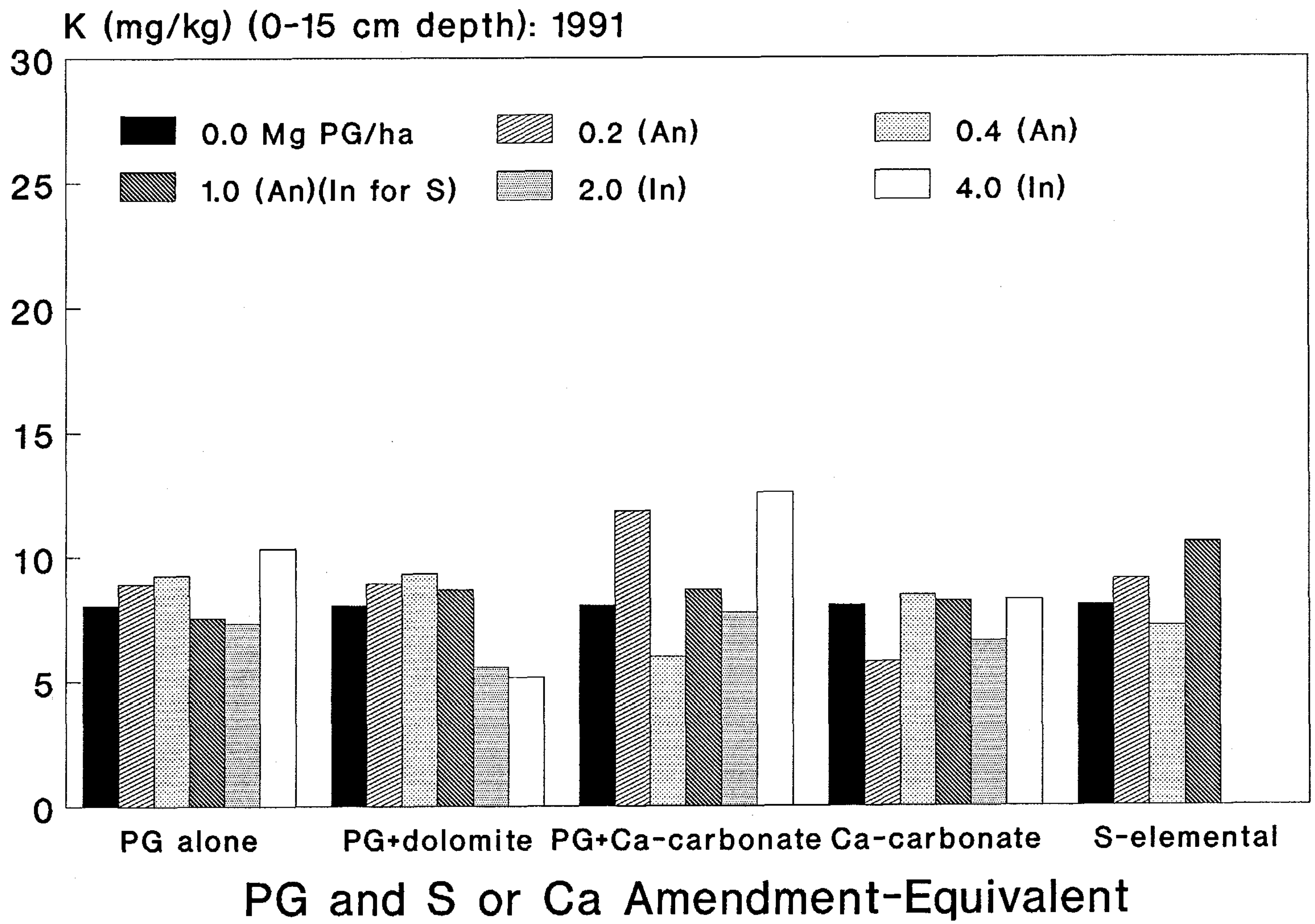


Figure 63. Potassium concentrations in the top 15 cm of a Florida Spodosol soil, 1991, under annual ryegrass which was amended with PG and other S or Ca amendments applied at annual (An) rates, 1990-92 to 1992-93, or at initial (In) rates, 1990-91.

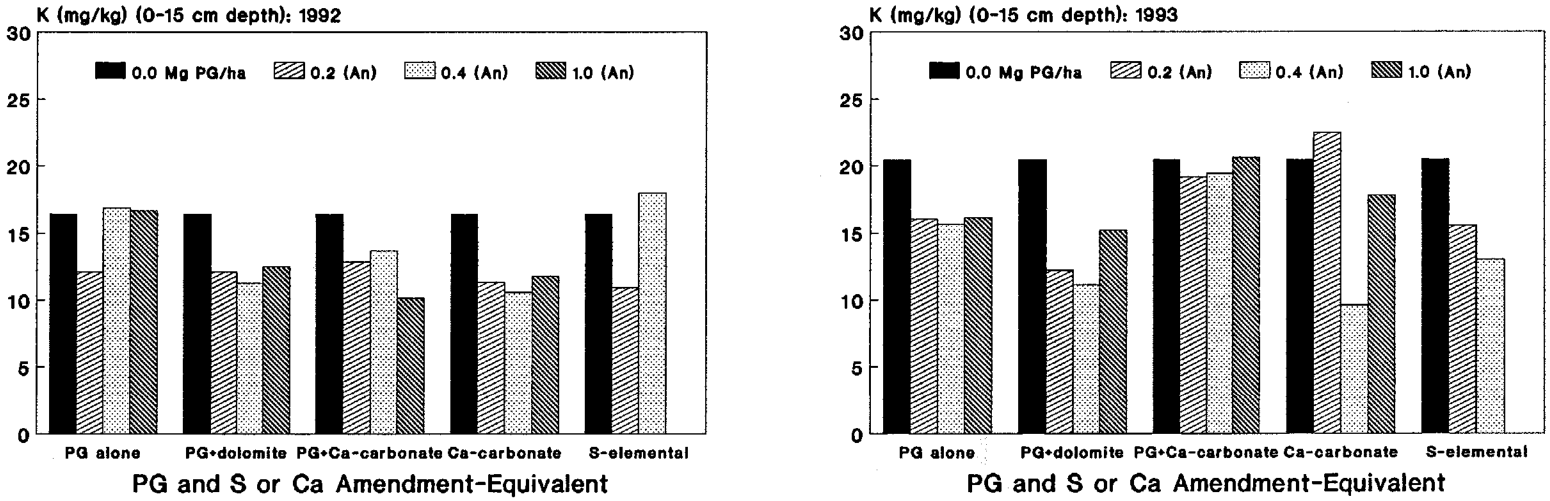


Figure 63A. Potassium concentrations in the top 15 cm of a Florida Spodosol soil, 1992 and 1993, under annual ryegrass which was amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

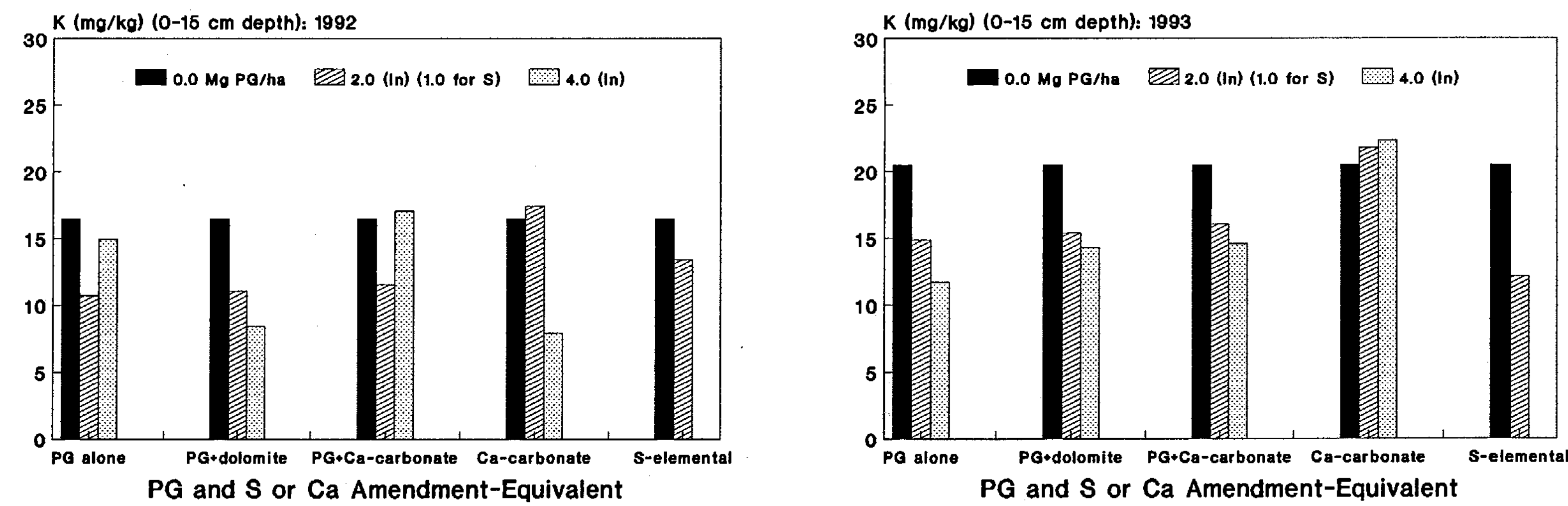


Figure 63B. Potassium concentrations in the top 15 cm of a Florida Spodosol soil, 1992 and 1993, under annual ryegrass which was amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

Table 109. Group treatments and Mg concentrations in the top 15 cm of a Florida Spodosol soil under annual ryegrass which was amended with PG and other S or Ca amendments, averaged across annual and initial rates, 1991 to 1993.

Group treatments[1]	Year		
	1991	1992	1993
	------------- mg Mg kg^{-1} ---------		
PG	108.9	184.1	122.5
PG+dolomite[2]	122.7	146.5	143.3
PG+$CaCO_3$[2]	114.5	167.3	126.3
PG_{all}[3]	115.4	166.0	130.7
S	134.3	214.4	163.0
$CaCO_3$	129.1	185.5	154.5
Control	143.0	264.7	218.7

[1]See Table 111 for the comparative statistics.
[2]1% by weight added to bring PG pH in water (1:1) to 5.5.
[3]Average over all treatments containing PG.

In 1992, the initial rates of the various PG amendments reduced soil Mg concentrations by 15.0 to 21.1 mg kg^{-1} per Mg PG ha^{-1}. On the average, PG_{all} initial reduced soil Mg by 18.4 mg kg^{-1} per Mg PG ha" (Table 110). The adverse effects of the PG amendments were much less in 1993 than in 1992, with PG_{all} initial reducing soil Mg by 12.1 mg kg^{-1} per Mg PG ha^{-1}.

The initial rates of $CaCO_3$ reduced soil Mg significantly in 1992 and 1993 by 17.7 and 12.4 mg kg^{-1} per Mg PG or unit equivalent ha^{-1}, respectively (table 110).

Elemental S at the initial rates also showed negative soil Mg slopes in 1992 and 1993 which, however, were not significant (Table 110).

PG versus other amendments. The comparison PG_{all} vs S showed slightly significant P-values with negative signs in 1992 and 1993 (Table 111). Hence, the effects of the PG amendments on soil Mg concentrations were slightly more adverse than the effects of elemental S.

The comparison PG_{all} vs $CaCO_3$ was significant in 1993 but not in 1991 and 1992. The significant difference was largely due to the third annual application of the PG amendments which resulted in higher negative slope in 1993 than in 1992. The initial rates slope of $CaCO_3$ had become less negative in 1993 than in 1992 and contributed to the widening differences between PG_{all} and $CaCO_3$.

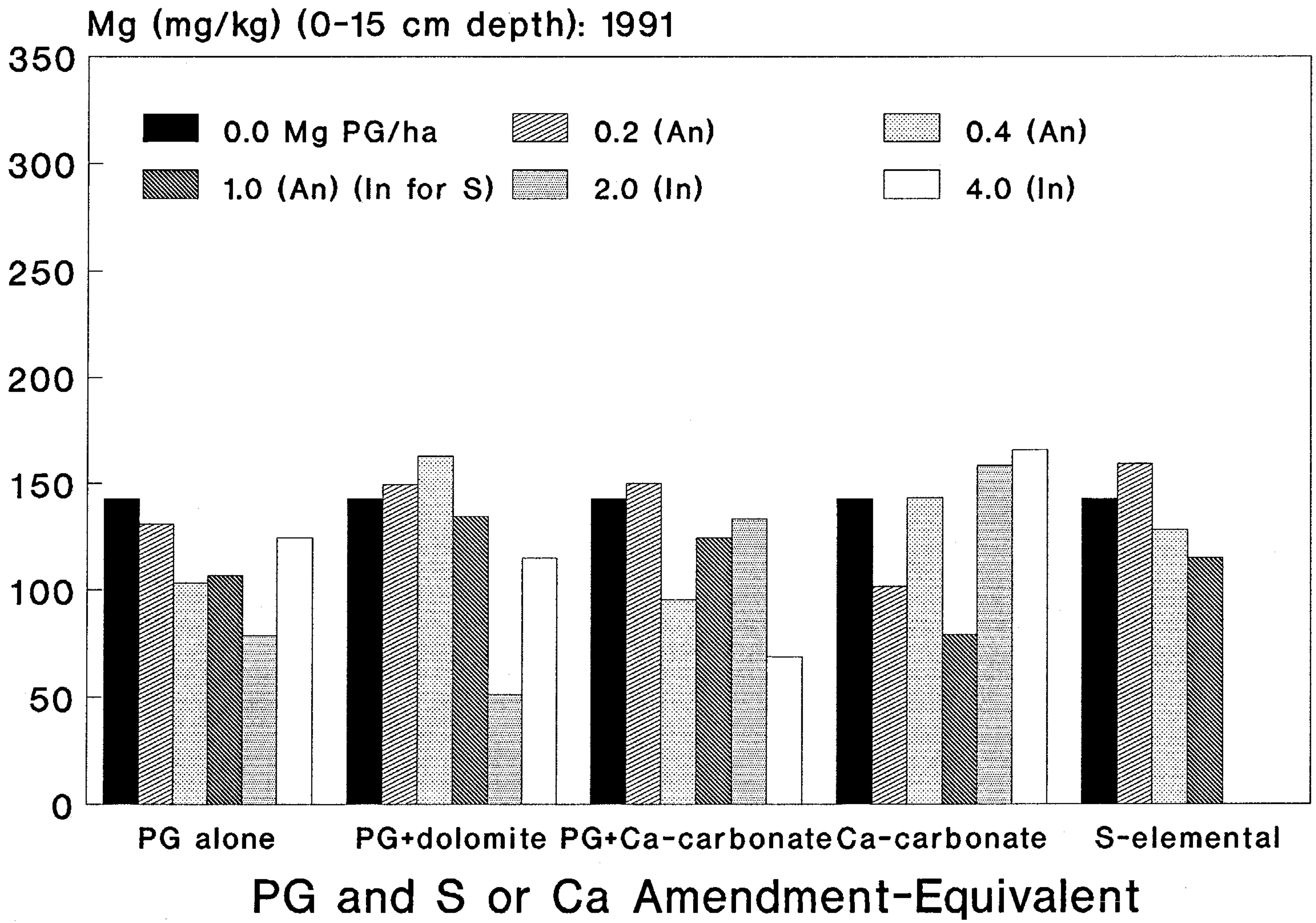


Figure 64. Magnesium concentrationsin the top 15 cm of a Florida Spodosol soil, 1991, under annual ryegrass which was amended with PG and other S or amendments applied at annual (An) rates, 1990-91 to 1992-93, or at initial (In) rates in 1990-91.

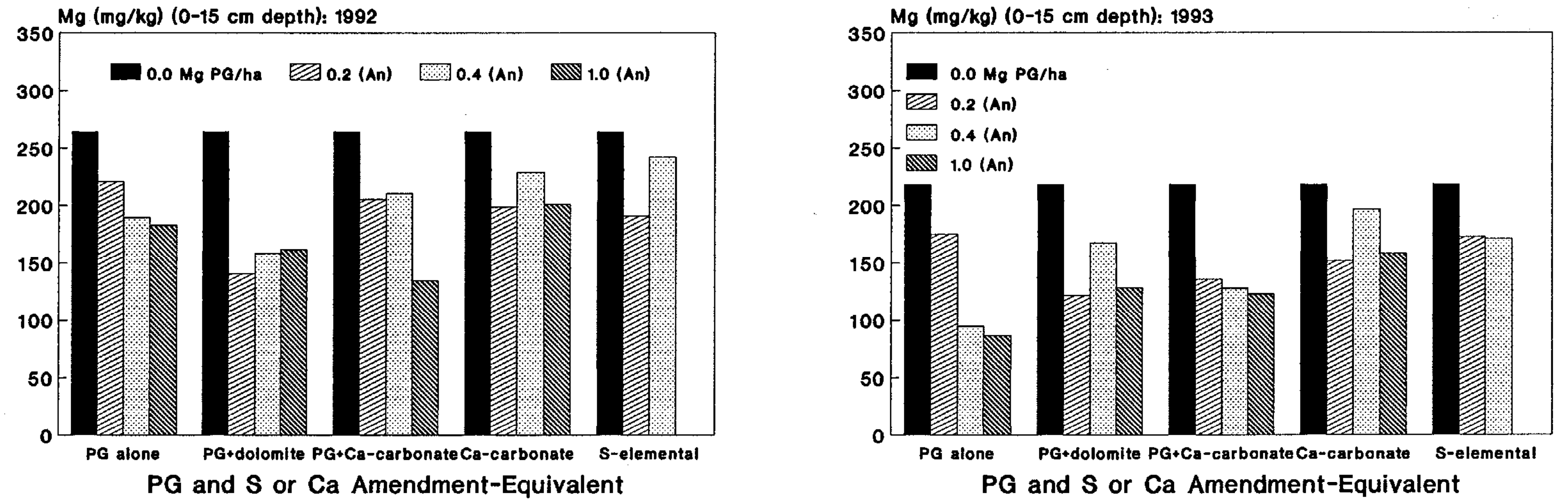


Figure 64A. Magnesium concentrations in the top 15 cm of a Florida Spodosol soil, 1992 and 1993, under annual ryegrass which was amended with PG and other S or Ca amendments applied at the annual (An) rates, 1990-91 to 1992-93.

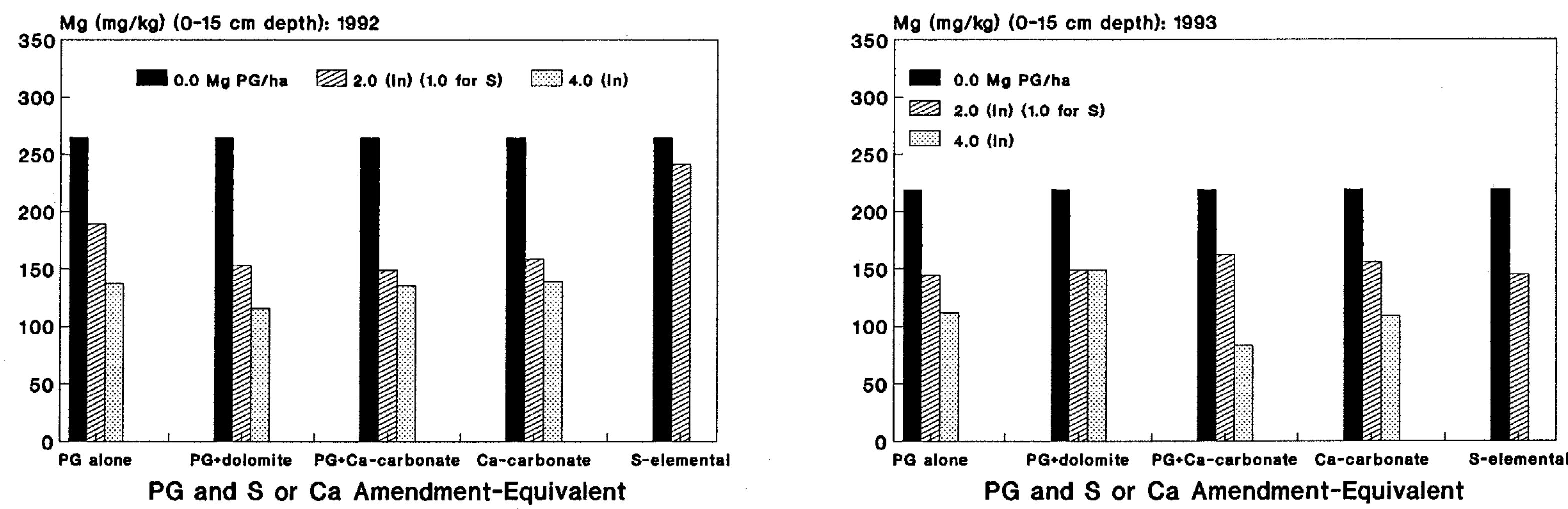


Figure 64B. Magnesium concentrations in the top 15 cm of a Florida Spodosol soil, 1992 and 1993, under annual ryegrass which was amended with PG and other S or Ca amendments applied at the initial (In) rates in 1990-91.

Table 110. Effects of annual (An) and/or initial (In) rates (slopes) of PG and other S or Ca amendments on Mg concentrations in the top 15 cm of a Florida Spodosol soil under annual ryegrass, 1991 to 1993.

Comparison	Year 1991[1]	1992	1993
Intercept	----------- $mg\ kg^{-1}$ -----------		
	139.4	227.4	186.3
	--------- (P-value)[2] ---------		
AR*GT	ns		
AR*GT*FREQUENCY[3]		0.0236	0.0036
Slope	------- $mg\ kg^{-1}/Mg\ PG\ ha^{-1}$ ----		
A. Rates, Annual (An):			
PG An Slope	ns	-15.9ns	-35.0^{***}
S An Slope	ns	- 2.3ns	- 8.7ns
$CaCO_3$ An Slope	ns	- 7.9ns	- 6.6ns
PG+$CaCO_3$ An Slope	ns	-24.2^{*}	-25.4^{***}
PG+dolomite An Slope	ns	-29.0^{**}	-19.3^{**}
B. Rates, Initial (In):			
PG In Slope	ns	-15.0^{**}	-13.1^{**}
S In Slope	ns	- 5.9ns	-13.5ns
$CaCO_3$ In Slope	ns	-17.7^{**}	-12.4^{***}
PG+$CaCO_3$ In Slope	ns	-19.1^{***}	-15.0^{***}
PG+dolomite In Slope	ns	-21.1^{***}	$- 8.2^{*}$
C. Rates, Avg Annual and Avg Initial:			
PG_{all} Avg An Slope	ns	-23.0^{**}	-26.6^{***}
PG_{all} Avg In Slope	ns	-18.4^{***}	-12.1^{***}

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant ($P>0.05$), $^{*}P<0.10$ (slightly significant), $^{**}P\leq0.05$, $^{***}P\leq0.01$.
[3]AR=amendment rates; GT=group treatment; FREQUENCY=annual and initial application frequency.

The significant P-value with negative sign for PG vs PG+dolomite indicated a more adverse effect of PG than that of PG+dolomite on soil Mg. This demonstrated that dolomite added to PG should significantly lessen the adverse effects of PG on soil Mg concentration.

Table 111. Comparisons between the slopes (effects of rates) of PG and the slopes of other S or Ca amendments and between the slopes of the annual (An) and the initial (In) rates on Mg concentrations in the top 15 cm of a Florida Spodosol soil under annual ryegrass, 1991 to 1993.

Comparison	Year		
	1991[1]	1992	1993
<u>Statistics:</u>	-------- (P-value)[2]	--------------	
AR*GT	ns		
AR*GT*FREQUENCY		0.0236	0.0036
<u>PG vs other amendments:</u>[3]			
PG_{all} vs S	ns	0.0987(-)	0.0745(-)
PG_{all} vs $CaCO_3$	ns	ns	0.0197(-)
PG vs PG+$CaCO_3$	ns	ns	ns
PG vs PG+dolomite	ns	ns	0.0435(-)
<u>Annual vs initial rates:</u>[4]			
PG An vs In	-	ns	ns
S An vs In	-	ns	ns
$CaCO_3$ An vs In	-	0.0509	0.0192
PG+$CaCO_3$ An vs In	-	ns	ns
PG+dolomite An vs In	-	ns	ns
PG_{all} Avg An vs Avg In	-	0.0907	ns

[1]In 1990-91 all rates were used in the analysis without distinction as to whether they are annual or initial rates.
[2]ns=not significant (P>0.05), but P<0.10 referred to as "slightly significant" are also given for reference.
[3]Slopes computed using both annual and initial rates.
[4]Slopes computed based on rates applied for that span of years.

<u>Annual versus initial rates.</u> The annual slopes used in these comparisons were 1/2 of the 1992 and 1/3 of the 1993 slopes in Table 110. The comparisons for the individual PG amendments showed no significant P-values. The P-values for PG_{all} indicated a slightly more negative slope for the initial rates than for the annual rates in 1992. The P-values for $CaCO_3$ indicated greater adverse effects on soil Mg for the initial rates than for the annual rates in 1992 and 1993 (Table 111). Thus, based on the actual amounts applied, the low annual rates appeared to have less adverse effects on soil Mg per Mg PG or equivalent rate ha^{-1} for PG and for $CaCO_3$. But based on the treatment rates, the annual PG amendments rates reduced soil Mg more than did the high initial rates in 1992 and 1993. However, the initial rates of $CaCO_3$ reduced soil Mg more than did the annual rates in 1992 and 1993.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions from the bahiagrass and the annual ryegrass experiments are given in their respective sections together with the recommendations. The conclusions were drawn from the agronomic experiment and from the agronomic results of the environmental experiment.

A. Phosphogypsum on Established Bahiagrass Pasture

1. Conclusions

Effect on forage. The summary results supporting the conclusions are found in the Executive Summary.

1. Phosphogypsum (PG) applied to bahiagrass on a Florida Spodosol soil can increase the regrowth forage dry matter (DM) yields of long-established bahiagrass pastures by 10 to 46%.

2. Phosphogypsum is a better amendment than either elemental S or $CaCO_3$ to enhance the forage yield of bahiagrass pastures.

3. Phosphogypsum supplies S to bahiagrass pastures much more readily than elemental S, effectively increasing %S in forage the same year PG is applied.

4. Phosphogypsum supplies Ca to bahiagrass pastures much more readily than $CaCO_3$, effectively increasing %Ca in forage the same year it is applied.

5. Phosphogypsum, elemental S, or $CaCO_3$ had no significant effect on %N in bahiagrass forage. However, the trends indicate that PG has the potential to increase N content, hence also protein content, in bahiagrass forage.

6. Phosphogypsum or $CaCO_3$, but not elemental S, can adversely affect P uptake by or availability to bahiagrass reducing %P in forage, and the reduction in P content due to CaCO was significantly much more than that due to PG. This effect was observed only in the first year.

7. Phosphogypsum, but not $CaCO_3$ or elemental's, can enhance K uptake by or availability to bahiagrass increasing %K in forage at all rates in the first year: in the following two years only the rates applied annually up to 1.0 Mg PG ha^{-1} showed this beneficial effect of PG.

8. Phosphogypsum, but not $CaCO_3$ or elemental S, at the high initial rates can reduce %Mg in bahiagrass forage, but this adverse effect was noted only in the first year. The environmental experiment showed that this adverse effect was significant only for the 4.0 Mg PG ha^{-1} rate.

9. Phosphogypsum and elemental S at the low annual rates or at the high one-time rates can reduce the N:S ratio to low levels in bahiagrass forage. The agronomic experiment gave an average N:S ratio range for the PG-fertilized forages of 4.3:1 - 4.7:1. In the environmental experiment, the PG-fertilized forages had annual average N:S ratios range of 6.7:1 - 7.5:1 which were considerably higher than pre-PG pre-N ratio of 4.3:1.

10. Phosphogypsum can enhance the in vitro organic matter digestibility (IVOMD) of bahiagrass forage. Phosphogypsum increased the digestibility of bahiagrass in certain harvests in a growing season in the environmental experiment. The agronomic experiment showed positive trends with PG rates.

11. Phosphogypsum, despite the large amounts of Ca added to the soil upon its application, gave a mean Ca:P ratio range of 1.7:1 to 2.2:1 in forage, well within the ideal Ca:P range of 1:1 to 2:1 in bones.

12. Averaged over a 3-year period, PG containing 0.43% F applied up to 4.0 Mg ha^{-1} showed no significant effect on F content in bahiagrass forage. The F contents ranged from 7.2 mg kg-1 in the control to 8.6 mg kg^{-1} in forage that received 4.0 Mg PG ha^{-1}. The upper value is considerably less than the 30 mg kg^{-1} limit in forage for bovines or the 15-20 mg F kg^{-1} range for pastures which IFAS considered usable for grazing research.

Effect on Soil. The effects of PG and other amendments on the soil presented here are limited to their effects on top 15 cm in both the agronomic and the environmental experiments.

1. Phosphogypsum had no effect on the pH of the top 15 cm of the soil as shown in the agronomic and the environmental experiments. Elemental S can reduce and $CaCO_3$ can increase the soil pH significantly relative to that of PG. The forage yield data suggest that the soil pH associated with each of the amendment has significant influence on the forage yields of bahiagrass.

2. Calcium from PG can be lost from the topsoil within a year's time, and the dissolution of the applied $CaCO_3$ is probably too slow to result in a measurable difference in exchangeable Ca in the topsoil. These were suggested by the fact that the Mehlich 1 extractable soil Ca at the top 15 cm did not show any measurable increase with PG or $CaCO_3$ at all rates in all three years.

3. Phosphogypsum, elemental S, or $CaCO_3$ had no significant effect, adverse or otherwise, on P concentration at the topsoil.

4. Phosphogypsum can reduce the exchangeable K concentrations in the topsoil within a year's time from application. The high initial rates of PG, but not the low annual rates, reduced exchangeable K concentration in the top 15 cm of the soil. Calcium carbonate also showed a negative effect with the rates. The adverse effect of PG on soil K one year after application was significantly greater than that of $CaCO_3$.

5. Phosphogypsum can reduce the levels of exchangeable Mg in the topsoil within a year's time, and the low annual rates or the high initial rates continued to reduce soil Mg for another year before soil Mg concentrations stabilized at much reduced levels.

6. Phosphogypsum had no effects on the levels of Cu, Fe, Mn, Na, Cl, and Zinc.

2. Recommendations

1. The decision to use or not to use PG on bahiagrass pastures should be based on the degree of S or Ca deficiency or sufficiency in the forage. When S appears to be sufficient, the N:S ratio should be considered to determine the need for S, especially in heavily N-fertilized pastures.

2. Because the acquisition and the transport costs of PG and the yield response of bahiagrass would vary from one ranch to another, it is recommended that ranchers experiment with PG to determine the economics of using PG as a fertilizer. A simple guide would be to consider that a 10 to 15% increase in forage yield could probably increase the carrying capacity of the pasture also by that much.

2. The optimum PG rate for established bahiagrass pastures should be not less than 0.4 nor more than 1.0 Mg PG ha^{-1}, on dry-weight basis, to be applied annually. The rate selected within this range should maximize the beneficial effects of PG on the pasture and on the soil with little or no adverse effects on both.

3. Bahiagrass has rather low N contents, and to maximize the benefits from PG, N fertilization should accompany PG application.

4. Phosphogypsum should be applied without any lime materials, and in soils that need Mg fertilization a Mg source other than dolomite should be used.

B. Phosphogypsum on Annual Ryegrass on Tilled Land

1. Conclusions

Effect on forage.

1. Phosphogypsum, elemental S, and $CaCO_3$ had no significant effects on the forage dry matter yield of annual ryegrass growing on former virgin saw palmetto land, cultivated for the first time, and limed with dolomite. However, there were indications that PG could significantly increase the forage yields of annual ryegrass if planted continuously on this type of land.

2. Phosphogypsum can increase the %DM or the solids in the regrowth forage of annual ryegrass. This would produce young, fresh regrowth forage with less water, hence less soggy, which should have some physiological significance to grazing ruminants.

3. Phosphogypsum supplies S to bahiagrass pastures much more readily than elemental S, effectively increasing %S in forage the same year PG is applied.

4. Phosphogypsum and $CaCO_3$ broadcast on the surface of a tilled land at the time of seeding or fertilizer application, as they were applied in the agronomic experiment, are equally effective as sources of Ca increasing the %Ca in ryegrass the same year the amendments were applied. But in the environmental experiment, PG, applied three months before seeding as it was done in the case of the first year applications of PG or a week or two before seeding in the subsequent years as it was done with the annual rate, was ineffective in increasing the Ca content in annual ryegrass forage.

5. Phosphogypsum, elemental S, or $CaCO_3$ had no significant effect on %N in annual ryegrass forage.

6. Phosphogypsum or $CaCO_3$, but not elemental S, can adversely affect P uptake by or availability to annual ryegrass. However, compared with $CaCO_3$, PG had significantly less adverse effect on P content in annual ryegrass than $CaCO_3$.

7. Phosphogypsum or $CaCO_3$, but not elemental S, can reduce K uptake by or availability to annual ryegrass, decreasing %K in forage at the annual or the initial rates in the second year but not in the other years. Comparisons between PG versus $CaCO_3$ showed their effects to be similar.

8. Phosphogypsum, but not $CaCO_3$, can reduce Mg uptake by or availability to annual ryegrass in dolomite limed soil, decreasing %Mg in forage at the annual or the initial PG rates for three consecutive years.

9. Phosphogypsum or elemental S, at the low annual rates or at the high one-time rates, can equally reduce the N:S ratio in annual ryegrass forage to within the ideal forage N:S ratio range of 12:1 to 15:1 for cattle. By the third year, the control and the $CaCO_3$-fertilized forages showed N:S ratios of 16.7:1 and 17.1:1, respectively, while the average ratios of the ryegrass forage fertilized with PG or elemental S remained well within the ideal range. Phosphogypsum, applied three months before seeding as was done in the environmental experiment, was not effective in reducing the N:S ratio in annual ryegrass forage.

10. Phosphogypsum, elemental S, or $CaCO_3$ had no significant effect on the IVOMD of annual ryegrass forage. However, in the first year, the trends showed clearly that PG has the potential to affect IVOMD positively.

12. Despite large amounts of Ca in PG, the annual mean Ca:P ratios ranged from 1.06 to 1.33 in annual ryegrass forage which were within the ratios of 1:1 to 2:1 in bones.

13. Averaged over a 3-year period, PG containing 0.43% F applied up to 4.0 Mg ha^{-1} showed no significant effect on F contents in ryegrass forage. The control forage had 8.4 mg kg^{-1} and the forage fertilized with 4.0 Mg PG ha^{-1} had 10.5 mg kg^{-1}. The upper value is considerably less than the 30 mg F kg^{-1} limit in forage for bovines or the 15-20 mg F kg^{-1} range for pastures which IFAS considered usable for grazing research.

Effects on Soil

1. Phosphogypsum, elemental S, or $CaCO_3$ had no effect on the pH of the top 15 cm of the soil. The dolomite applied earlier probably had greater influence on the pH of the soil than any of the various amendments.

2. Calcium from PG can be lost from the topsoil within a year's time, and the dissolution of $CaCO_3$ can be very slow to result in a measurable difference in exchangeable Ca at the top soil. The Mehlich 1 extractable soil Ca at the top 15 cm did not increase with PG or $CaCO_3$ application in all three years.

3. Phosphogypsum, elemental S, or $CaCO_3$ showed no significant effects on soil P concentration. However, by the third year, there were strong trends to indicate that the amendments could have adverse effects on extractable soil P.

4. Phosphogypsum, elemental S, or $CaCO_3$ had no significant effects on Mehlich 1 extractable K in the top 15 cm of the soil. But the trend in the third year data indicates that the PG rate of 4.0 Mg ha^{-1} could have adverse effects on the concentrations of K in the topsoil.

5. Phosphogypsum can considerably reduce the exchangeable Mg concentrations in the topsoil within two year's time, and the low annual rates as well as the high initial rates continued to reduce soil Mg in the third year.

6. Phosphogypsum had no effects on the levels of Cu, Fe, Mn, Na, Cl, and Zinc.

2. Recommendations

1. Although PG had not increased the forage yield of annual ryegrass in this study, PG fertilization should be considered for annual ryegrass to improve its forage quality by increasing its S contents and narrowing its N:S ratio to within the range of 12:1 to 15:1.

2. As with bahiagrass, PG at not less than 0.4 nor more than 1.0 Mg PG ha^{-1}, on dry-weight basis, to be applied annually would be about optimum. Any rate within this range should maximize the beneficial effects of PG on the pasture and on the soil with little or no adverse effects on both.

3. As with bahiagrass, PG application should be accompanied with N fertilization to maximize its benefits.

4. Phosphogypsum should be broadcast at the surface at the time of seeding or at the time of fertilizer application and not be plowed into the topsoil.

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