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Assessment of the Georgia Phosphorus Index on farm at the field scale for grassland management

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Abstract: In order to better manage agricultural phosphorus (P), most states in the United States have adopted a "P indexing" approach that ranks fields according to potential P losses. In Georgia, the Georgia P Index was developed to estimate the risk of bioavailable P loss from agricultural land to surface waters, considering sources of P, transport mechanisms, and management practices. Nine farm fields, managed as pasture or hay systems, were outfitted with 28 small in-field runoff collectors. Runoff P, soil P, and field management practices were monitored from 2004 to 2007. Fields varied from those rich in P (broiler litter or dairy slurry) to those without P amendments (inorganic nitrogen [N] or no amendments). Data relating to nutrient applications, soil properties, soil P, and management were used as input values to determine a Georgia P Index value estimating the risk of P export from each field. Results indicated that the Georgia P Index underrated the risk in only 2% of the cases when considering loads or mass losses of P, partly due to the influence of small annual runoff volumes and thus greater flow-weighted concentrations from some fields. While measured P export was generally low to moderate (<7.5 kg P ha^{-1} y^{-1} [<6.7 lb ac^{-1} yr^{-1}]) from fields rated as a low or medium risk of P export, findings from this study indicated that the Georgia P Index, at times, overestimated the risk of P losses for hay systems and underestimated the risk of P losses for pastures when no amendments were applied.

Key words: forages—phosphorus—phosphorus index—runoff—water quality

In beef cattle–poultry grassland systems typical of the Southern Piedmont (United States), nutrient imports in the form of fertilizers and poultry feed tend to be far greater than nutrient exports at both farm and regional scales (Sharpley et al. 2009). Most generated poultry litter or manure is applied to pasture land as good agronomic practice. However, when applied to meet crop nitrogen (N) requirements, applied phosphorus (P) is disproportionately high, leading to an accumulation of P in the soil and making it vulnerable to transport during storm events either in particulate or dissolved form.

To better manage agricultural P, 47 states have adopted a "P indexing" approach, which ranks fields according to potential vulnerability for P losses (Sharpley et al. 2003). Generally, the P indexing approach to P management works by accounting for both P-source and P-transport factors. Source factors include soil test P (STP) and fertilizer or manure applications, whereas transport factors include runoff, erosion, leaching, and proximity to streams. Other modifying factors may include soil texture, pH, P sorption capacity, flooding frequency, and various conservation factors (Sharpley et al. 2003).

The Georgia P Index (Cabrera et al. 2002; Gaskin et al. 2005) was developed to estimate the risk of bioavailable P loss from agricultural land to surface waters considering P-source factors, P-transport factors, as well as management practices that may impact P export. Potential export of P is divided into three loss pathways: (1) soluble P in runoff, (2) particulate P in surface runoff, and (3) soluble P in leachate. Within each pathway, P-source factors (STP, inorganic fertilizer P, or organic fertilizer P) are adjusted according to management practices and are summed to obtain a source-risk rating. Similarly, transport risk ratings are determined using factors such as risk of runoff, risk of sediment loss, and risk of leaching, respectively, for the three pathways. Additional factors, such as vegetative buffer widths and depth to water table are also considered. Risk ratings for each transport pathway are summed, and a numerical P index value is determined in order to place a field within four categories (low, medium, high, or very high) of risk for export of P to surface waters. As is the case for the P indices of Arkansas and North Carolina, the Georgia P Index uses a quantitative approach to estimate P losses, whereas the majority of P indices in the United States use a qualitative approach (Osmond et al. 2006).

Generally, there has not been extensive field-scale validation of P indices, although a few studies have examined the performance of the various P indices against various measures. Leytem et al. (2003) calculated P index ratings for 272 fields in Delaware and reported that the majority of fields were in the low-risk category, with only 28% of fields indicating that P-based management would be required. The authors contrasted this with the finding that 55% of all fields evaluated had "excessive" STP values and that approximately 14% of fields in the low rating category had unsustainable levels of soil erosion. Veith et al. (2005) compared P index values computed using the Pennsylvania P Index for 22 agricultural fields under field crop management to total P loss calculated by SWAT (Soil and Water Assessment Tool). The two assessment tools were correlated ($p = 0.002$) with 73% of fields ranked similarly by the two tools. Of the remaining fields, half were underpredicted and half were overpredicted.

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Table 1
Field characteristics, management, and number of runoff collectors (RC).

Field	Management	Crop*	Phosphorus amendments	Forage management	Number of RC
A	Pasture, no amendments	Unimproved pasture (TF–CB)	None	Pasture	3
B	Pasture, no amendments	Unimproved pasture (TF–CB)	None	Pasture	3
C	Pasture, no amendments	Unimproved pasture (TF–CB)	None	Pasture	3
D	Hay, inorganic N	Improved hay (PM–CR; summer 2005)†	None (inorganic N)	Hay	3
E	Pasture, poultry litter	Unimproved pasture (TF–CB)	Broiler litter	Pasture	4
F	Pasture, poultry litter	Unimproved pasture (TF–CB)	Broiler litter	Pasture	3
G	Hay, dairy slurry	Improved hay (HB–W–A; summer 2005)‡	Dairy slurry	Hay	3
H	Hay, poultry litter	Improved hay (HB–AR; summer 2004)	Broiler litter	Hay	3
I	Hay, poultry litter	Improved hay (HB–AR; summer 2005)	Broiler litter	Hay	3

Note: N = nitrogen.

* TF = Tall fescue ((*Lolium arundinaceum* (Schreb.) Darbysh.). CB = Common bermudagrass (*Cynodon dactylon* L.). PM = Pearl millet (*Pennisetum glaucum* (L.) R. Br.). CR = Cereal rye (Secale *cereale* L.). HB = Hybrid bermudagrass (*Cynodon dactylon* L.). W = Wheat (*Triticum* spp.). A = Alfalfa (*Medicago sativa* L.). AR = Annual ryegrass (*Lolium multiflorum* Lam.).

† Fields D, H, and I converted from tall fescue-common bermudagrass hay on date indicated in parentheses.

‡ Upper 1/3 of contributing area of runoff collector 3 in Field G is planted in alfalfa, converted from corn silage in summer 2005.

In the Southern Plains area of Oklahoma and Texas, Sharpley (1995) evaluated 30 watersheds, the majority of which were less than 5 ha (12.4 ac), and compared the original Lemunyon and Gilbert (1993) P index values to measured values of total P export over 16 years. Watersheds included both cropping and grassland management, as well as both P fertilized and unfertilized management. The author reported a logarithmic relationship between measured losses of total P and P index ratings (P Index = −5.7 + 6.3 log[total P loss]; coefficient of determination [r^2] = 0.70). In Arkansas, Delaune et al. (2004) measured annual P losses from two 0.4 ha (1 ac) watersheds with untreated poultry litter applied annually to one watershed and alum-treated poultry litter applied to the second one. The authors compared the range of P index values over six years of management to actual annual P losses from the field watersheds. The P index was successful in estimating the risk of P losses from these two field watersheds ($r^2 = 0.83, p < 0.0001$).

Using six cultivated and four pasture watersheds ranging from 3 to 20.8 ha (7.4 to 51.3 ac) in the Texas Blackland Prairie (predominance of Vertisols), Harmel et al. (2006) compared estimated P loss potentials determined from the Texas, Arkansas, and Iowa P Indices to measured P losses. In general, all three P indices were more highly correlated with dissolved P loads and concentrations than with total P and particulate P loads or concentrations. On pastured watersheds, dissolved P concentrations were well correlated with all three P index ratings: $r^2 = 0.86, 0.90,$

Table 2
Characteristics of contributing areas to each runoff collector (RC).

Field-RC	Contributing area (ha)	Hydrologic group	Mean slope (%)	Flow path length* (m)	Drainage density (m m^{-2})
A-1	0.196	B	8.0	60.6	0.12
A-2	0.601	B	3.7	119.0	0.12
A-3	0.188	B	8.6	88.5	0.13
B-1	0.090	B	9.8	113.8	0.17
B-2	0.343	B	8.7	158.1	0.15
B-3	0.107	B	8.3	79.8	0.12
C-1	0.093	B	11.1	95.9	0.13
C-2	0.054	B	10.9	70.5	0.11
C-3	0.056	B	7.6	77.7	0.14
D-1	0.336	B	4.8	104.7	0.13
D-2	0.453	B	5.4	103.3	0.12
D-3	0.006	B	8.5	16.1	0.04
E-1	0.065	B	5.7	48.4	0.08
E-2	0.009	B	13.9	14.7	0.01
E-3	0.056	B	8.3	50.7	0.07
E-4	0.047	B	6.5	55.8	0.10
F-1	0.058	B	14.3	75.9	0.12
F-2	0.176	B	8.3	120.0	0.15
F-3	0.136	B	6.3	149.6	0.06
G-1	0.300	B	5.2	119.2	0.15
G-2	0.085	B	7.9	62.5	0.14
G-3	6.038	B	2.7	594.8	0.13
H-1	0.075	B	4.3	45.8	0.14
H-2	0.097	B	5.3	63.3	0.13
H-3	0.740	B	4.2	161.7	0.14
I-1	0.023	B	1.9	28.4	0.09
I-2	0.248	B	5.2	50.1	0.10
I-3	0.056	B	5.2	40.1	0.07

Note: Field and management descriptions can be found in table 1.

* Distance from top of hillslope to the runoff collector (RC).

and 0.84 for the Texas, Iowa, and Arkansas Indices, respectively. The authors suggested that variation in soil erosion was a limitation of the three indices in that variation in annual soil erosion can introduce substantial error into ratings of the risk of P export.

Our objective was to use data collected on farm at the field scale to examine how measured losses of runoff P compare to risk ratings for P loss calculated by the Georgia P Index. Previously on a Georgia Piedmont Typic Kanhapludult soil, an estimate of bioavailable P was measured in unfiltered runoff using iron oxide–coated filter papers. We found that bioavailable P was approximately equal to dissolved reactive phosphorus (DRP) (Butler et al. 2008a). For this reason as well as the fact that soluble P in leachate is not a concern in the soils examined in this study, we largely focused on the relationship of DRP in runoff to the Georgia P Index. Considering that particulate and organic P in runoff also contribute to bioavailable P in surface waters through mineralization, we also present total P data in context of Georgia P Index risk ratings. Our hypothesis was that the Georgia P Index would underestimate edge-of-field losses of mass P.

Table 3
Mean soil test phosphorus (P), applied manure P, and calculated Georgia P Index for each field and year.

Field	Year	Mean Mehlich-1 soil P (mg P kg^{-1})	Applied manure P (kg P ha^{-1})	Georgia P Index value	Georgia P Index risk rating
A	2004	25.0 (15.7)*	0	3	Low
A	2005	24.6 (17.3)	0	3	Low
A	2006	50.4 (34.8)	0	3	Low
A	2007	41.6 (51.0)	0	5	Low
B	2004	30.5 (13.5)	0	2	Low
B	2005	24.8 (11.7)	0	2	Low
B	2006	34.2 (20.3)	0	2	Low
B	2007	38.4 (24.5)	0	2	Low
C	2004	26.7 (17.4)	0	2	Low
C	2005	26.3 (15.4)	0	2	Low
C	2006	36.8 (17.2)	0	2	Low
C	2007	28.5 (11.3)	0	3	Low
D	2004	90.2 (58.7)	0	2	Low
D	2005	83.8 (76.4)	0	14	Low
D	2006	92.5 (64.6)	0	12	Low
D	2007	95.1 (48.2)	0	15	Low
E	2004	158.8 (158.3)	80	43	Medium
E	2005	87.1 (70.0)	80	49	Medium
E	2006	107.7 (90.4)	0	7	Low
E	2007	111.8 (75.8)	80	31	Low
F	2004	134.6 (74.5)	108	53	Medium
F	2005	136.0 (59.8)	108	53	Medium
F	2006	95.4 (46.3)	108	54	Medium
F	2007	120.3 (70.5)	108	51	Medium
G	2004	110.2 (101.6)	34	7	Low
G	2005	117.2 (75.2)	0	4	Low
G	2006	72.4 (37.3)	0	3	Low
G	2007	65.4 (25.9)	90	12	Low
H	2004	177.1 (46.6)	65	26	Low
H	2005	166.7 (83.5)	60	12	Low
H	2006	154.2 (68.5)	86	16	Low
H	2007	242.7 (78.8)	67	15	Low
I	2004	164.6 (90.5)	117	21	Low
I	2005	171.3 (102.3)	116	47	Medium
I	2006	181.4 (118.5)	109	19	Low
I	2007	223.2 (133.2)	158	23	Low

Note: Field and management descriptions can be found in table 1.

* Numbers in parentheses show standard deviation.

Materials and Methods

Field Selection and Sampling. In 1998, 28 small in-field runoff collectors (Franklin et al. 2001) were placed in nine farm fields in cooperation with private land owners in northeast Georgia to evaluate the effect of agricultural management practices on surface water quality. This study presents data collected on these fields from 2004 through 2007. Field management was classified into five categories (table 1): (1) unimproved tall fescue (*Lolium arundinaceum* [Schreb.] Darbysh.)–common bermudagrass (*Cynodon dactylon* L.) pasture with no applied manure or P fertilizers (Pasture, no amendments), (2) hay fields with no applied manure or P fertilizer (Hay, inorganic N), (3) unimproved tall fescue-common bermudagrass pasture with applied poultry litter (Pasture, poultry litter), (4) hay systems with applied dairy slurry (Hay, dairy slurry), and (5) hay systems with applied poultry litter (Hay, poultry litter). Pastures were continuously grazed with similar stocking rates within amended and unamended fields, as described later. No operations were conducted to distribute cattle feces during the time of this study. Soils were all classified as hydrologic group B and predominantly Kanhapludults by the USDA Natural Resources Conservation Service.

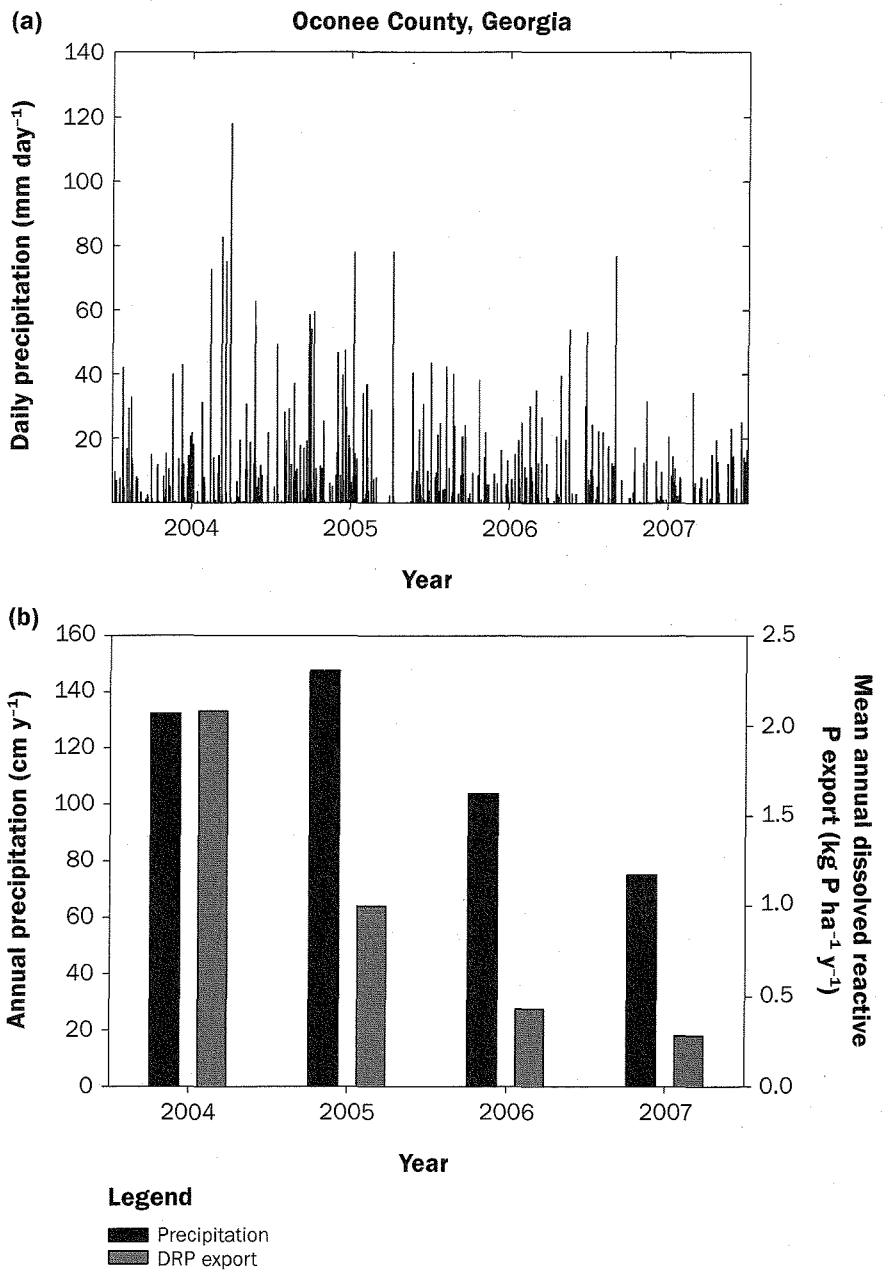
Beginning in late 2004 and continuing during the winter of each year for four years, soil cores (5 cm [2 in] internal diameter) were taken to a 10 cm (4 in) depth in triplicate at three points along a transect extending from the runoff collector to the top of the hillslope of the contributing area with point A at ~10 m (~33 ft) in front of the runoff collector,

point C at ~10 m from the top of the hillslope of the contributing area, and point B taken as the midpoint between points A and C. Soil samples were air-dried and sieved (<2 mm [<0.08 in]) and then were analyzed for Mehlich-1 STP (Mehlich 1953). Resulting filtrate was analyzed according to the molybdate-blue method (Murphy and Riley 1962). A soil subsample was dried at 105°C (221°F) for 48 hours to determine gravimetric soil moisture content and results expressed on a dry-soil basis.

Runoff Monitoring and Erosion Estimation. Runoff and precipitation were monitored throughout the study period. Runoff samples were collected immediately following events (within 48 hours) for determination of DRP and total P concentrations. All runoff collectors were covered with a small, wire and metal-frame protector in the field to prevent damage from cattle or haying equipment. One composite sample was collected from each runoff collector, placed in a cooler, and transported to the lab, where samples were filtered (0.45 μm [17.7 μin]) within 48 hours of the end of the runoff event. Filtrates were then sent to an analytical lab to be analyzed for DRP by the molybdate blue method (Murphy and Riley 1962). Unfiltered samples were analyzed colorimetrically for total P following a Kjeldahl digestion (USEPA 1979). Runoff volume for each of these events was calculated using the curve number method. Curve numbers were determined by soil types and observations of management and cover at the fields throughout the study. Mass of DRP and total P for each event was determined by multiplying calculated runoff volume for the contributing area by DRP or total P concentration determined for each collected runoff sample. Mass of DRP for each event was then summed annually and divided by the annual sum of the corresponding event runoff volumes to obtain the annual flow-weighted concentration.

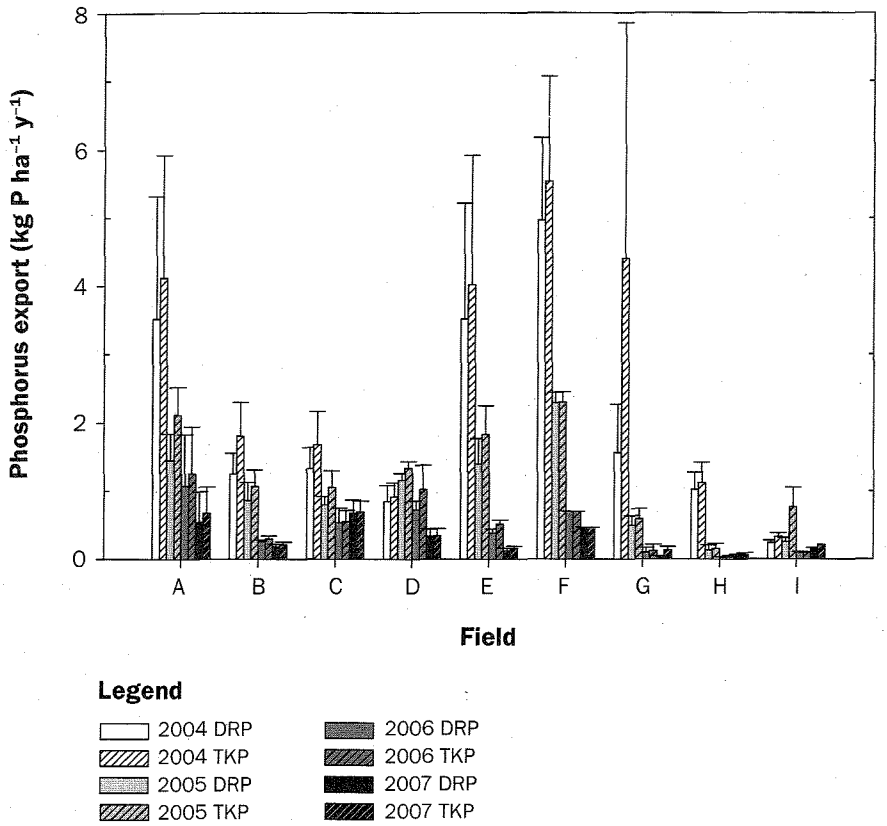
Figure 1

(a) Daily precipitation and (b) yearly precipitation for Oconee County, Georgia, and mean annual dissolved reactive phosphorus (DRP) from 2004 to 2007. Mean dissolved reactive phosphorus export is an average of all fields for that respective year. Tick marks indicate midyear in graph.



To determine the contributing area of each of the 28 runoff collectors, high resolution digital elevation models were created from global positioning system measurements taken in the field. Points were collected by mounting a Leica Wild SR399E sensor (Leica Geosystems, Heerbrugg, Switzerland) with an AT302 antenna equipped with a CR 344 controller onto a utility vehicle. Points were collected using kinematic sampling, with a point collected every 2 m (6.6 ft), while traveling in concentric circles around the field, approximately 1.5 m (4.9 ft) apart. Horizontal precision was set to collect points at an error of 4 cm (1.5 in) or less. Vertical coordinate (elevation) error was approximately 1.5 to 2.5 times the horizontal error (Van Niel et al. 2004; Yao and Clark 2000). Data points were imported into Arc/Map, where ordinary kriging interpolation using a spherical semivariogram model was used to interpolate a surface with 5 by 5 cm (2 by 2 in) pixels based on the elevation of the collected data points, thereby creating a digital elevation model. The hydrology functions in Arc/Map were then used to determine contributing areas of each runoff collector, which allowed DRP and total P loads to be calculated on a per area basis. Drainage density was determined by calculating the total length of the concentrated flow paths in each

Figure 2
Mean annual dissolved reactive phosphorus (DRP) and total Kjeldahl phosphorus (TKP) export for each field from 2004 to 2007.



Note: Field and management descriptions can be found in table 1.

contributing area and dividing by the contributing area (m m^{-2}).

Estimates of annual erosion were calculated by RUSLE2 (USDA ARS 2003) using corresponding climate, slope, soil properties, and management factors. Average slope and overland flow path length were calculated for each contributing area (table 2). Overland flow path length as used in RUSLE2 is defined as length from the area where overland flow begins to a point where it is deposited in a gully or channel. For the purposes of this study, the deposition point was considered the location of the runoff collector, making the overland flow path length the distance from the top of the hillslope to the location where sediments are deposited in the runoff collector.

Georgia P Index Evaluation. Management data were collected from each farm in order to calculate the risk of P losses for the contributing areas of each runoff collector for each year using the Georgia P Index. Dates and rates of manure applications and other amendments were determined from farmer animal waste reports and management records gathered during farmer interviews. Mean Mehlich-1 soil P for each collector and each year was used as the input for the STP value (mean of soil samples taken at points A, B, and C in each contributing area). Correlation of DRP loads and flow-weighted concentrations with risk ratings calculated by the Georgia P Index were examined using PROC GLM (SAS Institute 2008).

Results and Discussion

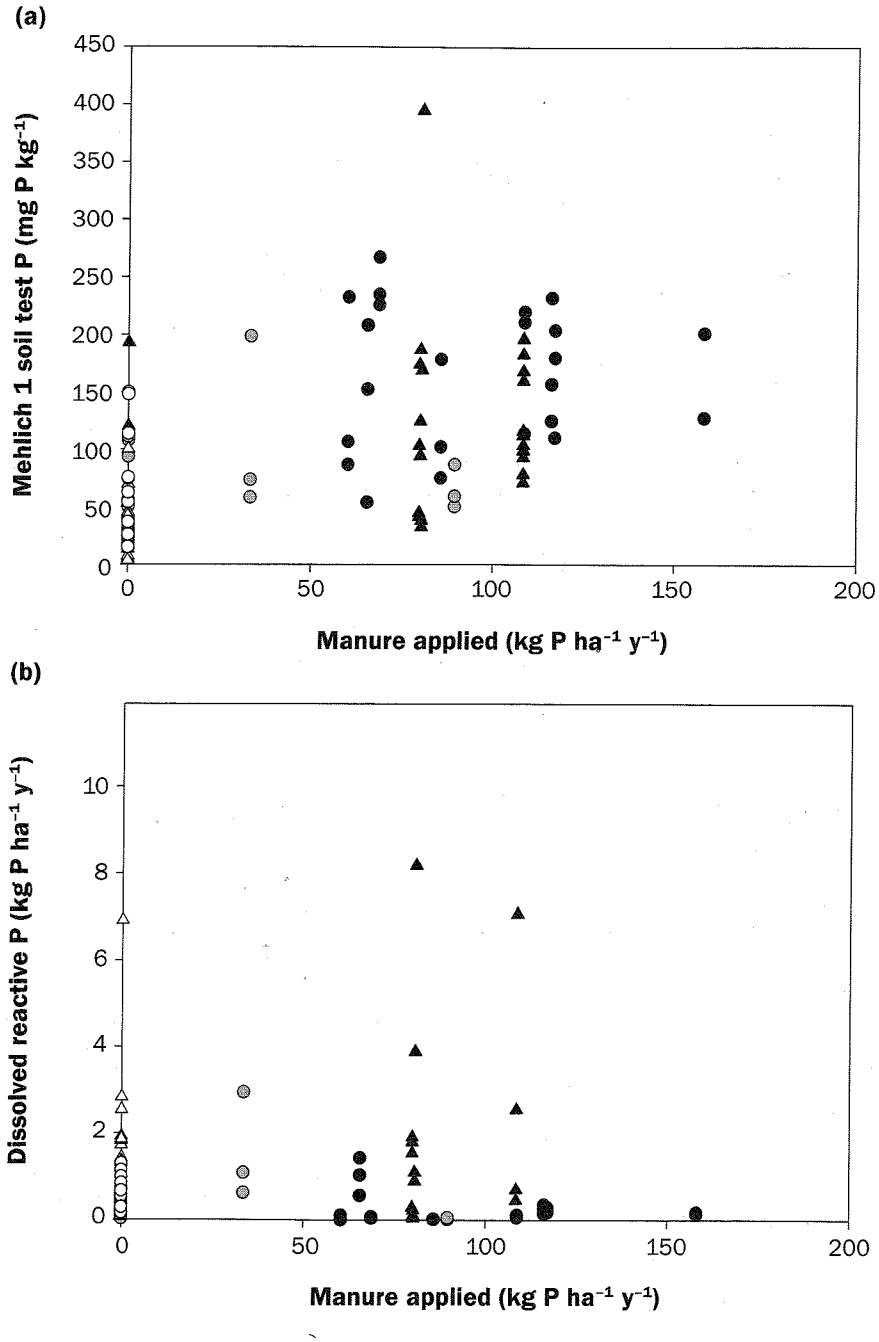
Manure and Soil P. Manure applications and soil P were generally consistent within each field throughout the study (table 3). Greater soil P levels in 2007 in fields H and I may have been partially due to droughty weather (figure 1), which reduced forage growth and consequently, the number of hay cuttings (and associated P removal). In general, the highest soil P values were observed from both hay and pasture systems with applied broiler litter (table 3). However, fields with the largest manure application rates did not have the greatest soil P levels (table 3). Soil P levels on fields with either applied dairy slurry or only inorganic N had similar soil P values.

Concentration and Mass Export of Dissolved Reactive Phosphorus in Runoff. Generally DRP and total P followed similar trends unless otherwise noted. Annual DRP export varied with year but was only somewhat similar to precipitation patterns. In 2005, DRP export decreased, while rainfall increased (figure 1b). In 2006 and 2007, both DRP and rainfall decreased; however, DRP decreased by a larger proportion than did rainfall. Annual export of DRP ranged between between 0.1 and 8.1 kg P ha^{-1} y^{-1} (0.1 and 7.2 lb P ac^{-1} yr^{-1}), and total P ranged between 0.1 and 11.3 kg P ha^{-1} y^{-1} (0.1 and 10.1 lb P ac^{-1} yr^{-1}). Both DRP and total P varied among fields (figure 2). Background annual DRP export associated with grazing as reported by Kuykendall et al. (1999) was less than 1 kg P ha^{-1} y^{-1} (0.9 lb P ac^{-1} yr^{-1}). In our study, with applied broiler litter on pasture systems, average annual DRP export was in some cases greater than 4 kg P ha^{-1} y^{-1} (3.6 lb P ac^{-1} yr^{-1}), which is nearly as high as that reported by Pierson et al. (2001) for pastures in the Southern Piedmont receiving high rates of broiler litter application.

Unexpectedly, neither STP nor annual DRP export was related to the amount of manure applied ($p > 0.05$) (figure 3). Mean DRP export was generally greatest from the fields in pasture management (triangles in figure 3b) and smallest for fields in hay management, regardless of nutrient inputs (circles in figure 4). Mean DRP export associated with applied broiler litter and dairy slurry was intermediate. Soil P values taken in the contributing area of each runoff collector during each year were regressed against annual export of DRP (figure 4) and total P (data not shown). In this case, soil P levels were not significantly related to annual export of DRP ($p > 0.05$) (figure 4) or total P in runoff ($p > 0.05$). Additionally, soil P levels at points A, B, and C along the flow path length of the contributing area were each regressed against measured P export in runoff and generally were not related to annual export of DRP in runoff.

Georgia P Index. The Georgia P Index was used to calculate the risk of P loss for the contributing areas of each runoff collector

Figure 3
(a) Mean Mehlich-1 soil test phosphorus (P) and (b) mean dissolved reactive phosphorus (DRP) export as related to applied manure P (evaluated for each runoff collector contributing area annually).



Note: Field and management descriptions can be found in table 1.

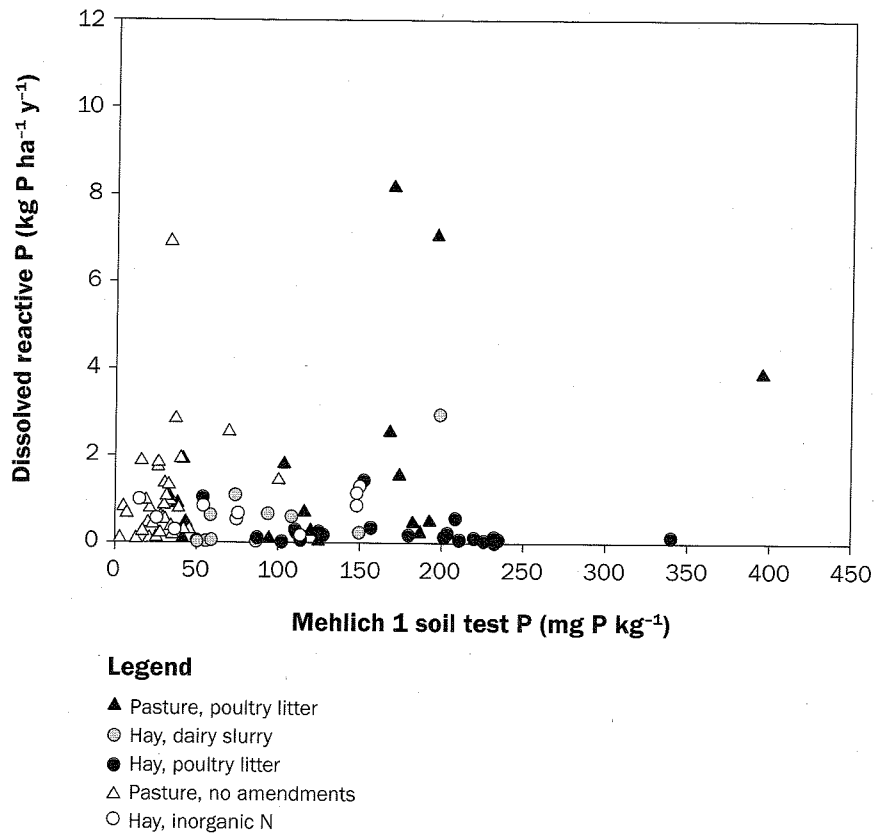
(28) for each of the four years of the study. Applications of manure P used as inputs along with soil, management, and landscape data collected are presented in table 2. Averaged across fields, risk ratings calculated by the P Index were predominantly in the low risk category (index < 40). Using a limit of 1 mg P L^{-1} (1 ppm) for direct discharge into streams (which is an acceptable concentration of P discharge from waste water treatment plants directly to streams), an annual runoff volume of 180 mm y^{-1} (7 in yr^{-1}) (Kuykendall et al. 1999), and a 15 m (49.2 ft) buffer strip to the stream, calculations place an acceptable level for edge-of-field losses at 4 kg P ha^{-1} y^{-1} (3.6 lb P ac^{-1} yr^{-1}). A 15 m buffer or riparian area has been shown to reduce the P load from the "edge-of-field" to the stream by at least 50% (Heathwaite et al. 1998; Osborne and Kovacic 1993). Therefore, an edge-of-field loss of 4 kg P ha^{-1} y^{-1} (3.6 lb P ac^{-1} yr^{-1}) would be reduced to 2 kg P ha^{-1} y^{-1} (1.8 lb P ac^{-1} yr^{-1}), which corresponds to an approximate flow-weighted concentration of 1 mg P L^{-1} in the discharge to the stream.

Phosphorus Export as Compared to the Georgia P Index. The risk rating calculated for each runoff collector and each year by the Georgia P Index was regressed against annual export of DRP and total P. Given that particulate and organic P can also contribute to bioavailable P in surface waters, total P was also examined for relationships to the Georgia P Index. However, because there was generally a consistent proportion of total P represented by DRP (figures 2, 5, and 6) and because the relationship between total phosphorus and the Georgia P Index was similar to that of DRP and the Georgia P Index, this paper will focus on DRP rather than total P. There were significant linear and quadratic relationships between annual export of DRP in runoff and Georgia P Index values (p = 0.018 and p = 0.001, respectively), although r^2 values were low (0.06 and 0.13, respectively). Regressions were also examined after eliminating data points for pastures with no amendments, which improved both the linear and quadratic relationships slightly (p = 0.0013 and 0.0007; r^2 = 0.16 and 0.22, respectively).

With one exception, DRP export values (figure 5a and 6a), were below 7.5 kg P ha^{-1} y^{-1} (6.7 lb P ac^{-1} yr^{-1}), which is equivalent to medium and low P export. All cases or points were also rated as low or medium risk of P export by the Georgia P Index. This

indicates that the Georgia P Index did function as intended in estimating whether fields are at a high risk of P export and if the fields under question would necessitate a change in management. However, when considering pastures with no amendments (figure 5) compared to the other management scenarios in which P loss is lower (than pastures with no amendments) yet the risk is higher (figure 6), further modifications to this P Index could be considered. Fields under hay management had very low levels of annual DRP export (generally <2 kg P ha^{-1} y^{-1} [1.8 lb P ac^{-1} yr^{-1}]), despite having risk ratings higher than fields under pasture management with no amendments (figure 5 and 6). Modification of the Georgia P Index to account for lower risk from fields under hay management rather than pasture management may need to be considered. Currently, differences in pasture and hay management can be accounted for in the Georgia P Index by larger curve numbers and greater soil erosion estimates, which can be associated with the impacts of grazing livestock. Underestimation of P loss from pastures with low soil P and no amendments likely results in an estimated low risk of excessive runoff P in several state P indices primarily due to a minimal source factor.

Figure 4
Mean annual dissolved reactive phosphorus (DRP) export as related to mean Mehlich-1 soil test P (evaluated for each runoff collector contributing area).



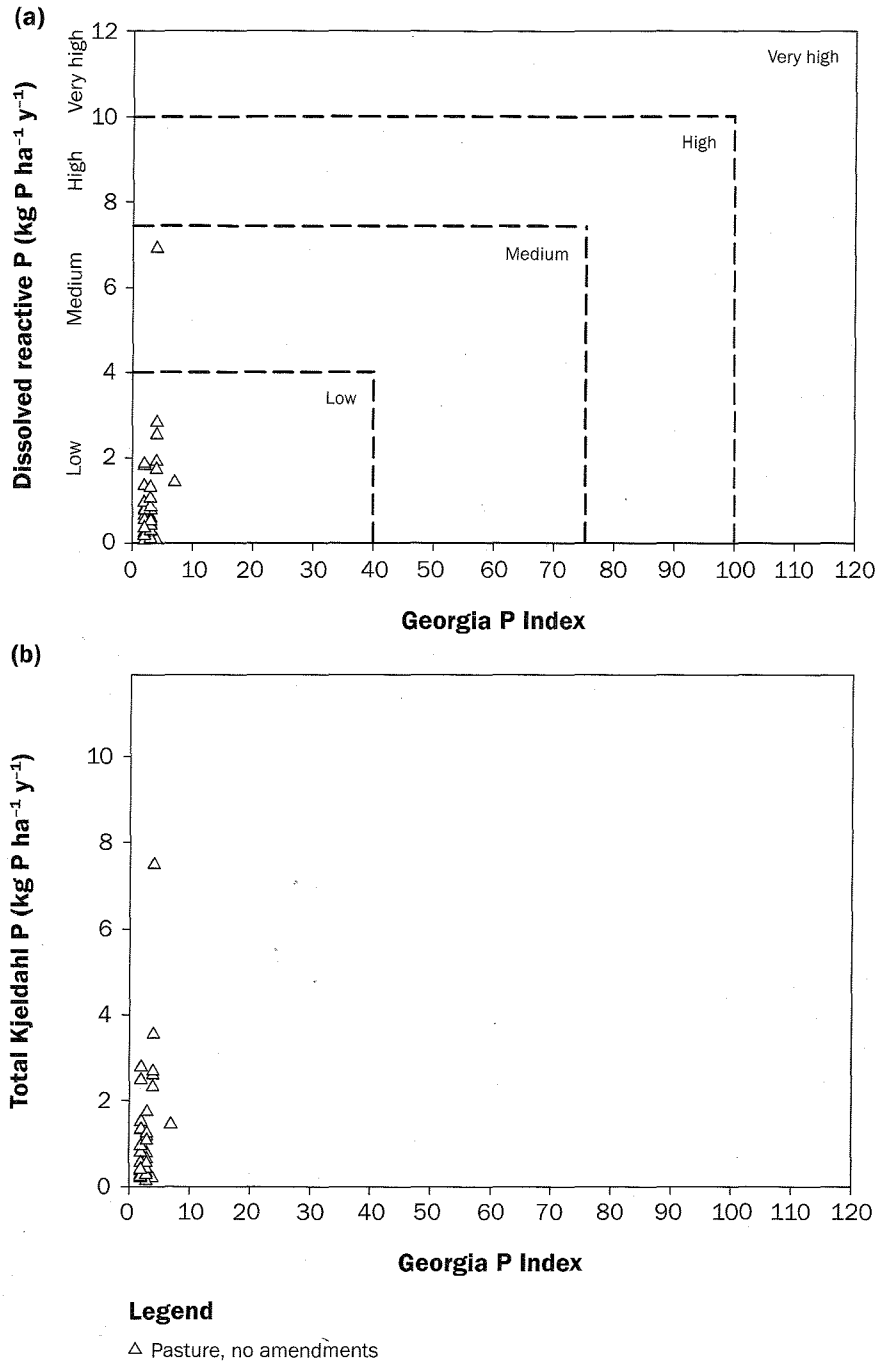
Pasture Management. It has been reported that fertilized pastures can be more productive and can carry more animals per given area (Burns and Fisher 2008), which suggests more biomass production (both plant and animal) and more feces deposition. In this study, the stocking density averaged over four years (2004 to 2007) was 1.6 animal unit (au) ha^{-1} (0.68 au ac^{-1}) with a range of 1.3 to 1.8 au ha^{-1} (0.54 to 0.72 au ac^{-1}) for unamended pastures, and 3.9 au ha^{-1} (1.6 au ac^{-1}) with a range of 2.0 to 5.4 au ha^{-1} (0.83 to 2.2 au ac^{-1}) for pastures fertilized with broiler litter. Clearly, amended pastures were carrying more animal units. Using data from similar farming systems in Arkansas (Sharpley et al. 2009), we estimated that P deposition by grazing animals was 12 kg P ha^{-1} (13.4 lb P ac^{-1}) in unamended pastures and 28 kg P ha^{-1} (31.6 lb P ac^{-1}) in pastures fertilized with broiler litter. Considering the high stocking densities and high soil P values, one is inclined to expect high P losses in runoff from pastures with applied broiler litter rather than pastures with no amendments, yet with the exception of 2004, P losses from both systems were comparable (compare fields A, B, and C with fields E and F in figure 2). This indicates that there are other ecological (environmental and phytological) factors at play.

Increased stocking density and cattle loafing have been shown to decrease infiltration and vegetative cover (Butler et al. 2007; Warren et al. 1986) and to increase N and P losses from grasslands (Mundy et al. 2003). At the same time, a well-fertilized plant can utilize more N and P through denser, larger root systems and more biomass, which could then reduce soil P and the source factor. Studies have also shown that decreased pasture mass or decreased pasture height increased P losses in runoff (Mundy et al. 2003). In this study, stocking density alone did not suggest higher P losses, which indicates that pasture management likely played a role. Animals were continuously grazed, and the grazing pressure was high in all cases; however, animals in the pastures with no amendments tended to congregate more on the lower side of the fields (closer to streams in concentrated flow areas) where soils were moister and cooler and where more shade was available because of shaded riparian areas. When loafing occurs in these areas, feces and urine deposition is concentrated in these lower portions of the pasture rather than evenly dispersed across the pasture. Whether plant biomass is less because of fertility or stocking densities, past research suggests (as do the results from this research) that further consideration to P losses in relation to grazing animal stocking density and pasture management (especially standing biomass) should also be given in P indices.

Of the 95 total observations of the Georgia P Index and annual DRP export, 15 were calculated in the medium risk category (Georgia P Index value > 40 [16%]), and 80 were calculated in the low risk category (84%). Of the 80 observations in the low risk category, all but 1 (99%) also exhibited what can be classified as low total annual export of DRP (<4 kg P ha^{-1} y^{-1} [<3.6 lb P ac^{-1} yr^{-1}]) (figures 5 and 6). Of the 15 observations in the medium risk category, all but 1 (94%) exhibited low to medium annual DRP

Figure 5

(a) Mean annual dissolved reactive phosphorus (DRP) export and (b) mean annual total Kjeldahl phosphorus (P) export as related to the Georgia P Index for fields managed as pasture with no nutrient amendments (evaluated for each runoff collector contributing area).



export (<7.5 kg P ha^{-1} y^{-1} [<6.7 lb P ac^{-1} yr^{-1}]) (figure 6). The outlying observations both occurred under pasture management. This is likely related to decreased cover in pasture systems as a result of grazing, as well as soil compaction and deposition of feces and urine by the grazing livestock in close proximity to the runoff collector. Additionally, many of the runoff collectors were placed at the field edge in concentrated flow paths, where the ground was cooler and more likely to be shaded and thus likely to be areas where cattle tended to congregate (Belsky et al. 1999). These lounging areas are often characterized by reduced forage ground cover, increased compaction, and greater deposition of feces and urine, resulting in larger edge-of-field P losses (Butler et al. 2008b).

Phosphorus Concentration as Compared to the Georgia Phosphorus Index. When examining annual flow-weighted concentrations of DRP versus Georgia P Index risk ratings, a somewhat similar picture emerges (figure 7). If we consider "low" concentrations to be those discharging below 1 mg P L^{-1} directly to the stream or 2 mg P L^{-1} at the edge-of-field, 23 observations were greater than the 2 mg P L^{-1} concentration considered to be "low" for edge-of-field loss. Of these 23 observations, 15 were placed into the low risk category by the Georgia P Index. The Georgia P Index underrated the risk in 16% (15 of 95) of the cases when considering flow-weighted concentrations and in only 2% (2 of 95) of the cases when considering loads or mass losses of P. This finding implies that runoff from smaller volume runoff events had higher P concentrations and that larger events resulted in more dilute P losses, which was not unexpected.

Eight of the 15 flow-weighted concentrations that were above 2 mg P L^{-1} and that were placed into the low risk category by the Georgia P Index were in the management classification pasture with no amendments (figure 7). These elevated concentrations may have been at least in part due to cattle loafing in low-lying areas at the lower edges of fields near the runoff collector, as mentioned previously. At this level of management (fenced riparian areas, low P soils, and no amendments) the land owner has only a few options. A potential management scheme or option might be rotational grazing that is timed so as to not allow cattle in critical source or vulnerable areas during periods when runoff is likely or during seasons when heat and humidity force animals to areas close to the stream. However, farms that have not had amendments applied are often indicative of limited available resources (money, time, and/or labor). Because of this, a change to the P Index may not be judicious nor feasible for these low-resource farms. Rather the findings of this on-farm field-scale research entreat further innovative management practices. Management practices that move cattle uphill and away from high risk or critical source areas and that are not money or labor intensive may be the most effective for minimizing the

risk of P losses, distributing nutrients around the entire pasture for efficient nutrient use, and distributing cattle traffic for efficient forage use.

Summary and Conclusions

Results from the on-farm, field-scale data in this study suggested that the Georgia P Index worked well in classifying the risk of P export from the farms monitored when considering loads. Monitored fields generally exhibited rather low to moderate levels of annual P export (<7.5 kg P ha^{-1} y^{-1} [6.7 lb P ac^{-1} yr^{-1}]) and were classified by the Georgia P Index into low or medium risk categories that did not suggest a change in management to reduce the risk of P loss. In just 2 of 95 observations (2%), the level of DRP export was greater than the risk rating calculated using the Georgia P Index. However, when considering concentrations a somewhat different picture emerges. The Georgia P Index underrated the risk in 16% of the cases when considering flow-weighted concentrations and only 2% of the cases when considering mass losses of P, partly as a result of low annual runoff volumes from some fields. The findings of this research indicate that simplification of P indices or risk assessment tools to one factor or trigger of risk may not be indicative of potential risk. In this study, we found that soil P concentrations as a stand-alone-indicator of P losses were inadequate as indicators of P loss in runoff and that management of vegetation, nutrients, and cattle all impact P losses in runoff.

Results from this study also indicated that with similar manure applications and soil P concentrations, there was lower risk of P losses from hay systems than from pastures—even more so than indicated by the Georgia P Index. This implies that hay management rotation can be used to remediate pastures or croplands high in soil P to prevent excessive loss of P to aquatic systems. Future research examining farms with a higher nutrient status that would place them in a higher category of risk for export of P would be useful in further evaluating the performance of the Georgia P Index in pastures and hayfields.

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Figure 6

(a) Mean annual dissolved reactive phosphorus (DRP) export and (b) mean annual total Kjeldahl phosphorus (P) export as related to the Georgia Phosphorus Index for fields managed as pasture with applied broiler litter or fields under hay management (evaluated for each runoff collector contributing area).

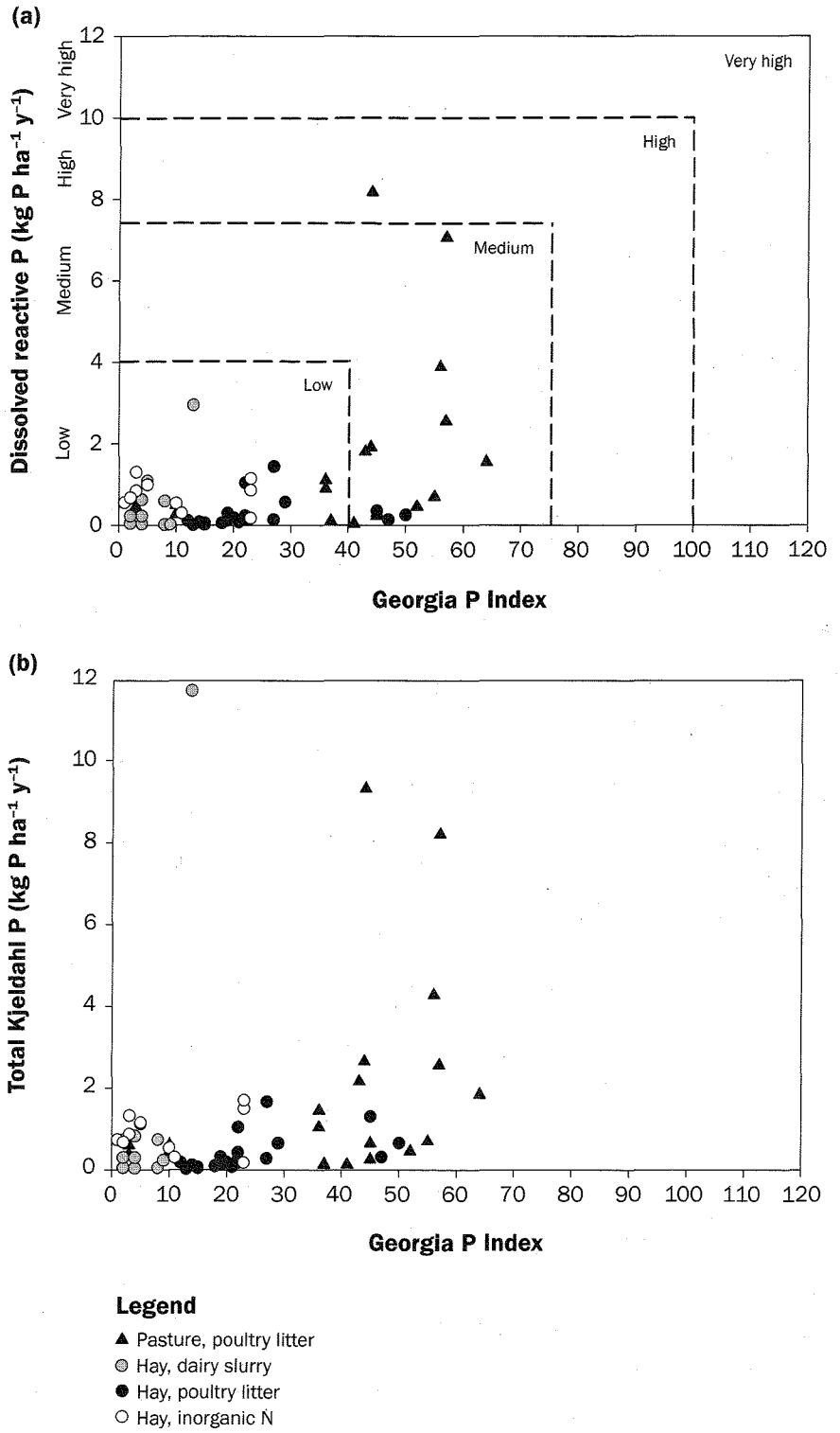
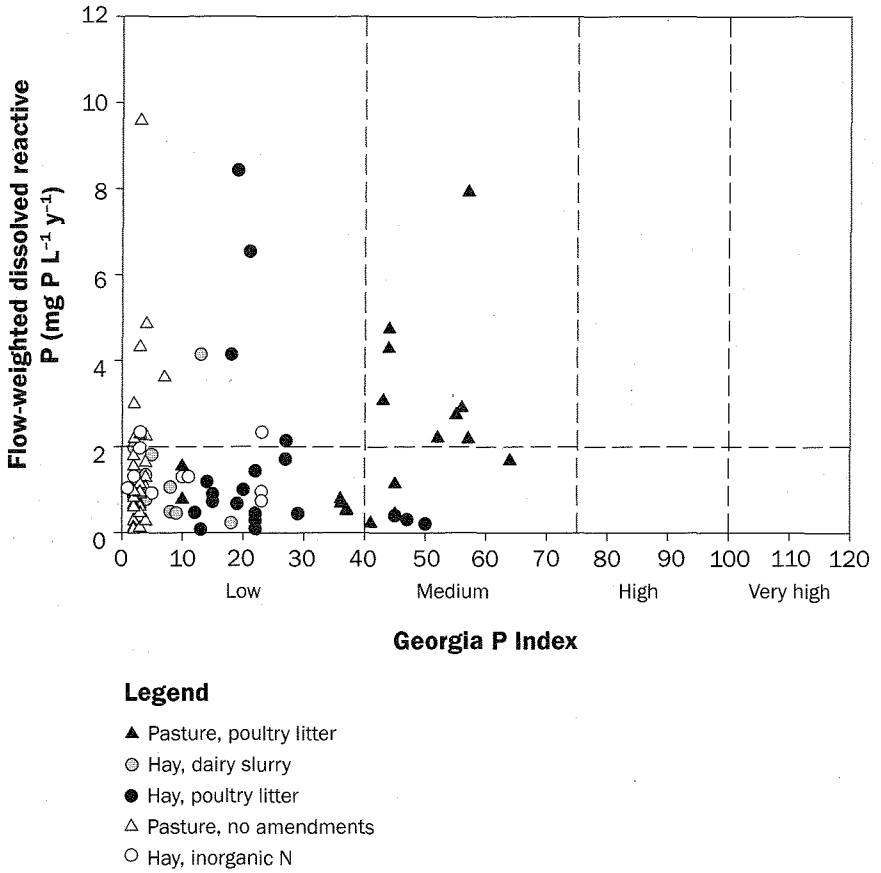


Figure 7

Mean annual flow-weighted dissolved reactive phosphorus (DRP) concentrations as related to the Georgia Phosphorus (P) Index (evaluated for each runoff collector contributing area). The dashed line at 2 mg P L^{-1} y^{-1} represents concentrations considered to be "low."



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