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REGULAR ARTICLE

Phosphorus runoff from a phosphorus deficient soil under common bean (*Phaseolus vulgaris* L.) and soybean (*Glycine max* L.) genotypes with contrasting root architecture

Amelia Henry · Peter J. A. Kleinman · Jonathan P. Lynch

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Abstract The selection and breeding of crop genotypes with root traits that improve soil resource extraction is a promising avenue to improved nutrient and water use efficiency in low-input farming systems. Such genotypes may accelerate nutrient extraction ("nutrient mining"), but may also reduce nutrient loss via soil erosion by producing greater shoot biomass and by direct effects of root traits on aggregate formation and water infiltration. Little is known about the effects of root architecture on phosphorus (P) runoff and soil erosion, and the relative importance of root and shoot traits on runoff P loss has not been determined. Four genotypes of common bean (*Phaseolus vulgaris* L.) and two genotypes of soybean (*Glycine max*) selected for contrasting root architecture were grown in a low P soil (Aquic Fragiudult, <20 mg kg^{-1} Mehlich-3 P, 3% slope) and subjected to rainfall-runoff experiments with and without shoot removal. Plots with intact shoots had significantly lower runoff volumes (1.3–7.6 mm) and total P loads in runoff (0.005–0.32 kg ha^{-1}) than plots with shoots removed (7.0–16.8 mm; 0.025–1.95 kg ha^{-1}). Dissolved reactive P leached from plant material did not contribute significantly to P loss in runoff. Total root length acquired from soil cores differed significantly among genotypes. Root length densities in the upper 15 cm of soil mid-way between rows were less than 4.0 cm cm^{-3} and variation in root length density was not correlated with runoff or P loss. Root length density also did not affect rainfall infiltration or surface runoff volume. We conclude that for annual dicotyledonous crops such as bean and soybean with relatively low root length densities, root traits have little direct effect on soil erosion.

Keywords Phosphorus · Runoff · Erosion · Root architecture · Common bean

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A. Henry · J. P. Lynch
Intercollege Program in Plant Biology,
The Pennsylvania State University,
University Park, PA 16802, USA

P. J. A. Kleinman
USDA-ARS, Pasture Systems and Watershed Management Research Unit,
University Park, PA 16802, USA

J. P. Lynch (✉)
Department of Horticulture,
The Pennsylvania State University,
University Park, PA 16802, USA
e-mail: jpl4@psu.edu

Introduction

Conservation of phosphorus (P) is a critical issue in soils of low native fertility, particularly in the developing world where fertilizer inputs are often unavailable to farmers (Fairhurst et al. 1999). The loss

of P via erosion is a primary pathway of concern (Larson et al. 1983). Many agronomic variables affect the potential for erosion, including tillage practices, residue management, and inherent crop characteristics (Renard et al. 1997). Canopy characteristics have been widely studied and their effects on runoff and erosion are well established (Meyer and Mannering 1971). According to Foot and Morgan (2005), plant height and percent canopy cover are the two most important canopy characteristics affecting erosion potential. In contrast to shoot effects, the effects of roots on erosion and P runoff are not well understood.

Root architecture is of increasing interest as a selection criterion for crop adaptation to edaphic stress in low-input agro-ecosystems (Lynch and Brown 2001; Lynch 2007). Root architectural traits that can improve P uptake in low-P systems include root hair length and density (Bates and Lynch 2001), basal root growth angle (Bonser et al. 1996, Lynch and Brown 2001), hypocoytl-borne (adventitious) roots (Miller et al. 2003), and lateral rooting (Zhu et al. 2005). Several crop breeding programs seek to improve root architectural traits for enhanced yield in low input farming systems. These include the Root Biology Center at the South China Agricultural University (Guangzhou), the Programa de Investigaciones en Frijol (PIF) at EAP-Zamorano University, Honduras, the Universidad de Michoacana, Mexico, the Institute of Agricultural Research of Mozambique (IIAM), as well projects at the International Center for Tropical Agriculture (CIAT; Cali, Colombia) and the International Maize and Wheat Improvement Center (CIMMYT; El Batan, Mexico) geared towards low fertility and drought.

Traits that increase P acquisition from low-P soil should increase total plant mass and canopy cover, potentially decreasing P loss through erosion. However, the direct effects of root traits on soil processes affecting P loss in runoff, including erosion, dissolution of soil P by root exudates, aggregate stability, and rainfall infiltration, are unclear. Using maize roots of increasing root length density and rainfall simulation, Bui and Box (1993) saw no differences in runoff between rooted and fallow soils. A comparison of the effects of dead roots of alfalfa, soybean, maize and bluegrass on erosion resulted in no differences in runoff among species, but lower sediment concentrations and soil loss with increasing amounts of dead roots (Ghidey and Alberts 1997). Gyssels and Poesen (2003) concluded that the plant effect on decreasing soil loss was explained by both shoot and root mass since shoot and root mass are correlated.

The effects of maize and soybean roots on soil strength, detachment rate, and rill erodibility were observed in the field (Mamo and Bubenzer 2001a) as well as in the laboratory using a hydraulic flume to study effects of living roots (Mamo and Bubenzer 2001b). Detachment rate decreased with root length density, which the authors hypothesized to be due to soil binding by the roots as well as division of shear stress into that acting on the soil and that acting on the roots. Live maize roots have been observed to decrease the permeability of a sandy loam by pore blockage and soil compaction in the rhizosphere (Barley 1954) and decrease stability of fresh soil aggregates (along with tomato and wheat, whereas alfalfa increased soil aggregates; Reid and Goss 1981). Hallet et al. (2003) used a miniaturized infiltrometer to observe slightly increased water repellency of rhizosphere soil compared to bulk soil. Whalley et al. (2004) also observed less infiltration in rhizosphere than bulk soil and proposed that increased soil density in the rhizosphere changes the hydraulic conductivity, but did not observe root mucilage making the soil more repellant to water as previously reported. These results are in agreement with reports that root mucilage is a material that can absorb water and stabilize soil aggregates (as reviewed in Young 1998).

Most of the research relating roots to erosion has been conducted with computer modeling. A modeling approach to root water uptake and effects on soil moisture, as described by Dunbabin et al. (2002) and Somma et al. (1998), can explain root contributions to subsurface soil drying that subsequently affects rainfall infiltration. A number of erosion/runoff computer models that take root growth into account use factors for root length density or number of roots in their equations (i.e. Flanagan and Nearing 1995; and Renard et al. 1997). Gyssels et al. (2005) reviewed a number of erosion models and field studies and summarized root effects on erosion as:

$$\mathrm{SEP} = e^{-b\mathrm{RP}} \tag{1}$$

where SEP is the soil erosion parameter (e.g. rill or interrill erodibility), RP is the root parameter and b is a constant that indicates the level to which roots

reduce erosion. The authors concluded from their review that plant cover is the most important factor in splash and interrill erosion, but that roots are just as important as shoots in the control of rill and ephemeral gully erosion.

One potential effect of selection for plants with different root characteristics and efficiencies in recovering soil P is variation in plant tissue P, which, in turn, could affect dissolved P in surface runoff. Root traits can increase efficiency of phosphorus uptake in low-P soils, which can increase P concentration and P total content of shoot tissue. Miller et al. (2003) reported >50% variation in shoot P content associated with variation in hypocotyl-borne roots among common bean genotypes in a Typic Paleudult (<15 mg kg^{-1} iron-oxide strip P) in Costa Rica. Root hair length and density have been shown to improve performance of common bean in low-P soils (Miguel 2004). Increased plant growth of genotypes with higher root length density in upper soil levels (shallow root architecture) have been observed in common bean (Ho et al. 2005) and maize (Zhu et al. 2005). However, abiotic stress may result in membrane leakage and loss of plant nutrients to runoff during rainfall. Sharpley (1981) found large differences in dissolved P leached from plant canopies when crops were stressed. After 80 d of crop growth on soils that were not fertilized with P, dissolved P in plant leachate averaged 30 g ha^{-1} for cotton, 108 g ha^{-1} for sorghum, and 54 g ha^{-1} for soybean. When the three crops were subjected to rainfall simulations, dissolved P derived from plant canopies contributed 4–94% of the dissolved P measured in surface runoff from the cotton, sorghum and soybean treatments (Sharpley 1981).

Given the importance of programs selecting for root traits and the inconclusive nature of existing information on the effects of root traits on erosion and runoff P loss, the objective of this study was to assess erosion and runoff from low P soils planted with bean and soybean genotypes differing in root architecture and root length density under simulated rainfall. Low P soils provide a unique opportunity to isolate plant effects on runoff by eliminating confounding effects of concentrated sources of P. Furthermore, low P soils are characteristic of most agro-ecosystems in developing countries (and therefore the majority of the world's cropped soils; Lynch 2007). Specific objectives of this study were to contrast the role of roots with shoots in controlling erosion as well as to assess the effect of contrasting root architectures on erosion and P runoff.

Materials and methods

Experiment location and plant material

Research was conducted on a Buchanan silt loam soil (fine-loamy, mixed, semiactive mesic, Aquic Fragiudult), averaging 3% slope at the Russell E. Larsen Research Center in Rock Springs, PA (Latitude: 40° 43.24′ N Longitude: 77°55.90′ W). The site falls in the Appalachian Ridge and Valley province of the eastern US (Major Land Resource Area 147, Natural Resource Conservation Service 2006). Average annual precipitation is 950 mm, and annual average temperature is 9°C.

In 2004 the site was converted from grass fallow by mowing and removal of cut grass, application of glyphosate (Roundup[1]) to eradicate existing grass at 4.68 L ha^{-1}, chisel plowing, rototilling, and another rototill after application of potassium (potash; 0–0–60) at 56 kg ha^{-1}. The site was planted with common bean and soybean and disked at the end of the season. In June 2005 glyphosate (Touchdown) was sprayed at 4.68 L ha^{-1} to eradicate the existing weeds, followed by chisel plowing, and finally disking after applying potassium (potash; 0–0–60) at 33.6 kg ha^{-1}. A mid-season (July) application of 0.88 L ha^{-1} sethoxydim (Poast) eliminated graminaceous weeds. In May 2006 plots were chisel plowed, culti-mulched, and metolachlor (Dual) was applied at 2.34 L ha^{-1}. Surface rocks were removed by hand at least once during soil preparation in all years. Fertilizer applications were based on results of soil analyses (Table 1), described below, using Penn State University's agronomic recommendation for K addition (Beegle 2007). Notably, P fertilizer was not applied to the site since the aim of this study was to investigate runoff from low P soils.

Field plots, 3×3 m in 2005 and 4×3 m in 2006, were planted with common bean (*Phaseolus vulgaris*) or soybean (*Glycine max*) with 50 cm inter-row and 5 cm intra-row spacing. Rhizobium inoculum for

[1] Mention of trade names does not indicate endorsement by the US Department of Agriculture.

Table 1 Properties of field soils at time of planting for 2005 and 2006 seasons

Soil property	2005	2006
pH	6.6±0.1	6.6±0.2
P (mg kg^{-1})	15±0.7	19±3.4
K (mg kg^{-1})	117±4.8	123±9.0
Mg (mg kg^{-1})	102±2.6	89±4.6
Ca (mg kg^{-1})	2,531±41	2,430±238
CEC (meq kg^{-1})	155±39.0	141±52.0

Nutrient availability and CEC was determined by Mehlich-3 extraction, pH was determined in water (1:1). Values shown are means ± standard error of the mean

bean or soybean (Histick NT) was applied each year according to manufacturer recommendations. Genotypes were selected to achieve a range of root distributions with depth among plots. Common bean and soybean genotypes have been previously screened for root architecture characteristics in field and laboratory conditions in Pennsylvania, Honduras, and China (Lynch and Brown 2001; Ho et al. 2005; and Zhao et al. 2004). The genotypes planted each year changed as on-going research revealed new genotypes with better rooting characteristics, but a range of deep-rooted to shallow rooted genotypes were planted each year of the study. In 2005, common bean recombinant inbred lines 57 (shallow-rooted) and 30 (deep-rooted) of the L-88 population (supplied by Dr. James Kelly, Michigan State University) and soybean varieties Local 2 (deep rooted) and Brazil 10 (shallow-rooted) were planted in a randomized block design. In 2006, only common bean genotypes were planted. Recombinant inbred lines L-88 57 and L-88 14 (shallow-rooted) and L-88 30 and L-88 63 (deep-rooted) were planted in a completely randomized design.

All plots were arranged among three strips of plowed land with >5-m grassy border between plowed strips. In 2005 plots were adjacent and in 2006 a 1-m alley was left between planted plots. Four repetitions of each genotype and space for unplanted control plots were allotted in both years. Rows were oriented perpendicular to the slope. All plots were weeded by hand throughout both seasons.

Rainfall simulations

Rainfall simulations were conducted according to the National P Research Project methods described by Sharpley et al. (2001). Hydrologically isolated runoff plots (2-m long and 1-m wide) were established within each of the treatment replicates, isolated on the upper three sides by steel frames driven approximately 5 cm into the soil and extending roughly 5 cm above the soil. At the lower end of each plot, a gutter was inserted 5 cm into the soil with the upper edge level with the soil surface. The gutter was equipped with a canopy to exclude direct input of rainfall and a 2-cm diameter plastic hose routed runoff water from the gutter to plastic collecting vessels.

All plant shoots were cut off at the soil surface and removed from one of the plot halves immediately (<30 min) before each rainfall simulation to isolate the effects of roots alone on runoff. Cut shoots were then dried to obtain total plot dry mass and subsamples saved for nutrient analysis.

Rainfall simulations were conducted 50–53 days after planting (DAP) in 2005, and 50–51 DAP in 2006 when plants were flowering and canopies had reached maximum size for the season. A rainfall simulator described by Humphry et al. (2002) was equipped with TeeJet™ 1/2 HH SS 50 WSQ nozzles[2] (Spraying Systems Co., Wheaton, IL) approximately 3 m above the soil surface. Rainfall was delivered at approximately 7.5 cm h^{-1} until 30 min of runoff was collected. Phosphorus content of the source water used for generating runoff was <150 μg L^{-1}. Following each simulation, runoff water was thoroughly stirred to re-suspend settled particles and immediately sampled. A filtered (0.45 μm) subsample was also obtained. Runoff samples were stored at 4°C prior to laboratory analysis. In this manuscript, use of the term 'runoff' refers to surface runoff.

Soil and root sampling

Soils were sampled to obtain general fertility recommendations for the field site as well to describe the conditions of individual plots. Sampling for field fertility recommendations was done in May before the growing season whereas plot specific sampling was done at the time of rainfall simulation. For field fertility recommendations, three composite samples were obtained, each representing approximately one third of the field. Composite samples were comprised of 15, 15-cm samples collected by stainless steel probe (2-cm diameter) and thoroughly mixed. To

represent individual field plots, one point from the border of each plot was selected for soil samples to be used for both antecedent gravimetric water content and P analysis in 2005 (2-cm diameter × 15-cm depth). In 2006, 10 samples (2-cm diameter × 15-cm depth of soil core) were collected along a diagonal transect within each plot and thoroughly mixed. All soil samples for chemical analysis were air dried in a greenhouse at 40°C. In 2006 soil moisture levels were determined before and after rainfall simulation using a capacitance sensor (Theta probe, Delta T Devices, Ltd., Cambridge, UK).

Additional soil samples were collected to determine root length density of individual plots at depth increments of 0–15, 15–30 and 30–45 cm using a 4-cm diameter soil corer (Giddings Machine Co., Windsor CO, USA). These samples were collected within one week of the completion of all rainfall simulations, with one soil core obtained per plot at approximately the mid-point between the central rows. Soil cores were refrigerated until analysis.

Sample analyses

Soils

Composite samples representing general field conditions were extracted with Mehlich-3 solution (0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.013 M HNO_3 + 0.001 M EDTA) by shaking 1.0 g of soil with 10 mL of solution for 5 min (Mehlich 1984). Extract P, potassium (K), calcium (Ca), and magnesium (Mg) were determined by inductively coupled plasma-optical emission spectroscopy (ICP-OES). Cation exchange capacity (CEC) was determined from Mehlich-3 analyses by sum of cations (Ross 1995). Soil pH was determined in water (1:1) following the recommended method of Eckert and Sims (1995).

Soil samples representing individual plots were analyzed for Mehlich-3 P. Soils were extracted by the method described above, and extract P was determined colorimetrically by the method of Murphy and Riley (1962).

Phosphorus sorption characteristics were determined in a composite of three subsamples from each plowed strip by constructing Freundlich sorption isotherms (Nair et al. 1984). One gram of soil was shaken with various additions of P in 25 mL of 0.01 M $CaCl_2$ on an end-over-end shaker at 25°C. Phosphorus in the solutions was added as KH_2PO_4 to achieve initial solution concentrations of 0 to 40 mg L^{-1}. After 24 h, the soil suspensions were centrifuged and filtered (0.45 μm), and the solution P concentration (C) was determined colorimetrically as described above. The amount of P sorbed was calculated as the difference between the initial and final solution P contents. Average Freundlich parameters obtained in 2005 and 2006 were 39.27 and 0.35 for K (L kg^{-1}) and N, respectively, with an equilibrium P concentration at zero net sorption/desorption (EPC0) of 1.19 mg L^{-1} by the optimizing routine developed by Bolster (2007) with the Freundlich sorption equation.

Plants (shoots and roots)

Shoot P content was determined from dried shoot subsamples of two plants collected from each plot and ground with a Wiley mill (# 40 mesh). Samples were ashed at 400°C for 16 h, dissolved in 100 mM HCl, and P determined colorimetrically. Soil cover by plant canopies was determined using overhead digital photographs taken at the time of rainfall simulation and analyzed with Photoshop (Adobe, Inc.) according to Klassen et al. (2003).

Root length and density with depth were determined from the 45-cm soil cores by first dividing them into 15-cm sections, then carefully washing all bean/ soybean roots from the soil. Root samples were stained with neutral red (0.162 g L^{-1}), scanned and analyzed using WinRhizo (Régent Instruments, Quebec, Canada) to determine total root length per core section (cm_{root} cm_{soil}^{-3}) and diameter. Average diameter and distribution of root length within root classes were determined, where roots 0.05–0.25 mm were classified as secondary lateral roots, roots 0.25–0.6 mm were classified as primary laterals, and roots 0.6–1.5 mm were classified as basal and tap roots.

Runoff water

Total P and total dissolved P in runoff were determined by acid potassium persulfate digestion on filtered and unfiltered runoff samples, and P standards according to Pote and Daniel (2000) using sand-filled electric skillets as a heat source in order to digest many samples at one time. Phosphorus concentration of digests was then determined colorimet-

rically by the ammonium molybdate method of Murphy and Riley (1962). Particulate P was determined as the difference between total and total dissolved P. Total solids content of runoff water was determined gravimetrically by drying 200 ml runoff at 60°C.

Statistical analyses

Data from each treatment were tested for normality and homogeneity of variance. All data not passing these tests (i.e., TP load, TP concentration) were log-transformed to comply with the assumption of Gaussian distribution required of parametric statistics. Data were analyzed by Student's t-test, one-way ANOVA, and both single and multivariate linear regression. All data were analyzed using SPSS v. 11 (SPSS Inc. 2005).

Results

Plant growth

Plant growth at the time of the rainfall simulations (50–53 DAP) was similar between years. In 2005, soybeans had three to 20 leaves and no flowers at the time of rainfall simulations while common beans had between 10 and 20 fully expanded trifoliate leaves, flowers, and some small pods. In 2006, soybean was not grown and all common bean genotypes were flowering at the time of rainfall simulation. No significant differences in shoot mass were observed among genotypes of a single species, and soybean had significantly lower shoot mass than common bean in 2005 (Table 2). Ground cover varied little between years (77–80%) for the common beans.

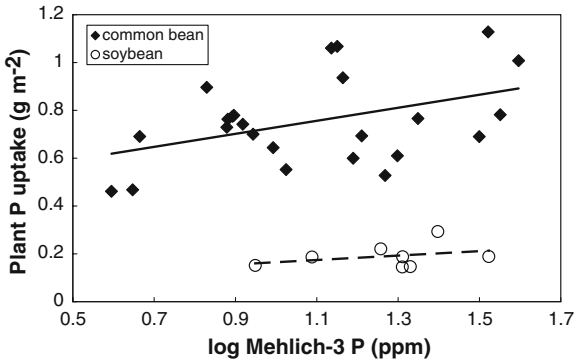

Fig. 1 Correlation between soil test P (Mehlich-3) and plant P uptake for each runoff plot. This relationship was significant for common bean (p=0.05; r^2=0.18, y=0.5448x+0.9134) but not for soybean (p=0.425, r^2=0.115, y=0.1871x+0.1422)

Low shoot P concentrations were observed in all genotypes in this study (<0.35% dry wt.) due to the low fertility of the soil, and were at the lower limit of the 0.3–0.5% shoot P requirement for optimal plant growth (Marschner 1995). Shoot P content and soil P concentration of individual plots were correlated (Fig. 1). Mehlich-3 soil P concentrations of individual plots ranged from 9 to 36 mg kg^{-1} in 2005 and 3 to 40 mg kg^{-1} in 2006, with coefficients of variation of 0.38 and 0.78, respectively.

Total root length in the entire 45-cm soil core averaged 308 cm for soybeans and 583 cm for common beans, differing significantly among genotypes in both 2005 (F=15.127, p<0.001) and 2006 (F=2.469, p=0.113; represented by the sum of the

Table 2 Shoot attributes of all genotypes in 2005 and 2006 at the time of rainfall simulation

		Shoot mass (g m^{-2})	Ground cover (%)	Shoot P (% dry weight)
2005				
Common bean	L-88 57	225±15	77.3±7.9	0.280±0.042
	L-88 30	242±16	77.2±2.3	0.291±0.028
Soybean	Brazil 10	65±6	22.9±2.5	0.302±0.040
	Local 2	68±13	19.5±2.9	0.289±0.024
2006				
Common bean	L-88 57	245±22	85.9±2.2	0.325±0.065
	L-88 14	244±22	78.3±3.1	0.355±0.025
	L-88 30	268±17	79.0±5.6	0.311±0.048
	L-88 63	216±33	77.2±3.3	0.342±0.019

Values shown are means ± standard error of the mean.

stacked bars in Fig. 2). Between soybean genotypes, Brazil 10 had longer total root length than Local 2 in the soils cores, and among bean genotypes L-88 57 had the longest total root length in 2005 whereas L-88 30 had the longest total root length in 2006. In 2005, root length densities (cm_{root} cm_{soil}^{-3}) differed significantly between common bean and soybean in the 0–15 cm soil samples (t=4.15, p=0.004). Significant intra-specific differences in root length densities in the upper 15 cm of soil were observed between Local 2 (mean=0.87 cm cm^{-3}) and Brazil 10 (mean=1.57 cm cm^{-3}) soybeans but not among bean genotypes. In 2006 root length densities did not differ significantly among genotypes in the top 15 cm. Root diameter did not differ among species or genotypes in the upper 15 cm of the soil cores but was significantly higher in 2006 (p<0.001), averaging 0.28±0.008 mm in 2005 and 0.34±0.01 mm in 2006. Root length distribution within root classes indicated that the majority of roots in all samples were lateral roots, with an average of 92±0.5% of total root length as laterals in 2005 and 88±0.8% in 2006 (Table 3).

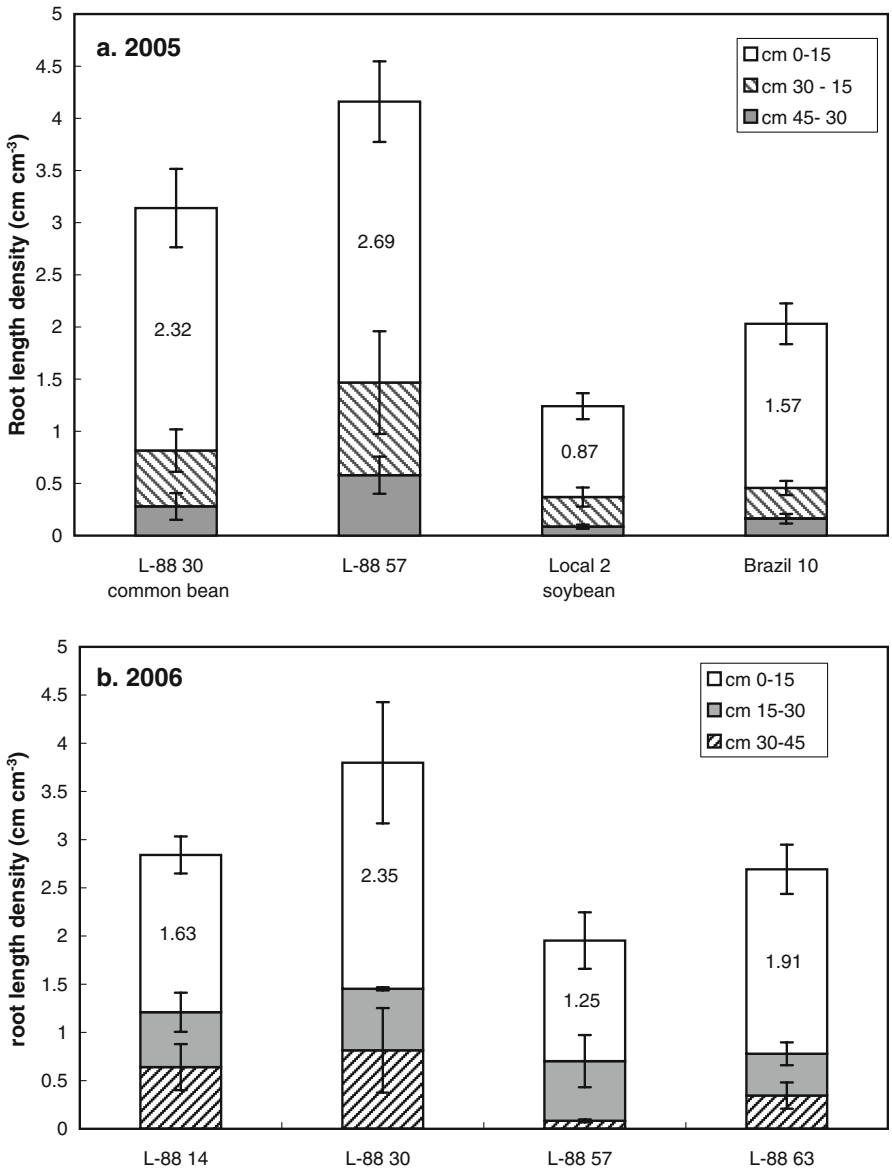

Fig. 2 Root length densities obtained from 15-cm segments of a 45-cm soil core (diameter=4 cm). In **a** 2005 and **b** 2006. Each *bar* is the mean of four measurements. *Error bars* represent ±SE. *Bar colors* represent different depths in the soil core. *Values in print* are the average root length density at 0–15 cm for each treatment. *Differences in the sum of the stacked bars* represent differences in total root length per soil core

Table 3 Root length (cm) by root type based on diameter at a soil depth of 0–15 cm

	Genotype	Secondary laterals	Primary laterals	Basal and tap
2005		0.05–0.25 mm	0.25–0.6 mm	0.6–1.5 mm
Common bean	L-88 30	229±41.2	227±29.8	26.5±6.20
	L-88 57	248±31.5	274±45.5	26.8±5.70
Soybean	Brazil 10	142±30.6	167±18.4	14.2±3.30
	Local 2	104±19.5	90.2±10.4	8.46±2.89
2006				
Common bean	L-88 14	119±15.1	146±20.2	27.3±6.23
	L-88 30	201±59.9	171±32.0	39.3±12.4
	L-88 57	93.6±28.7	100±22.0	19.7±2.54
	L-88 63	173±25.3	128±27.6	21.9±5.22

Values shown are means ± standard error of the mean

Runoff

Runoff depths ranged widely among plots and treatments (0.25–27 mm event^{-1}), with significantly more runoff in 2006 than in 2005 (Fig. 3). Cutting the shoots significantly increased runoff compared to plots with shoots intact (average difference=63%; Fig. 3). Runoff also differed significantly between common bean and soybeans, which had substantially different levels of ground cover (averaging 77% for common bean and 21% for soybean) but did not differ significantly among genotypes of the same species that had similar canopy characteristics (Table 2). The lower runoff depths in 2005 for all treatments were associated with dryer conditions that year compared to 2006 (Table 4). Antecedent soil moisture averaged 0.18 m^3 m^{-3} in 2005 and 0.21 m^3 m^{-3} in 2006.

Erosion and particulate P in runoff

Phosphorus in runoff was predominantly in particulate form, with particulate P averaging 97% of total P in 2005 and 96% of total P in 2006. Total solids concentration in runoff was correlated with particulate P concentration in runoff (Fig. 4), as well as to total P concentration (2005: F=43.196, r^2=0.532, p<

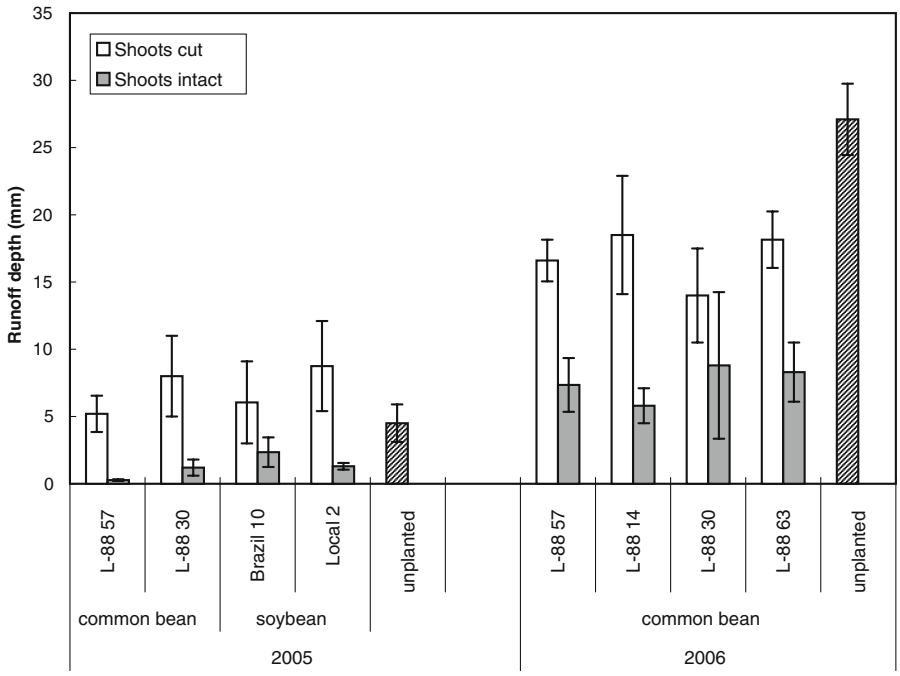

Fig. 3 Effect of crop, genotype, and shoot removal on runoff depth from 2×1-m plots during the first 30 min of runoff collection under simulated rainfall (7.5 cm h^{-1}). *Each bar* is the mean of four measurements, except n=8 for the 2005 unplanted treatment. *Error bars* represent ±SE

Table 4 Site moisture conditions

Hydrologic property	2005	2006
Antecedent soil moisture (m^3 m^{-3})	0.177±0.013	0.212±0.006
Rainfall infiltration		
Shoots cut (cm)	70.8	31.6
Shoots intact (cm)	91.0	45.2
Runoff		
Shoots cut (cm)	7.0	16.8
Shoots intact (cm)	1.3	7.5

0.001; 2006: F=29.931, r^2=0.517, p<0.001). Particulate P loads in 2006 were on average 6 times higher than in 2005, owing to greater runoff depths observed in 2006 that averaged 70% more than in 2005. Notably, the slope of particulate P vs. total solid concentrations (Fig. 4) differed significantly between the 2 years. Total solids concentrations did not differ significantly between the 2 years for plots with shoots intact, but were significantly higher in 2006 in plots where shoots were cut (t=4.05, p=0.006).

In 2005, erosion from soybean plots was significantly greater than from the common bean plots (Table 5). Concentrations of total solids in runoff averaged 2.4 g L^{-1} from the soybean plots with shoots intact and 1.9 g L^{-1} from the common bean plots. Combined with the observed differences in

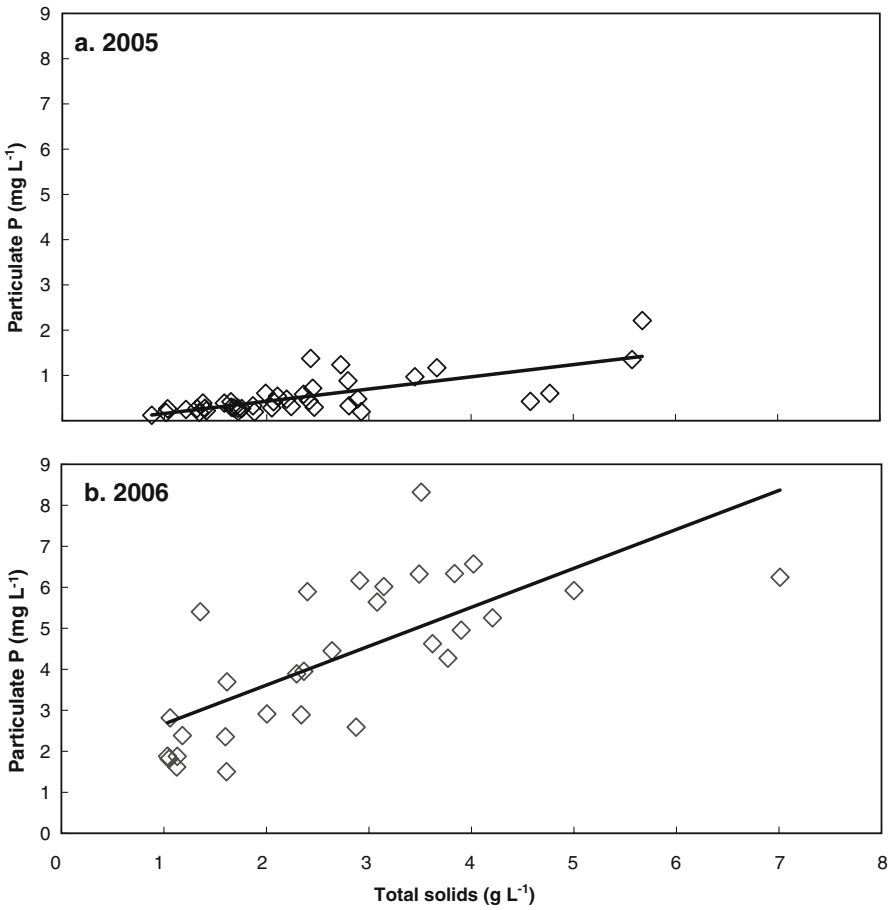

Fig. 4 Correlation between total solids and particulate P in runoff in **a** 2005 (r^2= 0.5293, y=0.2698x−0.1108) and **b** 2006 (r^2=0.5084, y= 0.9493x+1.17166). Not shown are six outliers from 2006 ranging from 40 to 65 mg L^{-1} in particulate P levels and 3 to 13 g L^{-1} total solids, all of which were from plots of very high soil test P or from the unplanted controls

Table 5 Concentration (mg L^{-1}) and load (g) of total P and sediment in runoff from 2×1-m plots during the first 30 min of runoff collection under simulated rainfall (7.5 cm h^{-1})

Species	Genotype	Total P concentration (mg L^{-1})		Total P load (mg)		Sediment concentration (g L^{-1})		Sediment load (g)	
		2005	2006	2005	2006	2005	2006	2005	2006
Shoots cut									
Soybean	Brazil 10	0.79±0.24		5.93±2.92		3.20±0.87		25.4±11.2	
	Local 2	0.36±0.07		7.51±3.60		2.41±0.76		45.6±18.2	
Common bean	L-88 30	0.57±0.27	15.71±10.3	5.42±1.30	293±114	2.11±0.15	2.79±0.57	31.2±10.3	81.1±31.7
	L-88 57	0.33±0.10	13.46±8.6	3.00±0.71	389±216	1.76±0.12	3.78±0.80	18.3±4.9	120±17.9
	L-88 14		6.02±0.49		218±54.0		4.38±0.93		174±78.2
	L-88 63		18.23±13.2		658±480		4.24±0.75		149±28.0
Shoots intact									
Soybean	Brazil 10	0.48±0.11		2.13±0.98		2.08±0.35		10.5±5.7	
	Local 2	0.54±0.24		1.22±0.43		1.87±0.30		4.74±0.85	
Common bean	L-88 30	0.27±0.06	4.20±0.61	0.62±0.29	58.9±32.1	1.37±0.25	1.86±0.32	3.09±1.4	22.9±10.5
	L-88 57	0.64±0.24	12.81±10.7	0.43±0.21	104±70.3	2.21±0.62	1.96±0.56	1.39±0.6	25.40±6.11
	L-88 14		3.25±0.84		31.8±4.33		1.61±0.43		19.3±7.36
	L-88 63		3.94±0.93		60.1±20.4		2.54±0.55		44.2±20.1
Unplanted control		0.65±0.23	31.02±15.1	3.90±0.96	1833±991	3.13±0.48	7.69±2.55	23.2±6.9	427±153

runoff depths, the greater concentrations of total solids in runoff resulted in loads from soybeans that averaged 1.6 times total solids in runoff from common beans. In 2006, concentrations of total solids in runoff from common bean plots averaged 2.4 g L^{-1}. Concentrations of total solids in runoff from unplanted plots averaged 3.13 g L^{-1} in 2006 and 7.7 g L^{-1} in 2006. No significant differences among genotypes of the same species were observed in erosion and particulate P losses.

Cutting the shoots of common bean and soybean plants increased sediment concentrations in runoff compared with plots with shoots intact as well as runoff depths (Table 5). As a result, total solids from plots with shoots removed averaged 0.15 and 0.66 kg ha^{-1} in 2005 and 2006, respectively, whereas total solids from plots with shoots intact averaged 0.025 and 0.14 kg ha^{-1} in 2005 and 2006.

No differences in sediment concentrations and erosion loads were observed among genotypes, contrary to the hypothesis that increases in root densities near the soil surface may improve resistance to erosion.

Total dissolved P in runoff

Total dissolved P levels in runoff were low, ranging from 20 to 250 μg L^{-1} (Fig. 5), reflecting the P status of soils in this study and were not correlated with any crop characteristic. Given the low soil P levels, total dissolved P in runoff was very sensitive to differences in soil P levels between the plots. Total dissolved P load was linearly correlated with soil P concentrations of individual plots (F=5.02, p=0.033, r^2=0.138). The fraction of total P in runoff that is dissolved decreased with increasing sediment concentrations (y=−0.0231Ln(x)+0.048, r^2=0.1092 in 2005 and, y=−0.258Ln(x)+0.0619, r^2=0.2229 in 2006).

Root length density and runoff

Since runoff and erosion by water are surficial processes, and because rainfall infiltration was expected to be most affected by the uppermost zones of soil, root length density values from the topmost (0–15 cm) soil core segment would be expected to have the greatest effect on these variables compared with root traits at a greater depth. However, root length density was not significantly correlated with runoff volume, total solids, TP concentration, TP load, DRP concentration, or DRP load (Fig. 6)—including when analyzed using a multiple regression with plot soil P as another independent variable. Concerning the question of deep roots affecting infiltration, no significant

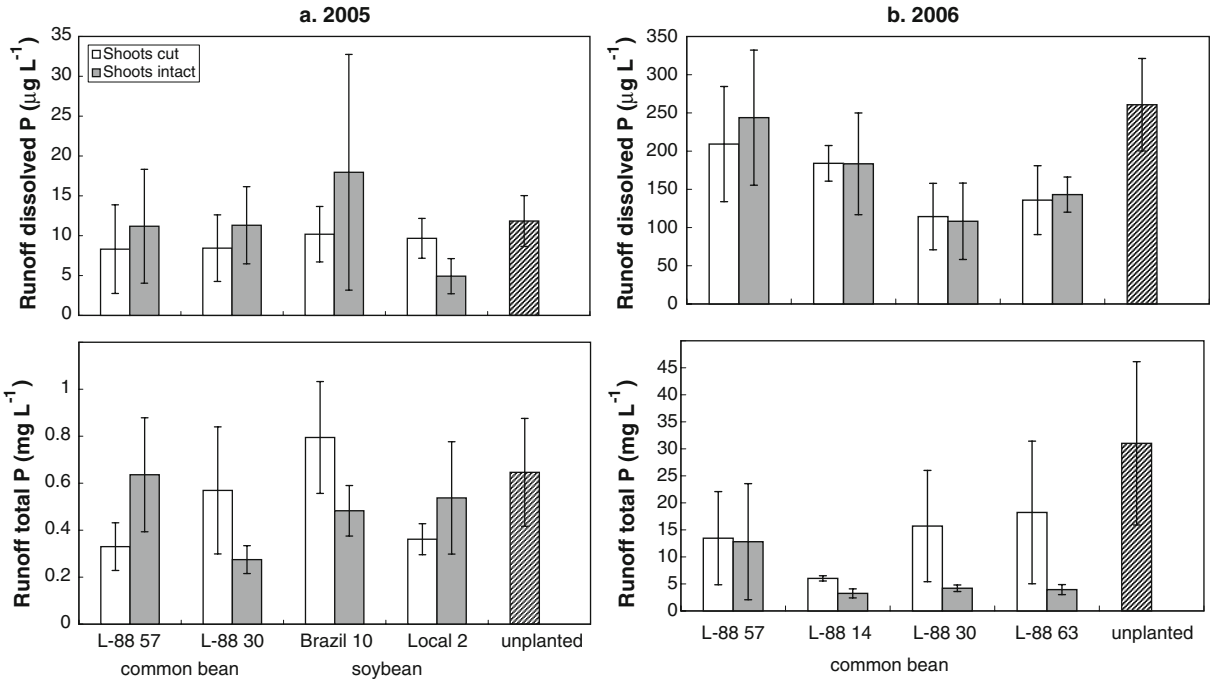

Fig. 5 Effect of crop genotype, and shoot removal on total and dissolved P in runoff in **a** 2005 and **b** 2006. *Each bar* is the mean of four measurements, except $n=8$ for the 2005 unplanted treatment. *Error bars* represent ±SE

interaction could be determined between root length at deeper segments of the soil core and runoff volume. Even the large species differences in root length density between common bean and soybean in 2005 did not affect runoff volume or P loss when shoots were removed.

Discussion

In this study, the plant canopy was the only plant attribute that reduced runoff and erosion of phosphorus and sediment in both soybean and common bean plots. Root traits alone, as examined in plots with the shoots cut immediately before rainfall simulation, did not explain variation in runoff and erosion. These results suggest that root architecture may only indirectly influence erosion in annual row crops by affecting shoot growth.

The lack of a root treatment effect on runoff seen here is most likely due to very low root length densities observed in the study (<4.0 cm cm^{-3}). These low densities are comparable to values for maize reported by Bui and Box (1993) who also simulated rain on plots with shoots cut and did not observe effects of root length density on runoff in a Cecil sandy loam (clayey, kaolinitic, thermic Typic Kanhapludult). Mamo and Bubenzer (2001a) also examined comparable root length densities to those in the current study and saw significant decreases in soil detachment rate with increasing root length density, but used a much different method of generating runoff without simulating rainfall, but by flooding the plot with drip irrigation at the upper end of the plot slope. Studies of plant species with large root length densities report decreasing erosion rates with increasing root length density. De Baets et al. (2006) studied grass sown at different densities that yielded root length densities of up to 600 cm cm^{-3} (on average 100 times greater than the root length densities of our study) and observed large reductions in soil detachment rate with a hydraulic flume at root length densities above 40 cm cm^{-3}, demonstrating the superior utility of grass as a cover crop in mitigating erosion even when shoots are removed, due to high levels of root growth. Similarly, Zhou and Shangguan (2007) reported that roots accounted for up to 90% of

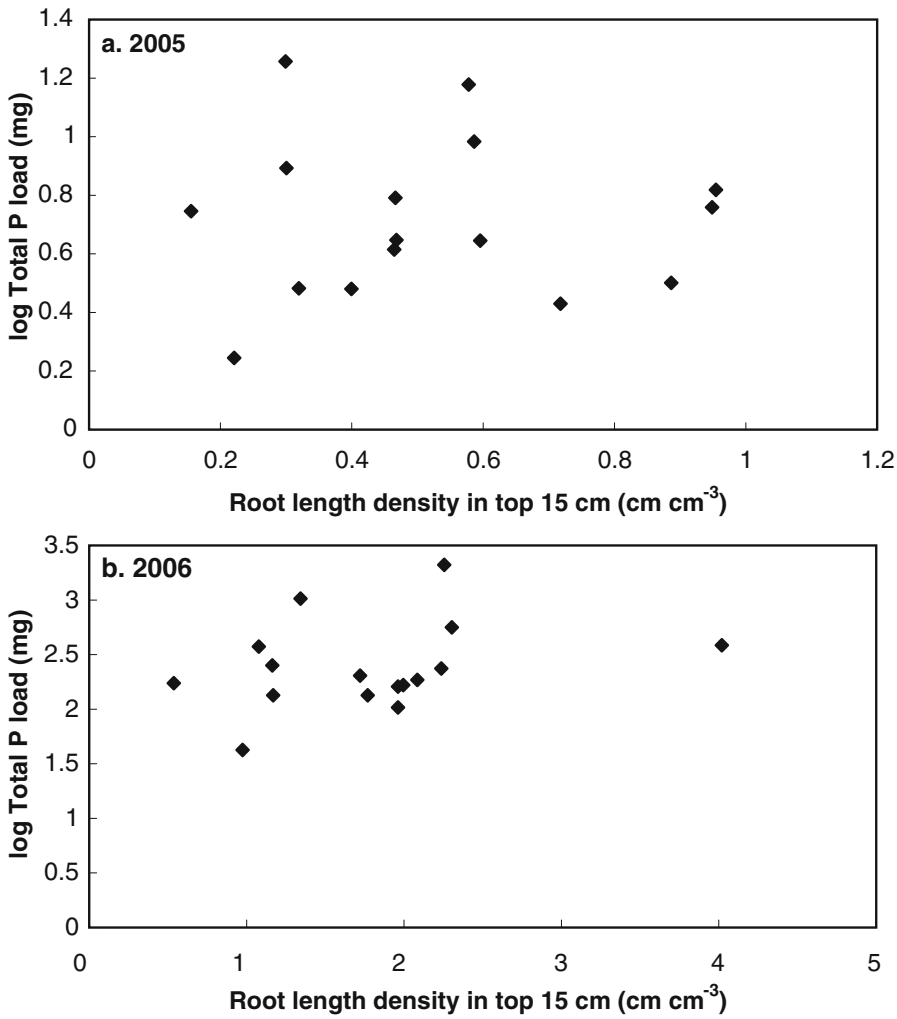

Fig. 6 Total P load was not correlated with root length density in **a** 2005 or **b** 2006

the reduction in erosion by 27-week old ryegrass under rainfall simulation at 1.5 mm min^{-1}. De Baets et al. (2007) saw decreasing soil detachment rates with decreasing root diameter, further suggesting that it is the low root length densities in the present study, not the small diameter of roots, that explains the lack of effect of roots on runoff and erosion.

Although root architecture and root length density did not directly affect erosion under the conditions in this study, there may be indirect effects of root growth on canopy growth in different low P soils. In soils where P levels are more stratified with depth and shallow roots result in better nutrient uptake and increased shoot growth compared to deep-rooted genotypes, shallow roots could increase the shoot cover that can intercept raindrops and thereby decrease runoff and erosion. Ho et al. (2005) observed increased shoot mass in genotypes with higher root length density in the top 15 cm of a low-P mollisol in Honduras. Studies addressing rill and gully erosion, as opposed to sheet flow which was examined in this study, might also reveal differences in runoff and erosion among genotypes. In soils with an increased presence of macropores and a decreased buffering capacity than the soil used in this study, leaching would be a more important form of P loss, and would be expected to be reduced in shallow-rooted genotypes whose increased canopy cover decrease rainfall infiltration and whose roots intercept subsurface P. More research is needed with genotypes of contrasting root architecture in very low P soils to explore these potential effects.

The distinct effect of cutting shoots on runoff highlights the importance of the crop canopy in

intercepting rainfall and minimizing surface sealing caused by direct impact (Bradford et al. 1987; Meyer and Mannering 1971). Although we expected the genotypes to differ in shoot mass and the extent of their ground cover based on differences in root architecture observed in preliminary tests, variability in soil P levels of the individual plots appeared to outweigh the genetic root trait differences that might have resulted in divergent canopy growth. The probable cause of the comparatively poor growth of the soybeans was their selection for root architecture rather than for adaptation to growth environment, which was originally southern China. The relationship between soil test P of individual plots and plant P uptake (Fig. 1) points to the importance of edaphic variability in crop response. Such variability in soil P and subsequent crop response is common due to the spatial dependency of soil P even in low P soils (e.g. Cox et al. 2003; and Di Virgilio et al. 2006). The absence of significant differences in shoot P concentrations and shoot masses among genotypes also minimized potential differences in plant P contributions to runoff water between genotypes.

The absence of differences among genotypes selected for root traits parallels the findings that ground cover and shoot mass did not vary significantly with root characteristics, and is likely due to the soil conditions in the current study. Shallow root growth has been shown to affect shoot growth in low P soils (Ho et al. 2005; Zhu et al. 2005b), and although the soils in the current study were relatively low P and no P was applied as fertilizer, P levels greater than 10 mg kg^{-1} (Mehlich-3) may not be low enough to cause stress symptoms that would distinguish shallow-rooted from deep-rooted genotypes.

The significant variability of total root length in the soil core demonstrates the contrasting root architecture of the selected genotypes, and supports the analysis of root architecture effects on runoff and erosion. The differences in root growth trends between the same genotypes in 2005 compared to 2006 are likely due to differing soil moisture contents between the 2 years that affected root growth (see Table 4). Climatic differences between the 2 years undoubtedly contributed to discrepancies in runoff from the unplanted plots between 2005 and 2006, which had no plant cover at any time during the study. In 2006, higher levels of precipitation during the growing season likely increased destruction of exposed surface soil aggregates, resulting in increased runoff volume due to surface sealing (Bradford et al. 1987).

Given the low P content of soils at the experiment site, P loss in runoff was expected to be primarily associated with erosion. This expectation was confirmed by the dominance of particulate P as the primary form of P in runoff. Higher concentrations of particulate P in 2006 may reflect differences in climate between the 2 years, with greater precipitation in 2006 producing greater destruction of soil aggregates prior to the rainfall simulations and therefore greater susceptibility of surface soils to erosion. The concentrations of total solids in runoff from unplanted plots reported here are about 25% of those reported by Engel et al. (2007), who conducted rainfall simulations on soybeans under conventional tillage at a similar crop stage as the current study, but in a Hapludox soil on a 16.5% slope.

The relationship of total dissolved P load and soil P concentration was consistent with apparent relationships of shoot P and root length density with soil P—all pointing to the importance of edaphic controls on runoff P loss, even in low P systems. Since nearly all of the P lost from the plots was in particulate form, it is unlikely that dissolved P in plant shoots or root exudates substantially affected P in runoff. Total dissolved P concentrations in planted plots remained as low as unplanted plots (<65 μg L^{-1} in 2005 and <0.45 mg L^{-1} in 2006) and did not increase when shoots were left intact or considering variation in shoot mass among plots. This suggests that the intact plant shoots, cut stems, or roots, contributed almost no P in the runoff. These data are in contrast to the findings of Sharpley (1981) who reported that plant-derived P could account for the majority of runoff P in several species, including soybean, under rainfall simulated at a rate of 6.0 cm h^{-1}. Other stresses have also been reported to increase plant contribution to runoff P, including freezing and thawing (Bechmann et al. 2005) and freezing or drying (Roberson et al. 2007). Reduced membrane integrity resulting in electrolyte leakage has been reported with freezing/thawing in wheat (Pukacki et al. 1991) and drought in common bean (França et al. 2000). In the current study, plants were not exposed to stresses such as drought or freezing, only P deficiency, and therefore likely had less P leakage from the shoots. Sharpley (1981) reported the greatest plant contributions to runoff P in high fertilizer

treatments, which further suggests that the plants in the current low P study had minimal P leakage under rainfall simulation.

It is likely that any P leached from plant tissue was sorbed by the intact soil or by sediment in runoff as has been described previously (Sharpley et al. 1981). The lower dissolved P proportions in samples with increasing sediment load indicates high rates of erosion. Kleinman et al. (2005) measured an exponential decrease in the fraction of total P that is dissolved with increasing suspended solid concentrations ranging from 0–2.5 mg L^{-1} from rainfall simulations at a rate of 6.0 cm h^{-1} on cover-cropped and bare Typic and Aquic Fragiudept soil. The authors observed a threshold for DRP saturation of suspended solids between 0.1 to 0.5 g L^{-1}. Since the suspended solid concentrations in the current study are all above these values, it can be concluded that erosion alone could sustain the low DRP concentrations in the runoff, including any DRP leached from plants or desorbed from the soil.

This study shows that maintenance of the canopy is of fundamental importance for mitigating the erosive and nutrient-depleting effects of rainfall on soil. The results presented here also demonstrate the vulnerability of continuously bare soils to erosion, as observed in the unplanted controls. Results from this study indicate that breeding for root traits to improve plant performance in low P soils is unlikely to affect erosion due to soil factors influenced directly by the roots, but decreases in erosion due to changes in plant canopy growth are possible.

Conclusions

The roots in this study may be affecting soil bulk density and water repellency (as suggested in papers such as Barley 1954; Hallet et al. 2003; and Whalley et al. 2004), but these effects are at the rhizosphere level and did not result in measurable effects on runoff and erosion for 2×1-m plots. In the low P soils used in this study, leachate from plant biomass did not contribute to P runoff in total or dissolved P pools. The effects of the annual row crops on mitigating runoff and erosion were mediated by the plant shoots. Root length densities in the upper 15 cm of soil halfway between rows were less than 4.0 cm cm^{-3} and had no measurable effect on runoff and erosion. Innate soil characteristics outweighed plant effects on total dissolved P even at these low soil P values. We conclude that for annual dicotyledonous crops such as bean and soybean with relatively low root length densities, root traits have little direct effect on soil erosion. Root architecture may be important at higher root densities such as in grass systems, soils more stratified in P with depth where shallow roots will increase P uptake and lead to development of bigger canopies, or where roots are exposed and can physically protect soil after leaf senescence.

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