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Phytoremediation of a high phosphorus soil by summer and winter hay harvest

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PHYTOREMEDIATION OF A HIGH PHOSPHORUS SOIL BY SUMMER AND WINTER HAY HARVEST

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The work presented in this thesis, is part of a 10 year study begun by Dr. Donald L. Robinson, continued under Dr. John Kovar and later transferred to Dr. Lewis Gaston.

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ABSTRACT

Phosphorus (P) loading into surface water from runoff and subsurface flow leaving soils subjected to long-term applications of poultry litter (PL) will degrade water quality. A practical way to reduce such loading is to remove soil P through plant uptake and harvest removal. The primary field study presented here examined the effectiveness of hay harvest utilizing a double-cropped system - perennial warm-season forage grass, common bermudagrass (CB; *Cynodon dactylon (L.) Pers.*), overseeded with annual ryegrass (ARG; *Lolium multiflorum Lam.*), a cool-season forage, in reducing soil P from a Ruston fine-sandy loam impacted by PL amendments. A secondary field study similarly examined CB, bahiagrass (BG; (*Paspalum notatum* Flugge.), crabgrass (CG; *Digitaria sanguinalis (L.) Scop.*) and switchgrass (SG; *Panicum virgatum L.*).

The primary study was conducted as a randomized block design with three replicate plots of four previous rates of PL (0, 5, 10 and 20 Mg ha^{-1}) applied annually (1996-2001) to CB sod, at the Calhoun Research Station in Calhoun, Louisiana. Following the last PL application, plots were overseeded with ARG in Fall 2001, forage harvested and analyzed for dry matter yield, tissue P concentration and P removal. Double-cropped ARG and CB were harvested as hay and analyzed as above through 2005, giving four years of data. In Spring 2002, four small sub-plots BG, CB, CG and SG were established in the upper end of the main plots used in the primary study and corresponding data for these warm-season forages was collected for three years.

Over four years, ARG removed more soil P than did CB (112 vs. 76 kg P ha^{-1}, averaged across all rates of previous PL application and soil Bray2 P levels) because of higher tissue P concentration. The double-cropped hay system, therefore, removed

nearly 200 kg P ha^{-1} or reduced soil P by about 100 mg kg^{-1}. Despite low tissue P concentration, high biomass production by SG extracted an average of 64 kg P ha^{-1} annually over three years. This rate was significantly greater than that for CB, BG or CB, and perhaps equaled or exceeded the combined rate for ARG and CB in the double-cropped system.

INTRODUCTION

In 2004, there were 1550 poultry farms in Louisiana (LCES, 2004), with the overwhelming majority concentrated in a twelve-parish region of north central Louisiana (LCES, 2004; Kovar et al., 1999). Besides marketable products, the industry generates over 75,000 Mg of poultry waste annually as by-product (based on LCES, 2004; and West, 2005) This waste, referred to as poultry litter (PL), consists of poultry manure, bedding (rice hulls, peanut hulls or pine shavings), feathers and wasted feed. Poultry litter is a bulky, low analysis organic fertilizer that is typically broadcast onto pastures or other crop fields in close proximity to the poultry houses (Robinson et al., 1994; Carpenter et al., 1998). When PL is applied as a nutrient source, the application rate has often been based on the nitrogen (N) need of the crop, accounting for any immediate post-application nutrient losses such as N volatilization (Gasser, 1987). However, since PL contains a higher phosphorus (P) to N ratio (average P:N = 1:3; Edwards and Daniel, 1993; Sharpley et al., 1994; Heckrath et al., 1995; Sims et al., 2000) than the P:N uptake ratio of crops (about 1:8; Edwards and Daniel, 1992), fertilization with PL tends to enrich the soil with P. Where PL is simply disposed as waste, the application rate is often well in excess of crop nutrient requirements, accelerating the build-up of soil P. This is problematic because P reaching the receiving waters may contribute to eutrophication of downstream fresh waters. Advanced eutrophication, characterized by increased growth of undesirable algae and aquatic vegetation, degrades water quality and impairs its use for fishing, recreation, and consumption. Additional problems arise as oxygen is depleted due to increased levels of microbial decomposition and increased nighttime respiration, further disrupting the ecosystem (EPA, 1976, Whithers and Sharpley, 1995).

Since about 1990, the practice of basing PL application rates on crop N requirement has been reconsidered (Robbins et al., 2000). Previously, while it was recognized that repeated applications of PL at these rates resulted in accumulation of soil P, it was thought that the excess P would be so firmly bound by the soil that it would be immobile and not enter surface or subsurface waters, provided erosion was controlled (Sample et al., 1980). However, it became evident that this is not necessarily the case. Long term application of PL tends to saturate the soil P sorption capacity, leading to release of applied P to surface and ground waters. (Sharpley et al.,1993, 1994; Sims et al., 2000; Gaston et al., 2003a).

In Louisiana, the poultry-producing region is concentrated in areas unsuitable for row crop production. The topography is undulating and the soils (principally Ultisols) have low fertility. Thus, the primary agricultural enterprises in this coastal plain region of Louisiana are cattle farming, forestry and poultry production. The predominant summer forage grasses utilized in this area are bahiagrass (*Paspalum notatum* L.) and bermudagrass *(Cynodon dactylon (L.) Pers.)*, the latter including common (CB) and hybrid varieties. Bermudagrass is a tropical, warm-season perennial grass that is well adapted to the climate and soils of northern Louisiana. It produces well under intensive grazing or hay management provided adequate rainfall (minimum 16 inch yr^{-1}) and ample nutrients are present (Robinson, 1996; Farm Science Genetics, 2003). Bermudagrass requires temperatures above 20°C for germination, reaches its peak growth from mid-April to late June and goes dormant in the fall, thus leaving four to five months of the year with no production (West, 2005). Commonly, ryegrass (*Lolium multiflorum* Lam.), a cool-season annual in Louisiana (ARG), is often overseeded into the existing sod. Its peak growth occurs from mid-September until the first heavy frost and from return of warmer temperature (13° C) in the spring until May. Ryegrass also tolerates close and continuous grazing, and can be harvested for hay. Like bermudagrass, it is adapted to a wide range of soils (Ball et al., 1996; West, 2005).

Some northern Louisiana CB or CB / ARG pastures and hayfields currently show elevated levels of soil P due to long-term application of PL (Robinson et al., 1994; Waldron et al., 2004). This situation would not pose a problem to agriculture or the environment if land resources were unlimited and the economic constraints imposed on farming were not so great. Hypothetically, as one field approached P-saturation, PL application would simply be shifted to another. However, this is currently not an option. Thus, the principal objective of the work reported in this thesis was to determine the effectiveness of hay harvest of CB and ARG to reduce the level of P in soils overly enriched in P. These species were chosen for study as they represent the core forages grown in this area, however, research has shown that other pasture grasses may be as well if not better suited for such P phytoremediation (Eilers, 1998; Lowrance et al., 2002; Newton et al., 2003). Therefore, the secondary objective of this work was to assess the effectiveness of three alternative grasses, crabgrass (*Digitaria sanguinalis (L.) Scop.*) (CG), and switchgrass (*Panicum virgatum L.*) (SW), compared to bahiagrass (BG) and common bermudagrass (CB), for removing soil P in hay harvest.

LITERATURE REVIEW

Phytoremediation

The terms *bioremediation* and *phytoremediation* were not adopted by the research community until 1991 when Raskin used them in one of the first in-depth writings characterizing the ability of different plant species and microbes to sequester and transform harmful pollutants into harmless and sometimes valuable end-products (McMutcheon, 2000). The term bioremediation refers to the use of biological agents, such as bacteria, to remove or neutralize contaminants, whereas phytoremediation refers to the use of plants to remedy or remediate a contaminated site. While bioremediation technology was researched intensely and rapidly adopted for use with high priority contaminants and sites, adoption of phytoremediation technology was much slower. However, the use of phytoremediation, also an *in-situ* technology, has increased due to the increasing number of sites recognized as needing remediation and the cheaper cost of this technology compared to conventional earth-moving methods. It is estimated that to clean the surface 15 cm of contaminated soil with traditional earth-moving methods would cost over $25,000 per hectare whereas phytoremediation would cost between $2500 to $15,000 (EEG, 2005).

Phytoremediation is most often associated with decontamination of organics such as petroleum hydrocarbons, pesticides or explosives, or heavy metals, particularly as hyperaccumulators of metals such as Ni, Zn or Co. However, the US EPA (1999) very generally defines phytoremediation as the “direct use of vascular plants, algae, and fungi for *in-situ* remediation of contaminated soil, sludges, sediments and ground water by plant contaminant removal, contaminant degradation or contaminant containment.”

Thus, while most current applications are with hazardous substances, phytoremediation can be used with any element or compound which possess a threat to the environment and which can be accumulated or transformed by a vascular plant, algae or fungi. All plants take up metals and other chemicals to varying degrees from their rooting media. However, the ability for the plant to hyperaccumulate or concentrate the target substance depends on both intrinsic (genetic) and extrinsic (environmental, such as temperature and light) factors and varies from plant species to species. For a hyperaccumulator, the tissue concentration of contaminant depends not only on the internal plant mechanisms but also on the concentration of the contaminant in growth medium. For example, McGrath et al. (2000) found increasing plant uptake removal of zinc with increasing concentration of zinc in the soil. There is similar evidence for CB and P (Gaston et al., 2003b).

Plant uptake of a contaminant and harvest removal, the focus of this thesis work, is only one of several different ways by which plants may remediate a contaminated site. The USEPA Phytoremediation Guide (2001) defines six types of phytoremediation based on contaminant fate, degradation process, extraction method, contaminant type or some combination of these.

Phytovolatilization is the use of plants to uptake and transpire the contaminant into the atmosphere, the (organic) contaminant thereafter subject to photodegradation.

Phytodegradation (also called *phytotransformation*) is the use of certain enzymes produced by metabolic processes occurring in an aquatic or terrestrial plant to degrade or breakdown a contaminant into a nutrient(s) useable by the plant or by microbes in the substrate.

Rhizofiltration is the adsorption or precipitation of contaminants in solution onto or within plant roots. The plants are established hydroponically and transferred to the contaminated aquatic site. When the plant roots become saturated with contaminants, the plants are removed.

Rhizodegradation is the breakdown of contaminants in the soil through enhanced microbiological activity in the rhizosphere. The increased microbial populations and activity are the result of enrichment with plant root exudates and the increased nutrient source, in the form of the contaminant.

Phytostabilization is the use of certain plant species to immobilize contaminants in the soil and ground water through absorption and accumulation by roots. These areas are devoid of natural vegetation, so the species utilized must be tolerant of long-term exposure to the contaminant and will serve as a permanent vegetative cover.

Phytoextraction (also called *phytoaccumulation*) refers to the ability of plant roots to take up metal contaminants from the soil and translocate them into the aboveground portions of the plant (hyperaccumulators absorb unusually large amounts compared to other plants). The contaminant-extracting plants are established, grown, harvested and this process continued until soil containment levels are adequately reduced.

Phytoremediation of High P Soil

There has been little interest in soil P phytoremediation until recently (Eilers, 1998; Delorme et al., 2000; Brink, et al., 2001, 2002, Gaston et al., 2003b; Rowe and Fairbrother, 2003.). In part, this is due to the earlier belief that any P not taken up by vegetation would be tightly bound to soil particles and immobile so that if erosion was controlled P would be contained in the field indefinitely (Baker et al., 1975; Sharpley and

Syers, 1979). The concern with P at that time was not its mobility but its immobility, that P was so tightly bound to the soil that it might become unavailable to plants (Arnon, 1953). Confidence in P immobility led to recommendations that animal manures such as poultry litter be land- applied at rates based solely on crop N requirements (Mozaffari and Sims, 1996; McDowell et al., 2001; Brink et al., 2002).

By the mid-1980s, it became evident that intensive livestock operations were a contributing factor to fresh water eutrophication. Soils which had been amended with animal manure for years were no longer able to bind the excess soil P not sequestered by vegetation and this excess P was being lost in runoff and percolation. Once these high P waters enter a water body, the soluble P portion quickly stimulates freshwater algae and aquatic vegetation growth, increasing the concentration of oxidizable organic matter and depleting the dissolved oxygen (Reddy et al., 1980; Edwards and Daniel, 1992; Kingery et al., 1994; Robinson et al., 1995; Sharpley et al., 1994; Breeuwsma et al., 1995; Mozaffari and Sims, 1996).

Two approaches to limiting such off-site loss of P have been considered. One is to amend the soil with low-cost material that has a high capacity to adsorb or precipitate P. The other is to remove soil P by plant uptake and harvest, i.e. phytoremediation. Among soil amendments, Peters and Basta (1996) found that municipal (two alum hydrosolids) and industrial (cement kiln and bauxite refining) wastes, high in Al, Fe or Ca, effectively reduced water-soluble and extractable P in soils that contained high levels of P. Similarly, water treatment wastes (Codling et al., 2002; Haustein et al., 2000) and by-products from the production of TiO_2 pigments (Codling et al., 2002), alum (Haustein et al., 2000) and aluminum (Wang and Zhang, 2004) production reduced water-soluble and extractable soil P. Although these amendments are effective for the immediate purpose, secondary effects, such as increased concentrations of Al and salts (Peters and Basta, 1996; Codling et al., 2000), on animal health, soil fertility and quality are uncertain. The alternative to chemical suppression of P solubility to reduce P loss to surface and ground waters is to remove soil P by plant uptake and harvest. (Brink et al., 2001)

MATERIALS AND METHODS

Plot Studies

The two plot studies presented in this thesis are part of a 10 year study conducted at the LSU AgCenter Calhoun Research Station in Calhoun, Louisiana. Initial experimental design was developed by Dr. Donald L. Robinson. The project was later overseen by Dr. John Kovar and since 2000 the project has been under the direction of Dr. Lewis Gaston. The field study has been maintained by Darren Cooper, research associate Calhoun Research Station. Data reduction, statistical analysis and interpretation were conducted by the author, who also contributed to recent laboratory analyses.

Plots were established on a Ruston fine sandy loam soil (fine-loamy, siliceous, thermic Typic Paleudult). The primary study was a randomized block design with three replicates each of four rates of poultry litter (PL; 0, 5, 10 and 20 Mg ha^{-1}) applied to 3 m wide by 13 m long (0.0039 ha = 0.01 ac) plots of common bermudagrass (CB, *Cynodon dactylon* (L.) Pers.). Plots were physically and hydrologically separated along the top and lateral sides by PVC pipe (7.5 cm diameter), partially buried approximately 2.5 cm into the soil. To further insure hydrologic isolation of plots, a soil berm was constructed and packed against the outside upper 5 cm of all pipe.

Prior to the study, which was begun 1995, the site was predominantly bahiagrass (*Paspalum notatum* Flugge) but this was replaced with common bermudagrass (CB; *Cynodon dactylon* (L.) Pers.) at plot establishment. Upon establishment of a good stand of CB, the PL treatments were applied in 1996. Following the sixth year of treatment application (2001), soil P concentrations (methodology described below) in plots that had received PL at the higher rates were excessively high and further application of PL was abandoned. Thereafter, these 12 plots were used to monitor P uptake and harvest removal of residual soil P by CB in the summer. Beginning in the Fall of 2001, plots were overseeded with annual ryegrass (ARG; *Lolium multiflorum* Lam.), and P uptake and harvest removal of soil P by ARG similarly tracked. Since 2001, CB and ARG plots have fertilized with N as per Louisiana Cooperative Extension Service (LCES) recommendations for hay production (rate) and K as indicated by soil test results and LCES recommendations (N is especially necessary for proper utilization of P by the plant and the amount applied will influence P uptake efficiency (Robinson, 1991).

In the Spring of 2002, four small sub-plots (0.375 m^2) of bahiagrass (BG), CB, crabgrass (CG; *Digitaria sanguinalis (L.) Scop.*) and switchgrass (SG; *Panicum virgatum L.*) were established in the upper end of the main plots described above. The SG was established by transplant and the other grasses, from seed. This secondary study was conducted to confirm earlier greenhouse results on the relative efficiencies of P uptake and harvest removal (Eilers, 1998). The four sub-plots per each of the 12 main plots (= 48) were fertilized with N and K as described above.

Plant Sampling and Tissue Analyses

Harvest was based on maturity. In the primary study, CB was cut four times in 2002 through 2004 and three times in 2005. The ARG was cut five times during the 2002 (Fall 2001 to Spring 2002) and 2004 seasons, and four times during 2003 and 2005. At harvest, the entire plot was cut but only a 1.1 m by 6.1 m sub-sample kept for measurements. Moisture content on a sub-sample of this was determined by drying at

55° C for 48 hours and dry matter yield calculated. Dried tissue sample was ground to pass a 0.833 mm sieve and a sub-sample of this acid-digested and analyzed for P concentration by inductively coupled plasma spectrometry (ICP) according to procedures of the LSU AgCenter Soil and Plant Analysis Laboratory (STPAL). Dry matter yields for entire BG, CB, CG and SG sub-plots were determined and tissue concentration of P measured as described for the primary CB / ARG main plots.

Soil Sampling and Analysis

Surface (0 to 15 cm) soil samples were collected at plot establishment (1995) and in the Spring annually thereafter (prior to PL application, through 2001) through 2005. Soil samples were air-dried, crushed, sieved (2 mm) and analyzed for Bray 2 available soil P (Byrnside and Sturgis, 1958) according to the LSU AgCenter STPAL.

Statistical Analysis

Mean separations were preformed by Fisher's protected least significant difference (LSD, $\alpha = 0.05$) where the F values were significant at the 0.05 probability level (SAS, 2002). Relationships evaluated by linear regression and the R^2 values reported herein are significant at the 0.05 probability level unless otherwise stated. Phosphorus recovery was calculated as the product of dry matter yield times P tissue concentration.

RESULTS AND DISCUSSION

Soil

Table 1 gives Bray 2 P concentrations in the surface 0 – 15 cm soil from study inception (1995) through termination of PL application (2001) to 2005. Several points stand out in the data. First, at the outset, all P levels were well above those recommended by the LCES for forage grasses (Table 2). Second, Bray 2 P increased generally proportional to annual PL application (1996 to 2001) rate, more than tripling under the highest rate (20 Mg ha^{-1}). Even at 5 Mg ha^{-1}, Bray 2 P nearly doubled, increasing the likelihood of off-site P loss and water quality impact (van Riemsdijk et al., 1987; Sharpley et al., 1998; Kingery et al., 1993). Third, after termination of PL application, P reduction occurred (presumably due to runoff and percolation losses, in addition to plant uptake and harvest removal) but Bray 2 P levels remained elevated relative to initial conditions four years post-application.

Slow attenuation of soil P (Table 1) is not unexpected in light of previous studies on the persistence of P added to soil. For example, Johnston and Poulon (1976) found that Olsen P (Olsen et al., 1954) in previously manure-amended soils decreased through crop removal from about 60 – 70 mg kg^{-1} to about 10 mg kg^{-1} over 73 years of harvest. Mozaffari and Sims (1996) reported that it took 16 years of cropping with corn and soybeans (average annual removal of 16 kg ha^{-1} per year) on a Portsmouth fine sandy loam to reduce Mehlich 1 P (Mehlich, 1984) levels to that at which a crop response to P fertilization would once again be expected (initial soil test P of ~ 100 mg kg^{-1}). In comparison to these studies, the 2001 to 2005 data in Table 1 are very promising. However, yield and tissue P data provide more definitive results.

Table 1. Bray 2 P concentrations in pasture plots as affected by rate of poultry litter fertilization. No application of poultry litter or other P fertilizer beyond 2001.

Year	Poultry Litter Application Rate (Mg ha^{-1})			
	0	5	10	20
1995	203 c	229 a	182 d	223 b
1996	159 a	165 a	167 a	215 a
1997	174 a	201 a	190 a	213 a
1998	166 b	172 b	204 ab	286 a
1999	184 b	207 b	274 ab	394 a
2000	153 c	230 bc	307 ab	345 a
2001	184 b	374 b	419 ab	782 a
2002	184 b	296 ab	446 ab	661 a
2003	178 b	242 b	310 ab	467 a
2004	162 b	245 ab	326 ab	517 a
2005	114 b	211 b	276 b	536 a

† For any year, means in a row followed by the same letter are not significantly different (Fisher's $\alpha = 0.05$).

Table 2. Louisiana Cooperative Extension Service ratings of Bray 2 P soil test levels for common bermudagrass grown for hay on fine sandy loam or loam soil of upland or alluvial origin. (LSU AgCenter Soil Testing and Plant Analysis Laboratory).

Soil Test P Level	Alluvial	Upland
	-------------------- mg kg^{-1}_{soil}	--------------------
Very low	10	60
Low	30	80
Medium	70	140
High	90	160

Yields, P Tissue Concentrations and Harvest Removal

Bermudagrass / Ryegrass Study

Bermudagrass

CB dry matter yield, tissue P concentration and P harvest removal for 2002 through 2005 for each prior PL treatment (0, 5, 10 and 20 Mg ha^{-1} annually, through 2001) are listed in Table 3. Although CB showed a significant response to PL rate when applied (Vervoort et al., 1998; Brink et al., 2002; Gaston et al., 2003b), there was no statistically significant response to residual fertility levels, even in the first year (2002) after PL application was abandoned.

Nor were there differences due to previous PL treatments in tissue concentration of P (Table 3), despite differences in Bray 2 available soil P among treatments (Table 1). This may reflect stability in the quantity of P a crop will absorb (Dean and Fried, 1953), however, more recent findings indicate increased tissue P with increased soil P (Evers, 2002) or N (Allen et al., 1977; Robinson et al., 1988; Heckrath et al., 1995). Lack of treatment differences also may be due to variability among replicates in Bray 2 P. Although Bray 2 P (Table 1) increased about 100 mg kg^{-1} per PL treatment level, the only significant difference up to 2005 was between the 0 and 20 Mg ha^{-1} PL rates (except in 2003 when Bray 2 P for 5 Mg ha^{-1} plots was lower than for 20 Mg ha^{-1} plots).

Regression analysis of the tissue P concentration data (Table 3) does suggest a trend toward higher concentration with higher Bray 2 P and when these data were related on a plot by plot basis (Fig. 1), regression analysis shows that tissue P concentration is positively and significantly related to soil Bray 2 P in all but the first year (2002). The implication is that the effectiveness of soil P phytoremediation is proportional to plant-available soil P concentration in manure impacted soils –a positive result supporting this remediation strategy.

Table 3. Mean bermudagrass yield, tissue P concentration and P removal, 2002 through 2005, for plots previously fertilized with poultry litter at different rates. No litter was applied during the study.

Year	Rate	# Harvests	Yield	Tissue [P]	P Removed
	Mg / ha		Mg / ha	%	kg / ha
2002	0	4	4.88 a†	0.418 a	20.20 a
	5		5.60 a	0.442 a	24.08 a
	10		5.84 a	0.418 a	23.80 a
	20		6.04 a	0.441 a	26.28 a
2003	0	4	5.28 a	0.273 a	14.96 b
	5		5.40 a	0.297 a	15.76 b
	10		6.24 a	0.324 a	19.68 ab
	20		6.40 a	0.352 a	22.12 a
2004	0	4	6.48 a	0.270 a	17.32 c
	5		6.52 a	0.321 a	20.36 bc
	10		7.16 a	0.310 a	21.60 ab
	20		7.60 a	0.326 a	24.40 a
2005	0	3	5.13 a	0.215 a	10.92 a
	5		5.01 a	0.274 a	13.53 a
	10		5.31 a	0.269 a	14.31 a
	20		5.55 a	0.299 a	15.21 a

† For any year, means in a column followed by the same letter are not significantly different (Fisher's α = 0.05).

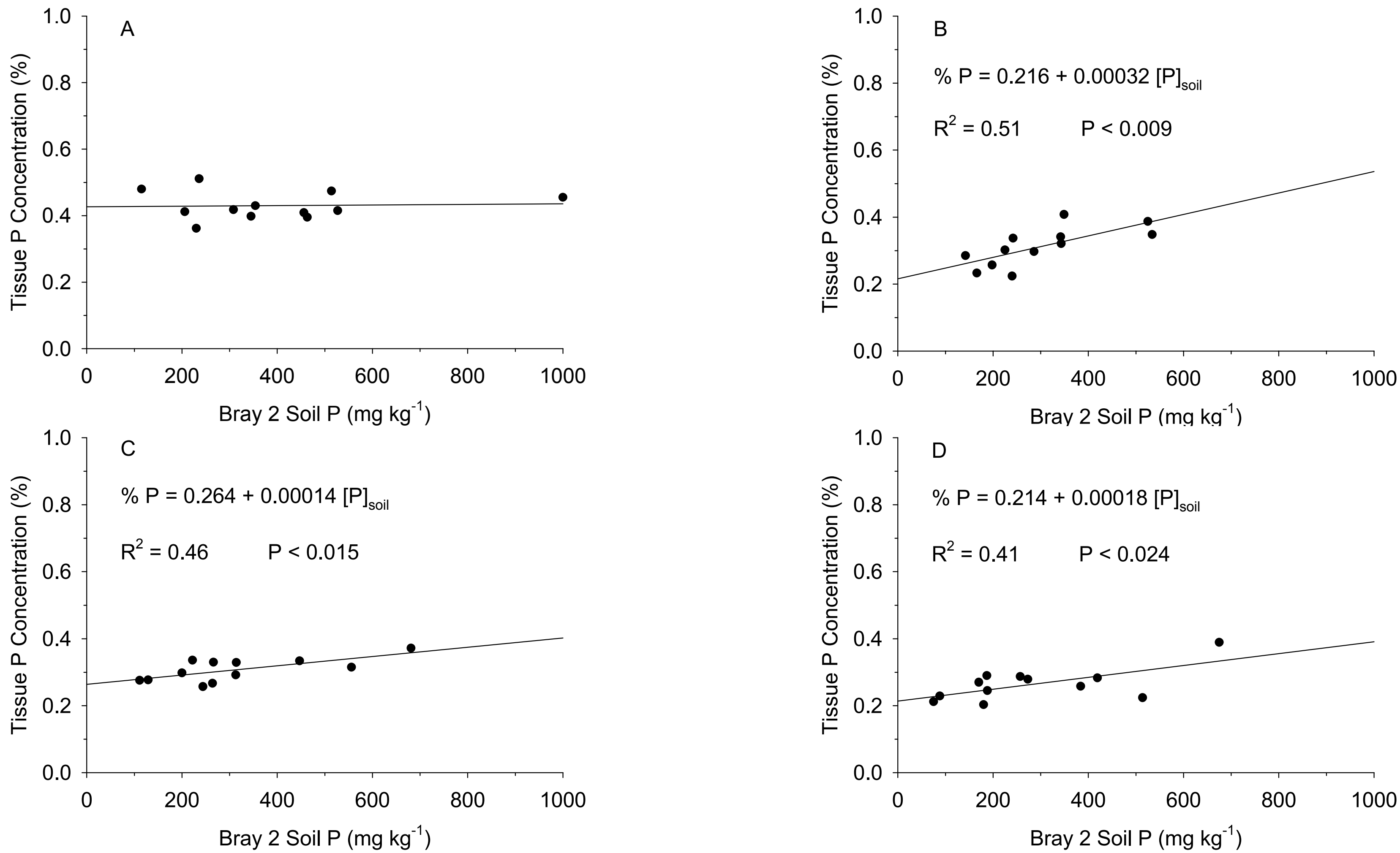

Figure 1. Relationship of tissue P concentration to Bray 2 soil P for bermudagrass samples in 2002 (A), 2003 (B), 2004 (C), and 2005 (D). The linear relationship was significant at $P < 0.05$ except in 2002.

Although there were no differences in CB yield or tissue P concentration due to prior PL application rates, the product of these variables, (dry matter x P concentration per unit dry matter) P removed in harvest was significantly related to prior PL application rate. More P was removed in hay harvest from the 20 Mg ha^{-1} treatment plots than from the 5 or 0 Mg ha^{-1} plots in 2003 and 2004 (Table 3), and more P was removed from the 10 Mg ha^{-1} plots than from the 0 Mg ha^{-1} plots in 2004. However, the year by year relationships of P removal to soil Bray 2 P (Fig. 2) were less encouraging than the tissue P concentration / Bray 2 P relationships (Fig. 1). The harvest removal of soil P was never linearly related to Bray 2 P at a level of significance $P < 0.05$, and only in 2003 and 2004 was it related at $P < 0.10$.

Ryegrass

Dry matter yields of ARG (Table 4) were similar to those of CB (Table 3) and showed no significant differences due to prior PL treatment level. This result is consistent with the findings of van Faassen and van Dijk (1987), who found residual P did not significantly influence yield at any level of soil P. Lack of ARG yield response to soil P may be related to decreased root density under higher available soil P (Fohse et al., 1988), however, other factors such as rainfall, temperature, day length and days between harvest also affect ARG yield (Henderson and Robinson, 1982; Eichhorn et al., 1984; Robinson, 1996).

Unlike CB, the tissue P concentration in ARG increased with increasing prior PL fertilization rate (Table 4). Furthermore, the positive, somewhat curvilinear relationship of tissue P concentration to soil Bray 2 P was highly significant in all years (Fig. 3), with R^2 values increasing from 0.50 in 2002 to nearly 0.80 in 2005 when described as a

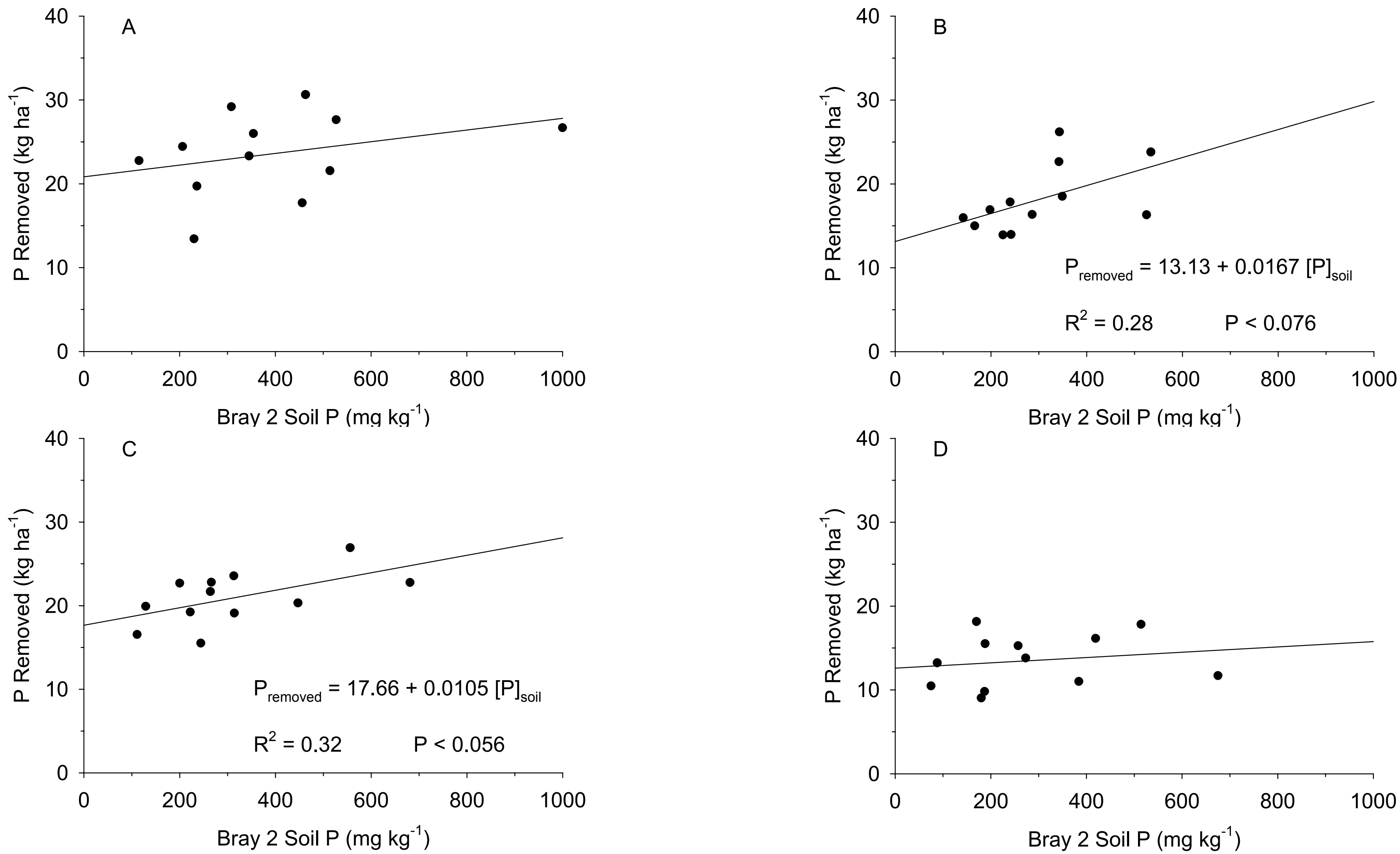

Figure 2. Relationship of P harvest removal to Bray 2 soil P for bermudagrass samples in 2002 (A), 2003 (B), 2004 (C), and 2005 (D). The linear relationship was significant at $P < 0.10$ in 2002 and 2003.

linear response. Results for ARG tissue P concentration are consistent with those of Allen (1977), Evers (2002) and Sharma et al. (2004) who found positive relationships between tissue and soil P concentrations. However, possibly higher residual soil N in plots previously fertilized with PL may have also led to higher tissue P concentrations (Allen, 1977; Robinson et al., 1987; Heckrath et al., 1995).

Given such strong relationship between tissue P and prior PL treatment (Table 4), it was not surprising to find consistent differences in P uptake removal (Table 4). In all years, more P was removed from the 20 Mg ha^{-1} plots than from the 0 Mg ha^{-1} plots, and in 2003, more P was removed from the 20 Mg ha^{-1} plots than from the 5 Mg ha^{-1} plots. Furthermore, in all but 2005, more P was removed from the 10 Mg ha^{-1} plots than from the 0 Mg ha^{-1} plots. Harvest removal of P in ARG was also more closely related to Bray 2 P than was the case for CB. When described as a linear response, the weakly curvilinear relationship was significant at $P < 0.05$ (2002 and 2003) and $P < 0.10$ (2005).

Although the objective of this study was to assess effectiveness of combined CB and ARG hay harvest to remove soil P, a comparison of the above data for these species is in order before summarizing the CB / ARG double-cropped system.

Combined Bermudagrass / Ryegrass

As suggested by comparison of the data in Tables 3 and 4, differences between dry matter production of CB and ARG were inconsistent year by year. CB produced more dry matter in 2003 and 2005, whereas ARG produced more in the 2002 and 2004 seasons. These results agree with those of Evers and Doctorian (1998) and Evers (2002), who found no difference between CB and ARG yields, possibly due to overlapping of growing seasons in April and May. In comparing tissue P concentration,

Table 4. Mean ryegrass yield, tissue P concentration and P removal, 2002 through 2005, for plots previously fertilized with poultry litter at different rates. No litter was applied during the study.

Year	Rate	# Harvests	Yield	Tissue [P]	P Removed
	Mg / ha		Mg / ha	%	kg / ha
2002	0	5	5.90 a[†]	0.435 c	25.05 b
	5		7.15 a	0.519 b	34.95 ab
	10		8.55 a	0.529 ab	42.90 a
	20		9.25 a	0.573 a	50.70 a
2003	0	4	4.24 a	0.406 d	17.36 c
	5		4.24 a	0.496 c	20.10 bc
	10		4.80 a	0.527 b	24.76 ab
	20		4.84 a	0.570 a	27.44 a
2004	0	5	6.05 a	0.384 c	22.85 b
	5		6.00 a	0.504 b	29.65 ab
	10		6.24 a	0.532 b	32.25 a
	20		6.25 a	0.594 a	36.70 a
2005	0	4	4.12 a	0.351 c	14.36 b
	5		4.64 a	0.435 b	19.72 ab
	10		4.56 a	0.461 b	20.60 ab
	20		4.76 a	0.540 a	25.92 a

[†] For any year, means in a column followed by the same letter are not significantly different (Fisher's $\alpha = 0.05$).

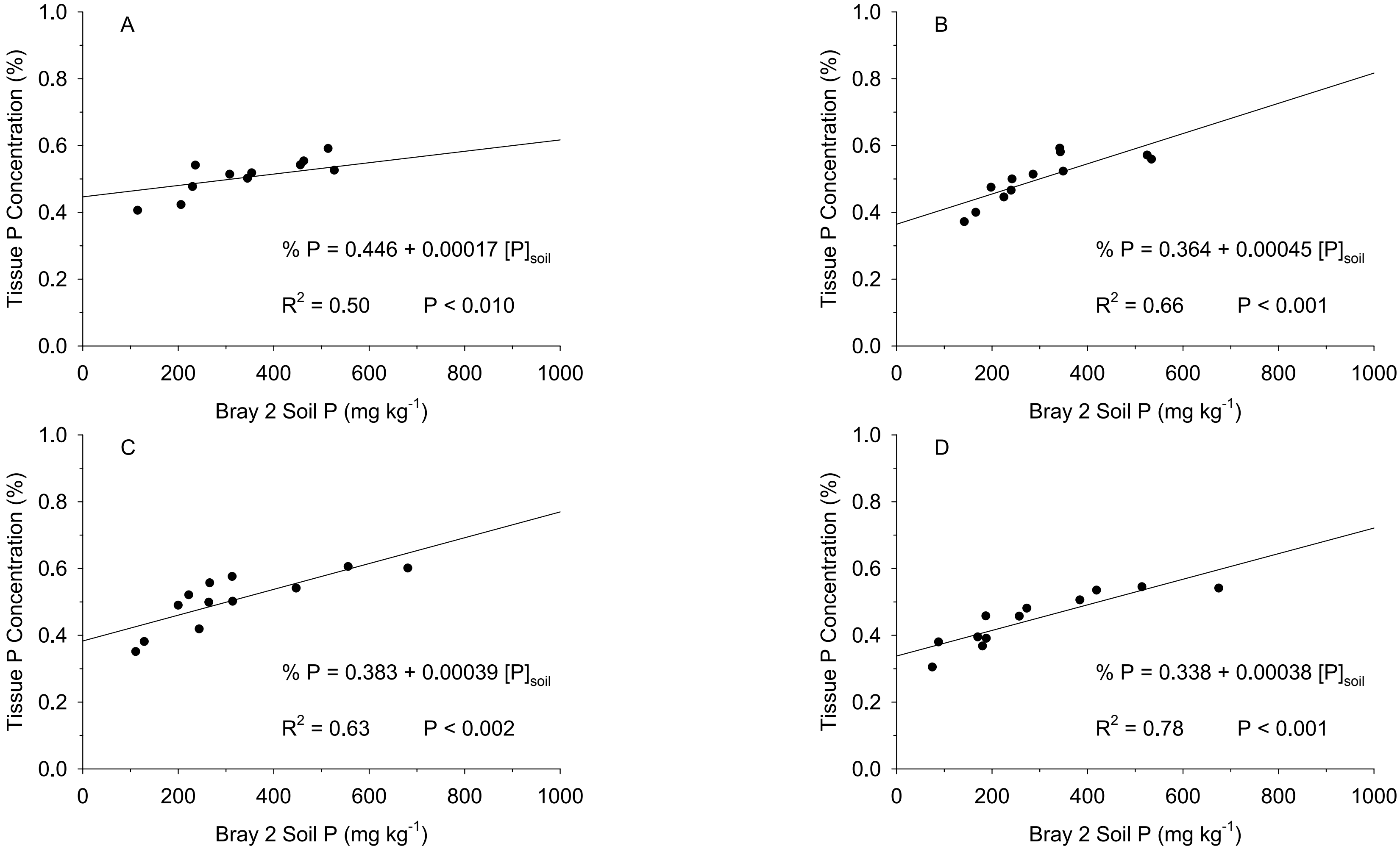

Figure 3. Relationship of tissue P concentration to Bray 2 soil P for ryegrass samples in 2002 (A), 2003 (B), 2004 (C), and 2005 (D).

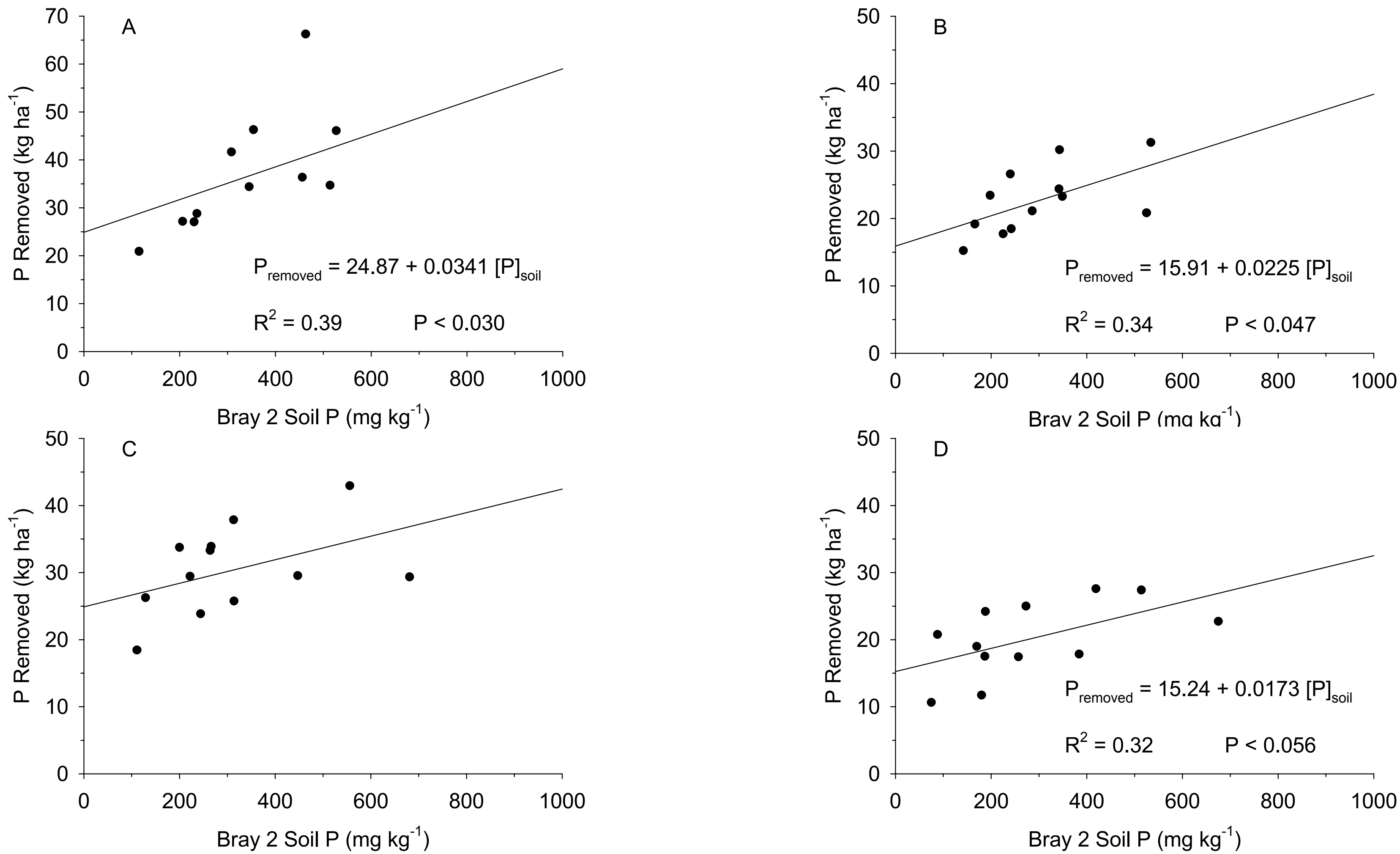

Figure 4. Relationship of P harvest removal to Bray 2 soil P for ryegrass samples in 2002 (A), 2003 (B), 2004 (C), and 2005 (D). The linear relationship was significant at $P < 0.05$ in 2002 and 2003 and at $P < 0.10$ in 2005

ARG had significantly greater tissue P concentration so that P removal by ARG was greater than by CB.

Cumulative (2002 through 2005) CB and ARG yields and P uptake data are given in Table 5. Neither CB total yield nor P uptake removal showed significant differences due to previous PL treatment. Thus, averaged across all plots, the expected P removal in annual CB harvest was 19 kg P ha^{-1}. While total yield of ARG did not show significant differences among previous PL treatments, P uptake removal did, with more P removed from the 20 Mg ha^{-1} plots than from the 0 Mg ha^{-1} plots. However, averaged across all plots, the expected P removal in ARG harvest was 28 kg P ha^{-1}.

As expected from the separate CB and ARG data, combined yield totals showed no significant effect due to previous PL treatment (Table 5). However, due to the contribution of ARG, the double cropped system (CB + ARG), removed significantly more P from soil with higher (20 Mg ha^{-1} plots) than lower (0 Mg ha^{-1} plots) Bray 2 P. At the lowest level of Bray 2 P, the removal rate was 36 kg ha^{-1} annually but at the highest level it was 57 kg ha^{-1} annually. Across all PL treatment plots, the average combined P removal per year was 47 kg ha^{-1}. This demonstrations the benefits of increased P removal from a double-crop system, results similar to those found by Evers (2002).

Table 5. Cumulative bermudagrass and ryegrass yield and P removal per harvest, 2002 through 2005, for plots previously fertilized with poultry litter at different rates. No litter was applied during the study.

Forage	Rate	# Harvests	Yield	P Removed
	Mg / ha		Mg / ha	kg / ha
Bermudagrass	0	15	21.79 a[†]	63.42 a
	5		22.54 a	73.68 a
	10		24.53 a	79.37 a
	20		25.62 a	88.03 a
Ryegrass	0	18	20.32 a	79.63 b
	5		21.97 a	105.33 ab
	10		24.21 a	120.51 a
	20		25.10 a	140.77 a
Combined	0	33	42.11 a	143.05 b
	5		44.51 a	179.02 ab
	10		48.74 a	199.88 ab
	20		50.72 a	228.80 a

[†] For any year, means in a column followed by the same letter are \
not significantly different (Fisher's α = 0.05).

BAHIAGRASS / BERMUDAGRASS / CRABGRASS / SWITCHGRASS STUDY

Table 6 gives annual and cumulative dry matter yield, tissue P concentration and P removal for the four grasses averaged over plots that had received six prior annual applications of PL at 0, 5, 10 and 20 Mg ha^{-1}. The dry matter yield of SG was greater than that of all other grasses in every year, however, its tissue P concentration was consistently lower than that of all other grasses. In contrast, crabgrass had the highest tissue P concentration in all years. Eilers (1998) earlier found superior yield of SG but low tissue P concentration. The high tissue P concentration of CG is also consistent with earlier results of that greenhouse study (Eilers, 1998).

Regardless of the low tissue P concentration of SG, its substantially higher dry matter yield more than compensated for this so that beyond 2002 P uptake removal by SG was significantly greater than the other grasses (Tables 6 and 7). Differences among the grasses for cumulative yield, average tissue P concentration and cumulative P removal followed annual differences, with SG having the greatest yield and P removal despite the least tissue P concentration (Table 6). Harvest removal of P followed the order, SG > CG > BG = CB, with SG harvest removing an average of 64 kg P ha^{-1} annually.

Table 8 gives combined BG, CB, CG and SW data for the different PL treatments. Total yield averaged across all species varied among PL treatments in 2002 and 2004, with higher yields from the 10 or 20 Mg ha^{-1} plots than from the 0 Mg ha^{-1} plots. Average tissue P concentrations were also higher in grass grown on the 10 or 20 Mg ha^{-1} plots than on the 0 Mg ha^{-1} plots (Table 7). Consequently, average P removal was greater from the 10 or 20 Mg ha^{-1} plots than from the 0 or 5 Mg ha^{-1} plots.

Table 6. Mean bahia-, bermuda-, crab- and switchgrass total yield, tissue P concentration and P harvest removal across plots that had previously been fertilized with poultry litter at 0, 5, 10 and 20 Mg ha^{-1}annually. Data for 2002 through 2004 are shown. No litter was applied during the study.

Year	Grass	# Harvests	Yield	Tissue [P]	P Removed
			Mg / ha	%	kg / ha
2002	Bahia	4	8.41 b†	0.305 b	26.03 c
	Bermuda	4	10.55 b	0.299 b	31.50 bc
	Crab	4	10.99 b	0.341 a	44.82 a
	Switch	4	18.58 a	0.224 c	39.84 ab
2003	Bahia	4	11.32 b	0.248 c	27.78 c
	Bermuda	3	10.68 b	0.289 b	30.91 bc
	Crab	3	12.24 b	0.316 a	40.72 b
	Switch	5	26.18 a	0.225 d	58.41 a
2004	Bahia	5	14.58 b	0.301 b	43.61 b
	Bermuda	3	7.24 c	0.291 b	20.17 c
	Crab	4	13.34 bc	0.405 a	54.28 b
	Switch	5	38.63 a	0.249 c	95.12 a
Total	Bahia	15	34.31 b	0.284 b	97.42 c
	Bermuda	10	28.48 b	0.293 b	82.58 c
	Crab	11	36.57 b	0.354 a	139.82 b
	Switch	14	83.39 a	0.233 c	193.37 a

† For any year, means in a column followed by the same letter are not significantly different (Fisher's $\alpha = 0.05$).

Table 7. Mean bahia-, bermuda-, crab- and switchgrass total yield, tissue P concentration and P harvest removal (2002 through 2004) by rate, for plots previously fertilized with poultry litter at different rates. No litter was applied during the study.

Year	Rate	Harvests	Yield	Tissue [P]	P Removed
	Mg / ha		Mg / ha	%	kg / ha
Bahia	0	5	25.89 b[†]	0.272 b	69.59 b
	5		36.00 a	0.274 b	98.67 a
	10		37.90 a	0.288 ab	108.62 a
	20		37.45 a	0.305 a	112.82 a
Bermuda	0	4	13.67 a	0.267 c	36.74 a
	5		27.14 a	0.274 c	70.82 a
	10		42.13 a	0.296 b	122.39 a
	20		30.87 a	0.334 a	100.37 a
Crab	0	5	27.52 b	0.330 b	93.34 b
	5		32.17 b	0.333 b	114.27 b
	10		41.33 a	0.388 a	174.54 a
	20		45.26 a	0.366 ab	176.15 a
Switch	0	4	68.03 a	0.220 a	147.49 a
	5		87.21 a	0.235 a	204.64 a
	10		87.73 a	0.235 a	205.76 a
	20		90.61 a	0.241 a	215.59 a

[†] For any grass, means in a column followed by the same letter are not significantly different (Fisher's $\alpha = 0.05$).

Table 8. Mean total yield, tissue P concentration and P harvest removal for bahia-, bermuda-, crab- and switchgrass for plots previously fertilized with poultry litter at different rates. Data for 2002 through 2004 are shown. No litter was applied during the study.

Year	Rate	Yield	Tissue [P]	P Removed
	Mg / ha	Mg / ha	%	kg / ha
2002	0	8.91 b[†]	0.273 c	23.28 c
	5	11.33 ab	0.286 bc	32.87 bc
	10	15.44 a	0.298 ab	46.61 a
	20	12.88 ab	0.313 a	39.42 ab
2003	0	11.84 a	0.242 b	28.50 b
	5	15.84 a	0.250 b	38.53 ab
	10	16.34 a	0.283 a	44.10 a
	20	16.40 a	0.303 a	46.37 a
2004	0	13.03 b	0.301 b	35.25 b
	5	18.48 ab	0.301 b	50.69 ab
	10	20.50 a	0.325 a	61.81 a
	20	21.78 a	0.319 ab	65.44 a
Total	0	33.78 b	0.272 b	87.04 c
	5	45.63 ab	0.279 b	122.10 b
	10	52.27 a	0.302 a	152.83 a
	20	51.07 a	0.312 a	151.23 a

[†] For any year, means in a column followed by the same letter are not significantly different (Fisher's $\alpha = 0.05$).

Averaged across all grasses, annual P harvest removal followed the PL treatment order, 20 = 10 > 5 > 0 Mg ha^{-1}, with 51 kg P ha^{-1} removed from the 20 and 10 Mg ha^{-1} plots and 29 kg P ha^{-1} from the 0 Mg ha^{-1} plots. The effect of prior PL treatment on P removal for BG, CB, CG and SG (data from Table 7) is shown in Fig. 5. Neither CB nor SG showed increased P removal with increased prior PL application rate, and P removal for BG and CG did nor increase above the prior 5 and 10 Mg ha^{-1} PL rates, respectively.

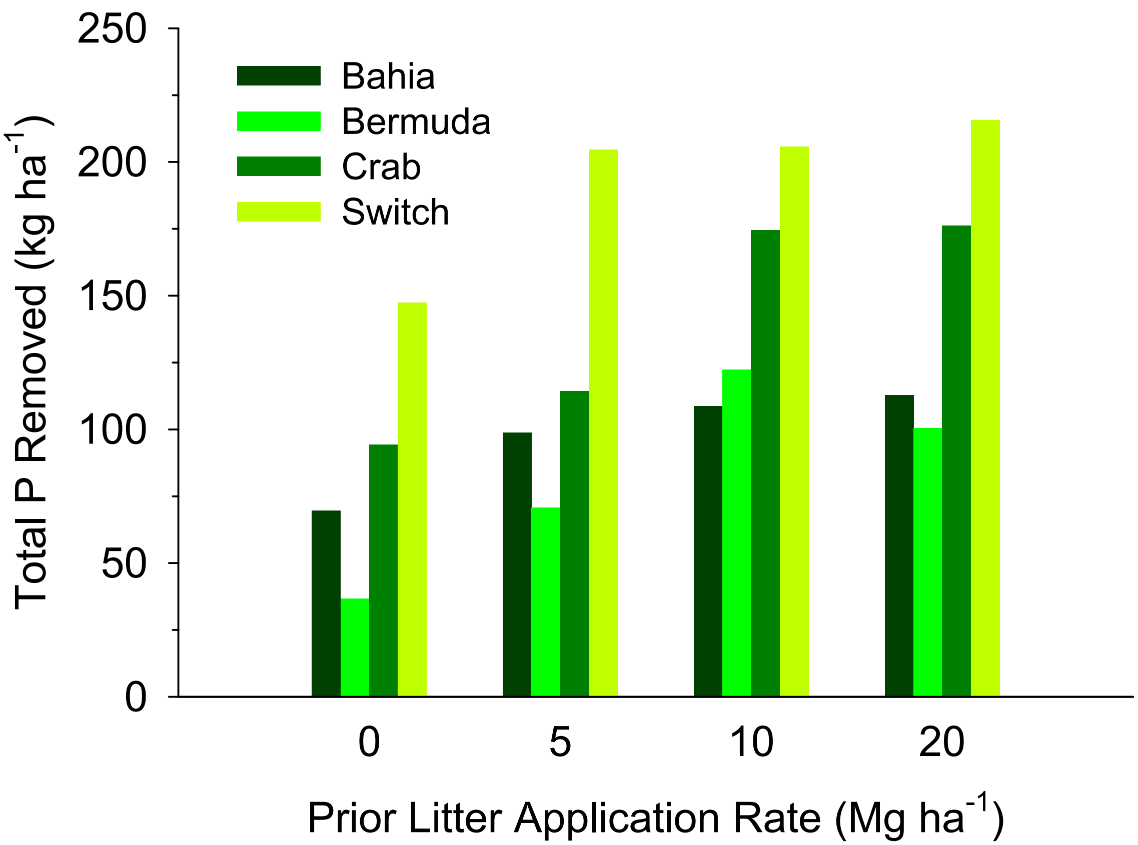

Figure 5. Total P harvest removal (2002 through 2004) for bahia-, bermuda-, crab- and switchgrass grown on plots that have received six annual applications of different poultry litter rates prior to 2002.

SUMMARY AND CONCLUSIONS

Since livestock production has become regionally concentrated and nutrients are no longer recycled through the environment, nutrients that are imported in feed tend to concentrate in farm soil. Thus, areas traditionally used for disposal of livestock waste (pastures and crop fields) are rapidly becoming enriched in nutrients, particularly P, leading to increased P loss to surface and ground waters. The problem is expected to worsen in north central Louisiana as poultry production expands. While the use of nutrient management plans and proper implementation of best management practices (BMPs) are effective in slowing the mobilization of P, without active efforts to chemically sequester or extract soil P, it remains a long-term source of water contamination. Currently, the lasting environmental consequences of soil amendments used to decrease P solubility are unknown. On the other hand, use of a hay-based forage removal strategy (phytoremediation) is environmentally sound.

The primary focus of the work reported in this thesis was to determine the effectiveness of spring and fall hay harvest of CB, double-cropped with ARG, in reducing the level of residual P in a soil previously treated with four rates of PL. Since these grasses are commonly grown in northern Louisiana, results of this study show the potential for soil P phytoremediation using an existing cropping system but managed for hay production rather than grazing. Also included in this thesis are results of a secondary study, conducted on sub-areas of plots in the primary study, to assess the comparative effectiveness of two alternative forage species, CG and SG, compared to BG (similar to CB in current use) and CB for removing soil P in hay harvest.

Dry matter yield of neither CB nor ARG was influenced by previous application of PL and there was no overall difference in yields between CB and ARG from 2002 through 2005. The tissue P concentration of CB increased with increasing concentration of soil Bray 2 P to some extent, but tissue P concentration increased significantly for ARG. Thus, while there was negligible response in CB harvest removal of P due to prior PL application or Bray 2 P, the response for ARG was significant. Across all previous PL rates, P harvest removal in CB was 19 kg ha^{-1} annually for the four years of this study. Average annual removal of P in ARG hay harvest ranged from 20 kg ha^{-1} for the 0 Mg ha^{-1} PL plots to 28 kg ha^{-1} for the 20 Mg ha^{-1} PL plots.

Across all rates of previous PL application, average annual P removal by SG hay harvest (64 kg P ha^{-1}) was significantly greater than removal by CG (47 kg P ha^{-1}) and this significantly greater than removal by BG and CB. Since the tissue concentration of P in SG was least, its superior performance in soil P phytoremediation was due to its large biomass production. Although SG is not a premier livestock forage, it has good forage quality as well as high biomass productivity (McLaughlin et al., 1999). Furthermore, it is a promising candidate as a biofuel feedstock and so presents commercial opportunities other than as a hay crop (McLaughlin et al., 1999), favoring its adoption.

The use of a warm season perennial / cool season annual (CB / ARG) hay harvest rotation provides is a simple way to export soil P. Switchgrass alone may extract even more soil P. Expansion of existing markets and development of new markets for SG make it an attractive alternative grass crop. Either system is consistent with on-going farm operations and would be applicable where soil P levels are high but not exceedingly high. Reduction of soil P by ~ 50 kg ha^{-1} annually by hay harvest would within a few years lower the P loss rating of a site (Louisiana P-index; NRCS, 2003), from high to moderate, relaxing management constraints imposed at the high category. It may similarly improve the P loss rating from very high to high, but substantial reduction in soil P from levels found at a few sites with long histories of PL application (Robinson et al., 1994; Waldron et al., 2004) would likely take much longer.

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APPENDIX A–BERMUDAGRASS DATA

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
4	0	07/12/02	1.62	0.231	3.74	206
4	0	07/31/02	1.52	0.576	8.77	206
4	0	09/04/02	1.24	0.544	6.75	206
4	0	10/15/02	1.74	0.297	5.18	206
5	0	07/12/02	1.05	0.334	3.52	115
5	0	07/31/02	1.65	0.545	8.99	115
5	0	09/04/02	0.96	0.698	6.69	115
5	0	10/15/02	1.03	0.345	3.55	115
10	0	07/12/02	0.72	0.445	3.18	230
10	0	07/31/02	1.34	0.291	3.90	230
10	0	09/04/02	1.10	0.328	3.61	230
10	0	10/15/02	0.72	0.384	2.76	230
3	5	07/12/02	2.41	0.280	6.74	308
3	5	07/31/02	1.77	0.535	9.45	308
3	5	09/04/02	1.34	0.564	7.54	308
3	5	10/15/02	1.87	0.292	5.47	308
6	5	07/12/02	1.28	0.354	4.53	345
6	5	07/31/02	1.71	0.587	10.03	345
6	5	09/04/02	1.04	0.307	3.20	345
6	5	10/15/02	1.62	0.343	5.57	345
12	5	07/12/02	1.14	0.356	4.07	236
12	5	07/31/02	1.03	0.946	9.70	236
12	5	09/04/02	0.77	0.430	3.32	236
12	5	10/15/02	0.84	0.312	2.62	236

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
2	10	07/12/02	2.02	0.272	5.49	354
2	10	07/31/02	1.58	0.546	8.60	354
2	10	09/04/02	1.14	0.593	6.77	354
2	10	10/15/02	1.66	0.311	5.15	354
7	10	07/12/02	1.78	0.345	6.12	527
7	10	07/31/02	1.52	0.673	10.20	527
7	10	09/04/02	1.55	0.281	4.36	527
7	10	10/15/02	1.92	0.361	6.96	527
9	10	07/12/02	1.40	0.431	6.05	456
9	10	07/31/02	1.40	0.382	5.33	456
9	10	09/04/02	0.95	0.398	3.77	456
9	10	10/15/02	0.60	0.423	2.55	456
1	20	07/12/02	1.98	0.294	5.84	1006
1	20	07/31/02	1.43	0.706	10.07	1006
1	20	09/04/02	1.17	0.444	5.19	1006
1	20	10/15/02	1.49	0.375	5.59	1006
8	20	07/12/02	2.16	0.321	6.92	463
8	20	07/31/02	1.86	0.663	12.31	463
8	20	09/04/02	1.72	0.263	4.51	463
8	20	10/15/02	2.08	0.332	6.90	463
11	20	07/12/02	1.27	0.338	4.30	514
11	20	07/31/02	1.28	0.866	11.08	514
11	20	09/04/02	0.79	0.230	1.83	514
11	20	10/15/02	0.94	0.463	4.35	514

Bermudagrass Data. Continued

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
4	0	06/16/03	1.79	0.242	4.33	166
4	0	07/14/03	2.10	0.283	5.93	166
4	0	08/12/03	1.12	0.182	2.04	166
4	0	09/17/03	1.20	0.226	2.70	166
5	0	06/16/03	1.76	0.257	4.54	142
5	0	07/14/03	1.73	0.361	6.26	142
5	0	08/12/03	0.77	0.196	1.52	142
5	0	09/17/03	1.11	0.327	3.63	142
10	0	06/16/03	0.72	0.250	1.81	225
10	0	07/14/03	1.56	0.452	7.04	225
10	0	08/12/03	1.01	0.281	2.83	225
10	0	09/17/03	1.01	0.224	2.25	225
3	5	06/16/03	2.01	0.252	5.07	198
3	5	07/14/03	2.22	0.276	6.12	198
3	5	08/12/03	0.87	0.238	2.08	198
3	5	09/17/03	1.38	0.264	3.64	198
6	5	06/16/03	1.74	0.280	4.86	286
6	5	07/14/03	1.70	0.333	5.66	286
6	5	08/12/03	0.86	0.332	2.84	286
6	5	09/17/03	1.22	0.244	2.98	286
12	5	06/16/03	1.44	0.260	3.75	242
12	5	07/14/03	1.14	0.395	4.50	242
12	5	08/12/03	0.83	0.405	3.34	242
12	5	09/17/03	0.82	0.287	2.36	242

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
2	10	06/16/03	2.07	0.163	3.37	240
2	10	07/14/03	2.44	0.302	7.37	240
2	10	08/12/03	1.38	0.205	2.83	240
2	10	09/17/03	1.87	0.228	4.26	240
7	10	06/16/03	1.75	0.355	6.22	342
7	10	07/14/03	2.40	0.430	10.33	342
7	10	08/12/03	0.82	0.324	2.65	342
7	10	09/17/03	1.36	0.254	3.46	342
9	10	06/16/03	1.45	0.331	4.79	349
9	10	07/14/03	1.34	0.491	6.58	349
9	10	08/12/03	0.74	0.466	3.46	349
9	10	09/17/03	1.06	0.346	3.68	349
1	20	06/16/03	1.64	0.499	8.20	534
1	20	07/14/03	2.37	0.269	6.39	534
1	20	08/12/03	1.20	0.337	4.03	534
1	20	09/17/03	1.81	0.285	5.17	534
8	20	06/16/03	2.23	0.346	7.70	343
8	20	07/14/03	2.63	0.347	9.15	343
8	20	08/12/03	1.43	0.321	4.60	343
8	20	09/17/03	1.76	0.270	4.76	343
11	20	06/16/03	0.74	0.385	2.86	525
11	20	07/14/03	1.67	0.410	6.86	525
11	20	08/12/03	0.85	0.450	3.84	525
11	20	09/17/03	0.91	0.303	2.75	525

Bermudagrass Data, Continued

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
4	0	06/07/04	2.05	0.231	4.73	129
4	0	07/07/04	2.17	0.240	5.20	129
4	0	08/06/04	1.57	0.341	5.35	129
4	0	09/10/04	1.57	0.295	4.63	129
5	0	06/07/04	1.89	0.280	5.30	111
5	0	07/07/04	1.76	0.255	4.49	111
5	0	08/06/04	1.13	0.288	3.26	111
5	0	09/10/04	1.25	0.281	3.52	111
10	0	06/07/04	1.71	0.232	3.96	244
10	0	07/07/04	1.62	0.319	5.19	244
10	0	08/06/04	1.46	0.252	3.68	244
10	0	09/10/04	1.20	0.224	2.69	244
3	5	06/07/04	2.20	0.246	5.41	200
3	5	07/07/04	2.32	0.308	7.15	200
3	5	08/06/04	1.70	0.333	5.65	200
3	5	09/10/04	1.47	0.305	4.46	200
6	5	06/07/04	1.95	0.306	5.97	222
6	5	07/07/04	1.58	0.304	4.80	222
6	5	08/06/04	1.27	0.425	5.38	222
6	5	09/10/04	1.00	0.307	3.07	222
12	5	06/07/04	2.07	0.263	5.43	314
12	5	07/07/04	1.99	0.282	5.61	314
12	5	08/06/04	1.17	0.483	5.67	314
12	5	09/10/04	0.84	0.287	2.40	314

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
2	10	06/07/04	2.56	0.244	6.24	264
2	10	07/07/04	2.35	0.263	6.16	264
2	10	08/06/04	1.77	0.324	5.72	264
2	10	09/10/04	1.51	0.237	3.57	264
7	10	06/07/04	2.33	0.280	6.55	266
7	10	07/07/04	1.92	0.287	5.52	266
7	10	08/06/04	1.49	0.378	5.64	266
7	10	09/10/04	1.36	0.373	5.07	266
9	10	06/07/04	1.78	0.307	5.48	447
9	10	07/07/04	1.96	0.312	6.12	447
9	10	08/06/04	1.29	0.423	5.44	447
9	10	09/10/04	1.11	0.294	3.26	447
1	20	06/07/04	2.76	0.277	7.66	313
1	20	07/07/04	2.33	0.237	5.53	313
1	20	08/06/04	1.75	0.370	6.49	313
1	20	09/10/04	1.36	0.285	3.89	313
8	20	06/07/04	2.96	0.306	9.04	556
8	20	07/07/04	1.82	0.297	5.41	556
8	20	08/06/04	1.98	0.358	7.10	556
8	20	09/10/04	1.79	0.300	5.38	556
11	20	06/07/04	1.49	0.417	6.21	681
11	20	07/07/04	1.70	0.399	6.78	681
11	20	08/06/04	1.68	0.388	6.52	681
11	20	09/10/04	1.16	0.281	3.25	681

Bermudagrass Data. Continued

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
4	0		2.13	0.227	4.83	88
4	0	07/29/05	2.34	0.209	4.90	88
4	0	09/06/05	1.39	0.252	3.50	88
5	0		2.00	0.229	4.57	75
5	0	07/29/05	1.80	0.172	3.10	75
5	0	09/06/05	1.18	0.237	2.79	75
10	0		1.46	0.214	3.12	180
10	0	07/29/05	2.08	0.176	3.65	180
10	0	09/06/05	1.03	0.220	2.27	180
3	5		2.48	0.288	7.13	188
3	5	07/29/05	2.58	0.204	5.28	188
3	5	09/06/05	1.28	0.243	3.10	188
6	5		2.07	0.330	6.84	257
6	5	07/29/05	1.95	0.243	4.74	257
6	5	09/06/05	1.29	0.286	3.68	257
12	5		1.43	0.285	4.09	187
12	5	07/29/05	1.20	0.290	3.48	187
12	5	09/06/05	0.76	0.295	2.24	187

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
2	10		3.06	0.281	8.61	170
2	10	07/29/05	2.50	0.223	5.58	170
2	10	09/06/05	1.29	0.306	3.96	170
7	10		2.17	0.277	6.01	273
7	10	07/29/05	1.64	0.314	5.16	273
7	10	09/06/05	1.07	0.245	2.62	273
9	10		1.66	0.278	4.63	384
9	10	07/29/05	1.50	0.268	4.01	384
9	10	09/06/05	1.05	0.228	2.38	384
1	20		2.70	0.255	6.88	419
1	20	07/29/05	1.91	0.319	6.11	419
1	20	09/06/05	1.15	0.275	3.15	419
8	20		2.84	0.294	8.34	514
8	20	07/29/05	3.28	0.194	6.38	514
8	20	09/06/05	1.69	0.184	3.10	514
11	20		1.16	0.484	5.61	675
11	20	07/29/05	1.19	0.253	3.01	675
11	20	09/06/05	0.72	0.429	3.09	675

APPENDIX B – RYEGRASS DATA

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
4	0	12/4/2001	1.73	0.426	7.36	206
4	0	1/30/2002	1.10	0.473	5.22	206
4	0	3/5/2002	1.56	0.338	5.28	206
4	0	4/3/2002	1.04	0.378	3.92	206
4	0	4/22/2002	1.07	0.499	5.35	206
5	0	12/4/2001	0.35	0.402	1.40	115
5	0	1/30/2002	0.86	0.437	3.77	115
5	0	3/5/2002	1.80	0.315	5.67	115
5	0	4/3/2002	0.74	0.388	2.88	115
5	0	4/22/2002	1.48	0.486	7.19	115
10	0	12/4/2001	0.52	0.518	2.72	230
10	0	1/30/2002	0.98	0.527	5.18	230
10	0	3/5/2002	2.25	0.375	8.43	230
10	0	4/3/2002	1.17	0.439	5.12	230
10	0	4/22/2002	1.06	0.527	5.60	230
3	5	12/4/2001	1.44	0.492	7.10	308
3	5	1/30/2002	1.44	0.611	8.81	308
3	5	3/5/2002	2.79	0.403	11.24	308
3	5	4/3/2002	1.41	0.529	7.47	308
3	5	4/22/2002	1.31	0.535	7.01	308
6	5	12/4/2001	0.55	0.646	3.53	345
6	5	1/30/2002	1.40	0.484	6.80	345
6	5	3/5/2002	2.65	0.391	10.37	345
6	5	4/3/2002	1.52	0.496	7.54	345
6	5	4/22/2002	1.25	0.493	6.18	345
12	5	12/4/2001	0.43	0.579	2.49	236
12	5	1/30/2002	0.78	0.533	4.15	236
12	5	3/5/2002	2.27	0.419	9.50	236
12	5	4/3/2002	0.97	0.556	5.40	236
12	5	4/22/2002	1.18	0.617	7.28	236

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
2	10	12/4/2001	1.33	0.514	6.85	354
2	10	1/30/2002	2.09	0.496	10.37	354
2	10	3/5/2002	2.89	0.393	11.36	354
2	10	4/3/2002	1.79	0.591	10.56	354
2	10	4/22/2002	1.20	0.594	7.15	354
7	10	12/4/2001	1.20	0.537	6.47	527
7	10	1/30/2002	1.78	0.570	10.14	527
7	10	3/5/2002	2.55	0.416	10.62	527
7	10	4/3/2002	1.66	0.478	7.93	527
7	10	4/22/2002	1.74	0.628	10.92	527
9	10	12/4/2001	0.41	0.629	2.55	456
9	10	1/30/2002	1.18	0.515	6.09	456
9	10	3/5/2002	2.99	0.368	10.98	456
9	10	4/3/2002	1.57	0.544	8.57	456
9	10	4/22/2002	1.24	0.656	8.14	456
1	20	12/4/2001	1.80	0.538	9.68	1006
1	20	1/30/2002	1.75	0.568	9.92	1006
1	20	3/5/2002	2.54	0.456	11.56	1006
1	20	4/3/2002	1.94	0.561	10.87	1006
1	20	4/22/2002	1.23	0.745	9.16	1006
8	20	12/4/2001	1.68	0.486	8.19	463
8	20	1/30/2002	2.08	0.542	11.26	463
8	20	3/5/2002	4.35	0.475	20.66	463
8	20	4/3/2002	2.21	0.665	14.69	463
8	20	4/22/2002	1.89	0.604	11.45	463
11	20	12/4/2001	0.38	0.556	2.09	514
11	20	1/30/2002	0.87	0.520	4.53	514
11	20	3/5/2002	2.84	0.410	11.62	514
11	20	4/3/2002	1.16	0.738	8.59	514
11	20	4/22/2002	1.08	0.731	7.88	514

Ryegrass Data, Continued

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
4	0	1/7/2003	0.98	0.301	2.95	166
4	0	3/3/2003	1.35	0.577	7.81	166
4	0	3/31/2003	1.45	0.369	5.37	166
4	0	5/12/2003	0.87	0.350	3.03	166
5	0	1/7/2003	1.02	0.266	2.71	142
5	0	3/3/2003	1.28	0.439	5.62	142
5	0	3/31/2003	0.91	0.448	4.09	142
5	0	5/12/2003	0.84	0.336	2.81	142
10	0	1/7/2003	1.04	0.278	2.89	225
10	0	3/3/2003	0.96	0.628	6.04	225
10	0	3/31/2003	0.97	0.531	5.16	225
10	0	5/12/2003	1.05	0.348	3.64	225
3	5	1/7/2003	1.30	0.310	4.05	198
3	5	3/3/2003	1.41	0.663	9.38	198
3	5	3/31/2003	1.35	0.476	6.41	198
3	5	5/12/2003	0.80	0.450	3.61	198
6	5	1/7/2003	1.34	0.313	4.18	286
6	5	3/3/2003	1.08	0.758	8.17	286
6	5	3/31/2003	0.90	0.563	5.05	286
6	5	5/12/2003	0.88	0.420	3.72	286
12	5	1/7/2003	0.87	0.318	2.75	242
12	5	3/3/2003	0.89	0.661	5.90	242
12	5	3/31/2003	1.08	0.543	5.88	242
12	5	5/12/2003	0.83	0.477	3.94	242

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
2	10	1/7/2003	1.28	0.330	4.22	240
2	10	3/3/2003	1.37	0.654	8.97	240
2	10	3/31/2003	1.75	0.493	8.62	240
2	10	5/12/2003	1.24	0.388	4.81	240
7	10	1/7/2003	1.39	0.370	5.14	342
7	10	3/3/2003	0.85	0.787	6.66	342
7	10	3/31/2003	1.07	0.691	7.42	342
7	10	5/12/2003	0.99	0.521	5.17	342
9	10	1/7/2003	1.12	0.360	4.04	349
9	10	3/3/2003	1.02	0.675	6.87	349
9	10	3/31/2003	1.23	0.614	7.57	349
9	10	5/12/2003	1.08	0.442	4.80	349
1	20	1/7/2003	1.63	0.412	6.70	534
1	20	3/3/2003	1.40	0.798	11.16	534
1	20	3/31/2003	1.36	0.579	7.89	534
1	20	5/12/2003	1.23	0.446	5.51	534
8	20	1/7/2003	1.49	0.396	5.91	343
8	20	3/3/2003	1.05	0.728	7.68	343
8	20	3/31/2003	1.51	0.694	10.50	343
8	20	5/12/2003	1.20	0.507	6.11	343
11	20	1/7/2003	0.92	0.462	4.24	525
11	20	3/3/2003	0.95	0.746	7.09	525
11	20	3/31/2003	0.84	0.633	5.32	525
11	20	5/12/2003	0.95	0.444	4.19	525

Ryegrass Data, Continued

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
4	0	12/11/2003	2.08	0.307	6.38	129
4	0	1/22/2004	1.30	0.295	3.82	129
4	0	3/8/2004	1.34	0.558	7.46	129
4	0	4/1/2004	1.81	0.302	5.48	129
4	0	4/21/2004	0.71	0.442	3.12	129
5	0	12/11/2003	1.22	0.264	3.20	111
5	0	1/22/2004	0.93	0.292	2.72	111
5	0	3/8/2004	1.25	0.585	7.30	111
5	0	4/1/2004	1.19	0.257	3.06	111
5	0	4/21/2004	0.60	0.358	2.16	111
10	0	12/11/2003	1.26	0.383	4.82	244
10	0	1/22/2004	0.97	0.406	3.93	244
10	0	3/8/2004	1.28	0.588	7.51	244
10	0	4/1/2004	1.37	0.281	3.86	244
10	0	4/21/2004	0.85	0.439	3.73	244
3	5	12/11/2003	1.63	0.392	6.38	200
3	5	1/22/2004	1.32	0.434	5.71	200
3	5	3/8/2004	1.26	0.626	7.92	200
3	5	4/1/2004	1.79	0.402	7.21	200
3	5	4/21/2004	1.10	0.593	6.54	200
6	5	12/11/2003	1.41	0.480	6.76	222
6	5	1/22/2004	0.95	0.485	4.59	222
6	5	3/8/2004	1.21	0.640	7.72	222
6	5	4/1/2004	1.32	0.478	6.30	222
6	5	4/21/2004	0.78	0.522	4.08	222
12	5	12/11/2003	1.29	0.329	4.23	314
12	5	1/22/2004	0.78	0.463	3.63	314
12	5	3/8/2004	1.18	0.634	7.49	314
12	5	4/1/2004	1.19	0.530	6.28	314
12	5	4/21/2004	0.74	0.556	4.12	314

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
2	10	12/11/2003	1.87	0.325	6.07	264
2	10	1/22/2004	1.40	0.468	6.57	264
2	10	3/8/2004	1.30	0.679	8.86	264
2	10	4/1/2004	1.44	0.460	6.64	264
2	10	4/21/2004	0.91	0.565	5.15	264
7	10	12/11/2003	2.00	0.376	7.51	266
7	10	1/22/2004	1.17	0.493	5.78	266
7	10	3/8/2004	1.23	0.579	7.12	266
7	10	4/1/2004	1.19	0.617	7.36	266
7	10	4/21/2004	0.85	0.722	6.11	266
9	10	12/11/2003	1.48	0.406	6.01	447
9	10	1/22/2004	0.90	0.505	4.56	447
9	10	3/8/2004	1.24	0.723	9.00	447
9	10	4/1/2004	1.11	0.522	5.81	447
9	10	4/21/2004	0.75	0.550	4.15	447
1	20	12/11/2003	1.69	0.467	7.90	313
1	20	1/22/2004	1.22	0.526	6.43	313
1	20	3/8/2004	1.55	0.593	9.17	313
1	20	4/1/2004	1.26	0.638	8.03	313
1	20	4/21/2004	0.96	0.656	6.32	313
8	20	12/11/2003	1.92	0.532	10.20	556
8	20	1/22/2004	1.25	0.532	6.65	556
8	20	3/8/2004	1.48	0.721	10.65	556
8	20	4/1/2004	1.59	0.610	9.68	556
8	20	4/21/2004	0.91	0.637	5.77	556
11	20	12/11/2003	1.09	0.515	5.63	681
11	20	1/22/2004	0.95	0.515	4.87	681
11	20	3/8/2004	1.04	0.687	7.14	681
11	20	4/1/2004	1.12	0.670	7.51	681
11	20	4/21/2004	0.68	0.618	4.18	681

Ryegrass Data, Continued

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
4	0	12/10/2004	1.45	0.331	4.81	88
4	0	2/15/2005	1.37	0.343	4.69	88
4	0	4/1/2005	1.72	0.449	7.73	88
4	0	4/20/2005	0.89	0.396	3.53	88
5	0	12/10/2004	0.98	0.276	2.70	75
5	0	2/15/2005	1.21	0.234	2.82	75
5	0	4/1/2005	0.83	0.341	2.83	75
5	0	4/20/2005	0.62	0.367	2.30	75
10	0	12/10/2004	1.26	0.333	4.18	180
10	0	2/15/2005	1.07	0.315	3.36	180
10	0	4/1/2005	0.98	0.425	4.17	180
10	0	4/20/2005	0.72	0.398	0.00	180
3	5	12/10/2004	1.35	0.345	4.66	188
3	5	2/15/2005	2.00	0.372	7.45	188
3	5	4/1/2005	2.00	0.430	8.63	188
3	5	4/20/2005	0.82	0.418	3.45	188
6	5	12/10/2004	1.14	0.416	4.75	257
6	5	2/15/2005	1.01	0.386	3.89	257
6	5	4/1/2005	1.04	0.512	5.32	257
6	5	4/20/2005	0.67	0.514	3.47	257
12	5	12/10/2004	1.12	0.383	4.28	187
12	5	2/15/2005	0.95	0.419	3.98	187
12	5	4/1/2005	1.13	0.590	6.66	187
12	5	4/20/2005	0.59	0.440	2.59	187

Plot	Rate	Date	Yield Mg ha^{-1}	%P	P out kg ha^{-1}	Soil P mg kg^{-1}
2	10	12/10/2004	1.33	0.347	4.62	170
2	10	2/15/2005	1.58	0.328	5.17	170
2	10	4/1/2005	1.31	0.454	5.96	170
2	10	4/20/2005	0.72	0.451	3.24	170
7	10	12/10/2004	1.26	0.409	5.17	273
7	10	2/15/2005	1.36	0.363	4.95	273
7	10	4/1/2005	1.98	0.579	11.44	273
7	10	4/20/2005	0.60	0.571	3.45	273
9	10	12/10/2004	0.95	0.429	4.07	384
9	10	2/15/2005	1.24	0.460	5.69	384
9	10	4/1/2005	0.81	0.598	4.85	384
9	10	4/20/2005	0.60	0.538	3.24	384
1	20	12/10/2004	1.49	0.440	6.54	419
1	20	2/15/2005	1.32	0.416	5.49	419
1	20	4/1/2005	1.72	0.659	11.33	419
1	20	4/20/2005	0.68	0.627	4.24	419
8	20	12/10/2004	1.39	0.467	6.50	514
8	20	2/15/2005	1.43	0.442	6.32	514
8	20	4/1/2005	1.46	0.666	9.74	514
8	20	4/20/2005	0.80	0.606	4.85	514
11	20	12/10/2004	0.89	0.481	4.30	675
11	20	2/15/2005	0.85	0.421	3.56	675
11	20	4/1/2005	1.65	0.692	11.43	675
11	20	4/20/2005	0.60	0.571	3.41	675

APPENDIX C –BAHIA-, BERMUDA-, CRAB- AND SWITCHGRASS DATA

Year	Grass	Plot	Rate	Yield Mg ha^{-1}	%P	P out kg ha^{-1}
2002	Bahia	4	0	5.12	0.2910	15.23
2002	Bahia	5	0	4.59	0.2963	14.15
2002	Bahia	10	0	9.76	0.2953	29.05
2002	Bahia	3	5	6.35	0.2963	19.81
2002	Bahia	6	5	9.17	0.2988	27.55
2002	Bahia	12	5	11.79	0.2832	32.88
2002	Bahia	2	10	4.75	0.2838	14.74
2002	Bahia	7	10	9.07	0.2979	27.81
2002	Bahia	9	10	14.99	0.3215	47.60
2002	Bahia	1	20	6.13	0.3243	19.79
2002	Bahia	8	20	6.93	0.3431	24.38
2002	Bahia	11	20	12.32	0.3249	39.42
2002	Bermuda	4	0	3.25	0.2533	8.44
2002	Bermuda	5	0	11.68	0.2850	33.05
2002	Bermuda	10	0	3.47	0.2576	9.49
2002	Bermuda	3	5	1.60	0.2604	4.45
2002	Bermuda	6	5	21.33	0.2798	59.67
2002	Bermuda	12	5	3.20	0.3283	11.46
2002	Bermuda	2	10	14.51	0.2612	36.87
2002	Bermuda	7	10	27.25	0.3083	83.39
2002	Bermuda	9	10	11.57	0.3343	38.44
2002	Bermuda	1	20	7.09	0.3608	24.88
2002	Bermuda	8	20	18.61	0.3141	56.76
2002	Bermuda	11	20	3.04	0.3414	11.07

Year	Grass	Plot	Rate	Yield Mg ha^{-1}	%P	P out kg ha^{-1}
2002	Crab	4	0	6.13	0.3423	23.29
2002	Crab	5	0	9.65	0.3246	32.89
2002	Crab	10	0	8.53	0.2997	26.97
2002	Crab	3	5	10.14	0.3138	40.60
2002	Crab	6	5	10.13	0.3476	43.68
2002	Crab	12	5	7.57	0.3158	29.12
2002	Crab	2	10	13.23	0.3339	57.28
2002	Crab	7	10	9.49	0.4320	55.08
2002	Crab	9	10	13.92	0.3336	57.73
2002	Crab	1	20	15.95	0.3567	67.79
2002	Crab	8	20	18.08	0.3450	71.20
2002	Crab	11	20	9.01	0.3512	32.21
2002	Switch	4	0	11.68	0.2064	22.82
2002	Switch	5	0	12.27	0.2190	24.67
2002	Switch	10	0	20.75	0.2054	39.36
2002	Switch	3	5	15.79	0.2185	32.34
2002	Switch	6	5	19.68	0.2815	55.03
2002	Switch	12	5	18.88	0.2047	37.90
2002	Switch	2	10	27.15	0.2291	58.55
2002	Switch	7	10	19.04	0.2513	47.09
2002	Switch	9	10	20.27	0.1833	34.75
2002	Switch	1	20	18.51	0.2258	40.10
2002	Switch	8	20	18.99	0.2589	47.15
2002	Switch	11	20	20.00	0.2101	38.28

Bahia-, Berumda-, Crab- and Switchgrass Data, Continued

Year	Grass	Plot	Rate	Yield Mg ha^{-1}	%P	P out kg ha^{-1}
2003	Bahia	4	0	8.59	0.2072	17.23
2003	Bahia	5	0	9.65	0.2176	21.11
2003	Bahia	10	0	11.25	0.2616	28.77
2003	Bahia	3	5	13.28	0.2340	32.40
2003	Bahia	6	5	12.11	0.2469	30.25
2003	Bahia	12	5	9.12	0.2446	22.21
2003	Bahia	2	10	10.67	0.2840	28.73
2003	Bahia	7	10	12.16	0.2670	31.19
2003	Bahia	9	10	12.69	0.2260	27.58
2003	Bahia	1	20	15.20	0.2642	39.25
2003	Bahia	8	20	8.64	0.2687	21.93
2003	Bahia	11	20	12.48	0.2557	32.68
2003	Bermuda	4	0	1.28	0.2215	2.77
2003	Bermuda	5	0	5.92	0.2711	16.93
2003	Bermuda	10	0	10.83	0.2477	26.89
2003	Bermuda	3	5	8.59	0.2526	22.67
2003	Bermuda	6	5	12.91	0.2595	32.01
2003	Bermuda	12	5	12.85	0.2534	30.60
2003	Bermuda	2	10	10.40	0.3065	32.31
2003	Bermuda	7	10	19.84	0.2779	51.83
2003	Bermuda	9	10	9.07	0.3022	29.08
2003	Bermuda	1	20	8.37	0.3578	28.59
2003	Bermuda	8	20	9.55	0.4186	41.62
2003	Bermuda	11	20	18.61	0.2935	55.60

Year	Grass	Plot	Rate	Yield Mg ha^{-1}	%P	P out kg ha^{-1}
2003	Crab	4	0	7.47	0.2905	23.36
2003	Crab	5	0	12.75	0.3004	41.23
2003	Crab	10	0	10.29	0.2535	28.17
2003	Crab	3	5	8.91	0.2755	26.44
2003	Crab	6	5	14.56	0.2803	42.58
2003	Crab	12	5	13.28	0.2845	39.06
2003	Crab	2	10	12.85	0.3866	53.58
2003	Crab	7	10	15.73	0.3335	55.37
2003	Crab	9	10	13.76	0.3218	43.17
2003	Crab	1	20	9.81	0.3900	40.10
2003	Crab	8	20	13.97	0.3231	45.96
2003	Crab	11	20	13.55	0.3486	49.63
2003	Switch	4	0	15.95	0.2086	33.52
2003	Switch	5	0	16.64	0.2224	37.10
2003	Switch	10	0	31.52	0.2054	64.97
2003	Switch	3	5	31.73	0.2166	69.41
2003	Switch	6	5	21.28	0.2534	53.33
2003	Switch	12	5	31.52	0.1949	61.42
2003	Switch	2	10	41.04	0.2263	92.89
2003	Switch	7	10	14.45	0.2416	34.44
2003	Switch	9	10	23.36	0.2239	52.75
2003	Switch	1	20	28.85	0.2487	72.09
2003	Switch	8	20	20.53	0.2481	50.04
2003	Switch	11	20	37.28	0.2143	78.97

Bahia-, Berumda-, Crab- and Switchgrass Data, Continued

Year	Grass	Plot	Rate	Yield Mg ha^{-1}	%P	P out kg ha^{-1}
2004	Bahia	4	0	10.96	0.2751	31.12
2004	Bahia	5	0	11.17	0.2836	31.33
2004	Bahia	10	0	6.59	0.3174	20.78
2004	Bahia	3	5	14.37	0.2949	41.60
2004	Bahia	6	5	14.88	0.2763	40.63
2004	Bahia	12	5	16.93	0.2893	48.68
2004	Bahia	2	10	15.04	0.2967	43.82
2004	Bahia	7	10	20.21	0.3046	60.98
2004	Bahia	9	10	14.13	0.3067	43.41
2004	Bahia	1	20	18.40	0.3469	62.45
2004	Bahia	8	20	17.15	0.2957	49.47
2004	Bahia	11	20	15.09	0.3220	49.09
2004	Bermuda	4	0	0.59	0.2946	1.76
2004	Bermuda	5	0	2.77	0.2837	7.40
2004	Bermuda	10	0	1.23	0.2844	3.49
2004	Bermuda	3	5	1.23	0.3305	4.44
2004	Bermuda	6	5	7.57	0.2449	18.02
2004	Bermuda	12	5	12.16	0.2534	29.13
2004	Bermuda	2	10	8.11	0.3104	23.30
2004	Bermuda	7	10	15.63	0.2764	43.04
2004	Bermuda	9	10	10.03	0.2894	28.91
2004	Bermuda	1	20	7.84	0.2863	22.10
2004	Bermuda	8	20	9.81	0.3058	28.25
2004	Bermuda	11	20	9.97	0.3301	32.22

Year	Grass	Plot	Rate	Yield Mg ha^{-1}	%P	P out kg ha^{-1}
2004	Crab	4	0	8.61	0.4053	34.14
2004	Crab	5	0	8.24	0.3649	30.53
2004	Crab	10	0	10.88	0.3867	42.43
2004	Crab	3	5	8.00	0.4403	35.41
2004	Crab	6	5	12.19	0.3646	42.18
2004	Crab	12	5	11.73	0.3751	43.74
2004	Crab	2	10	12.64	0.4676	57.73
2004	Crab	7	10	18.16	0.4642	84.10
2004	Crab	9	10	14.19	0.4205	59.59
2004	Crab	1	20	21.01	0.4334	90.41
2004	Crab	8	20	18.61	0.3700	70.65
2004	Crab	11	20	15.79	0.3722	60.44
2004	Switch	4	0	27.15	0.2653	72.24
2004	Switch	5	0	23.81	0.2345	54.32
2004	Switch	10	0	44.35	0.2110	93.48
2004	Switch	3	5	40.29	0.2541	103.61
2004	Switch	6	5	41.31	0.2635	107.91
2004	Switch	12	5	41.15	0.2309	92.97
2004	Switch	2	10	54.72	0.2656	145.80
2004	Switch	7	10	21.95	0.2687	58.56
2004	Switch	9	10	41.20	0.2278	92.44
2004	Switch	1	20	39.55	0.2641	106.49
2004	Switch	8	20	23.07	0.2596	60.00
2004	Switch	11	20	65.04	0.2423	153.65

VITA

Veronica Ryan was born in Baton Rouge, Louisiana, in 1959. She earned a Bachelor of Science degree in agriculture – wildlife and fisheries in 1991 from Louisiana State University. She began her career in 1991 as a soil conservationist with the United States Department of Agriculture in Ozark, Alabama, where she worked with farm operators and landowners to assist them with their natural resource concerns and to put conservation “on the ground”. Upon returning to Louisiana, she began pursuing a Master of Science degree in agronomy and environmental management under the guidance of Dr. Maud Walsh and Dr. Lewis Gaston while working fulltime, managing the family farm and running a household.