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Phosphorus export by runoff from agricultural field plots with different crop cover in Lake Taihu watershed

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Abstract: Runoff and soil losses from agricultural fields are investigated as major nonpoint sources of phosphorus (P) entering lakes of Eastern China. There is relatively little information on P transport from ricefield and cropland of Lake Taihu watershed in Eastern China. Soil and P in surface runoff from a series of plots in the watershed were evaluated under simulated rainfall conditions. The objectives of this study were to evaluate the effects of crop cover, slope, and fertilizer application on P concentrations in surface runoff and eroded soil. Accumulated sediment yields varied from 7.1 to 300 g/m^2 for croplands, depending on management practices. For all experiment plots, weighted average concentrations of total-P (TP), dissolved P (DP) and particulate P (PP) are much higher than 0.02 mg/L, the limiting concentration for lake water. This result showed the potential contamination of lake water from agricultural surface runoff. Accumulated TP losses were 3.8 and 18.8 mg/m^2 for ricefield and cropland, respectively. The estimated annual loss of TP was 0.74 kg/(hm^2·a) for cropland. Most of P loss is in the PP form, which accounts for more than 90% of TP loss for cropland.

Keywords: cropland; phosphorus; ricefield; sediment; surface runoff; Lake Taihu

Introduction

Water eutrophication is one of the global environmental problems, and agricultural nonpoint source pollution has been given increased attention (Sharpley, 1994; Harris, 1995; Tiessen, 1995; Tonderski, 1996; Daniel, 1998). Lake eutrophication has been identified as a critical problem of surface water quality of China. Agriculture is the major source of nutrients in lakes, accounting for more than half the total load (Tu, 1990; Jin, 1990). Because phosphorus (P) is the limiting factor of eutrophication of water bodies (Fox, 1993; Lean, 1973), input of P in agricultural surface runoff may accelerate the eutrophication of P-sensitive surface waters (Sharpley, 1987; Krogstad, 1989). On the other hand, annual application of P fertilizer has resulted in elevated levels of P in soil and an increase of P concentration in lakes and rivers of China (Yan, 1999a; Duan, 2000). High soil P problems are often aggravated by bothering with P-sensitive waters of China, such as Taihu Lake, Chaohu Lake, Baiyangdian Lake, and Bohai Bay. Therefore, the water eutrophication caused by P transport from agricultural fields is rather serious in China.

China is the largest producer and consumer of mineral fertilizers in the world. However, there are few data concerning the contamination caused by over-applied fertilizers. Recently, China National EPA launched a national water pollution control project to improve water quality in "three lakes and three rivers" during "the 9th 5 - year plan", and to target long-term planning on lake eutrophication control in China by 2010. However, information on processes, mechanisms and influencing factors of P transport from agricultural lands to waters is minimal in China. This study reports P loss from different agricultural fields under simulated rainfall conditions in an experimental lake watershed of Eastern China.

1 Experimental site

Studies were conducted in an experimental lake watershed - Lake Taihu watershed. Lake Taihu, one of the five largest freshwater lakes in China, is located in Eastern China (30°55′ - 31°33′N and 119°53′ - 120°36′E) on a tributary of the Yangtze River and covers a surface area of about 2340 km^2. Like most of the lakes in eastern and central China, Lake Taihu is quite shallow, with an average depth of only 2.0m. In the recent modernization process, with rapid industrial development and heavy application of fertilizers, nutrient-rich waters have drained increasingly into the lake, causing unprecedented water eutrophication. For most of the area around the Lake Taihu, a triple cropping system consisting of early rice, late rice, and oilseed rape is adopted in the irrigated rice fields. Nonirrigated farmland is normally cultivated with wheat (*Triticum aestivum* L.), cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogaea* L.), soybean (*Glycine max* L. Merr.), and other vegetables. Similar to most of the areas in Eastern and Central China, chemical fertilizers are increasingly applied in the watershed. Fertilizer applications were 1200 kg/hm^2 of NH_4HCO_3 (17.7% of N), 300 kg/hm^2 of $CO(NH_2)_2$ (46.7% of N), and 600 kg/hm^2 of $Ca(H_2PO_4)_2$ (14.0% of P_2O_5) for rice production. In addition, there were 600 kg/hm^2 of NH_4HCO_3, 200 kg/hm^2 of $CO(NH_2)_2$, and 400 kg/hm^2 of $Ca(H_2PO_4)_2$ for wheat, oilseed rape, and other crops. Normally, fertilizers are surface-applied by hand. The 30 year mean annual precipitation is 1100 mm/a, with average intensity of rainfall events of 70 mm/h. Most heavy rainfall occurs in April through September each year.

2 Methods

Field experiments under simulated rainfall conditions were carried out to study P loss from agricultural lands from July 16

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to 28, 1998 at Jurong County of the Lake Taihu watershed. Six field plots, each 2 × 5 m in dimension, were established in the watershed. A detachable protective extension with 50 cm in height was placed in the other three sides of each plot to prevent rain and runoff water from splashing and moving between the outside and inside of plots. Plot descriptions are listed in Table 1. A sprinkling device for the simulated rainfall, developed and described by Luk *et al*. (Luk, 1986), was used to supply water to these plots. This simulator delivers rainfall with 90% of the kinetic energy of natural rainfall and a comparable drop size distribution. Surface runoff rates were determined by taking timed volumetric samples of the water discharge with type V flumes, equipped with plastic containers in the lowest side of the plot. Samples were collected at 3 min intervals. After sampling, water and sediment were vigorously stirred. Following that, 200 ml aliquots from each water sample were digested with $K_2S_2O_4$ solution and analyzed for total phosphorus (TP), additional 200 ml aliquots from each sample were filtered through 0.45 μm pore-size glass fiber filters, and analyzed for dissolved phosphorus (DP) and PO_4^{3-} (DRP). The method of Murphy and Riley (Murphy, 1962) was used for all P determinations. Sediment phosphorus or particulate phosphorus (PP) was calculated as the difference between TP and DP. Dissolved organic phosphorus (DOP) was calculated as the difference between DP and DRP. Sediment concentration was determined in duplicate as the difference in weights of 250 ml aliquots of unfiltered and filtered samples after evaporation to dryness at 378K. Contents of P in the applied water were subtracted from the contents in runoff to estimate the net loss in runoff. Before each rainfall, the soil was sampled to a depth of 50 mm in the plot and analyzed for physical-chemical properties (Table 2 and Fig. 1). Enrichment ratios were calculated by dividing P contents of sediment by P contents of the top 50 mm source soil.

Table 1 The selected plot information

Plot No.	Crop	Crop height, cm	Crop cover, %	Slope, %	Moisture content of soil before rain, %	Fertilizer applied
A	Rice	40	90	0 - 1	Submerged	No*
B	Rice	40	90	0 - 1	Submerged	Yes**
C	Fallow	10	10	0 - 1	23.4	No
D	Cotton	90	80	7 - 8	21.0	No
E	Cotton	70	80	0 - 1	19.1	No
F1#	Maize	100	35	0 - 1	12.0	No
F2#	Maize	100	35	0 - 1	18.2	No

: Same plot with different rainfall intensity; * : no fertilizer added before rainfall;
** : fertilizer rate at 0.6 kg $Ca(H_2PO_4)_2$ before rainfall

Table 2 Characteristics of soils in the selected plots

Plot No.	Soil type	Texture class	OM, %	CEC, me/100g	Density, g/cm³	TP, mg/kg	Bioavail. - P*, mg/kg	Particle-size distribution, % Clay(< 2μm)	Silt(53 - 2μm)	Sand(> 53μm)
A	Paddy soil	Clay	1.52	14.88	1.54	197.7	24.1	54.1	39.2	6.7
B	Paddy soil	Clay	1.52	14.88	1.54	197.7	24.1	54.1	39.2	6.7
C	Yellow brown soil	Clay loam	1.29	16.03	1.67	336.1	29.3	47	45.8	7.2
D	Yellow brown soil	Clay loam	1.29	16.03	1.67	336.1	29.3	47	45.8	7.2
E	Yellow brown soil	Clay loam	1.29	16.03	1.67	336.1	29.3	47	45.8	7.2
F1	Yellow brown soil	Clay loam	1.21	12.55	1.45	458.6	52.4	48.2	44.5	7.3
F2	Yellow brown soil	Clay loam	1.21	12.55	1.45	458.6	52.4	48.2	44.5	7.3

* $NaHCO_3$-extractable P

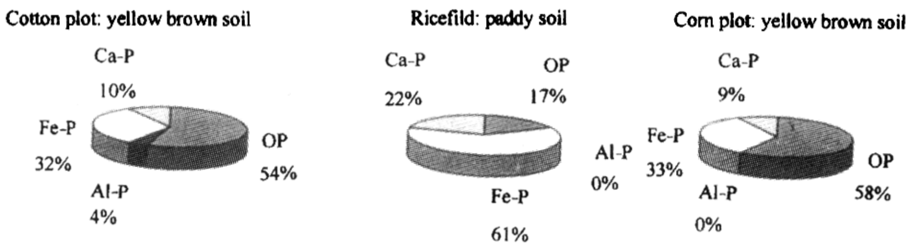

Fig. 1 Phosphorus forms in source soil of Taihu Lake watershed

3 Results and discussion

3.1 Discharge and sediment yield

Rainfall-runoff relationship for 6 field plots is given in Table 3. There is a significant difference ($p = 0.05$) at time when runoff occurs for different plots under simulated rainfall conditions. Runoff starts about 110 and 130 seconds after the beginning of simulated rainfall for plot C and D, respectively, suggesting that crop cover and slope are important factors influencing runoff occurring time. In contrast with plot C and D, there is a longer interval between the beginning of rainfall and the start of runoff for plot A (17 min 5 second) and B (10 min 37 second). This is because the ricefield ridges retained rainfall water until rainfall caused the ridge mouth to overflow. Accumulated runoff and sediment yields are shown in Fig. 2 and 4, respec-

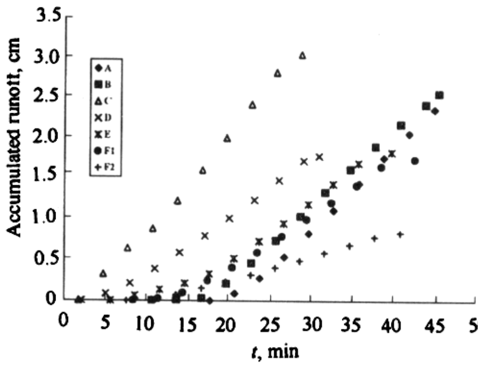

Fig.2 Accumulated runoff from each plot under simulated rainfall conditions

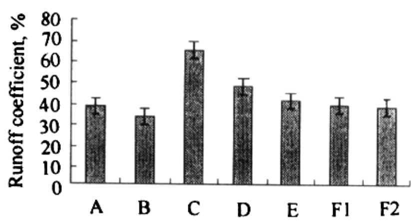

Fig.3 Runoff coefficient (discharge/precipitation × 100%) for the tested plots

tively. As shown in Fig. 2, there is a significant difference in runoff ($p = 0.05$) among different plots. Runoff from plot C is greater than that from any other plot. Plot C is fallow land, with < 10% soil surface covered by plant. This result showed that the less the surface crop cover is, the greater the runoff yields. Besides plot C, plot D also had high runoff due to its greater slope, while plot F2 had the least runoff among all the plots. Crop cover, slope and rainfall intensity are the main factors influencing runoff volumes. Mean volumetric runoff coefficients (total runoff as a percentage of total rainfall) (Fig. 3) were 38.7, 33.5, 65.4, 48.1, 41.4, 39.0 and 37.8 for plot A, B, C, D, E, F1 and F2, respectively. Thus, in the rainfall simulation experiments, the runoff from different fields within the watershed was very high. Sediment yield had a similar pattern to runoff (Fig.4). Plot D yielded the greatest sediment among all the plots, about 300g/m^2. Plot C also had a great sediment loss, about 43 g/m^2, while plot F2 had the least sediment loss, about 7.1 g/m^2. These results suggest that slope, crop cover, and rainfall intensity are the key factors influencing sediment yield.

3.2 Phosphorus loss

Volume-weighted mean concentrations of all phosphorus forms (TP, DP, PP, DRP and DOP) in surface runoff for each plot are presented in Table 4. Phosphorus concentrations in surface runoff varied with different plots. No relationship was found between discharge and the concentration of TP ($r = 0.51$) in water surface runoff (Fig. 5a). This observation is consistent with the results of Yan *et al*. (Yan, 1998) obtained from a 732 hm^2 agricultural watershed planted with rice, wheat, cotton and other crops; and McDowell *et al*. (McDowell, 1989) obtained from the study of a watershed planted with cotton. Likewise, no rélationship was observed between discharge and the concentration of PP ($r = 0.51$) in runoff (Fig. 5b). Phosphorus concentrations were higher in the runoff from plot B than any other plot, which had average concentrations of 3.69 mg TP, 2.99 mg DP, 0.70 mg PP, 2.64 mg DRP and 0.36 mg DOP L^{-1} (Table 4). Phosphorus concentrations in the runoff from plot B, as a result of fertilizer application (60g $Ca(H_2PO_4)_2/m^2$) before the rainfall, were about 10 times greater than that from plot A. This observation is consistent with the result of Yan *et al*. (Yan, 1999b), suggesting that P was readily transported by surface runoff from ricefields within 7 - 10 days after surface application of fertilizer. For cropland plots (plot C - F2), plot D had the highest average concentrations of 9.463 mg TP, and 9.434 mg PP L^{-1}, but the lowest average concentrations of 0.029 mg DP, 0.006 mg DRP and 0.023 mg DOP L^{-1}.

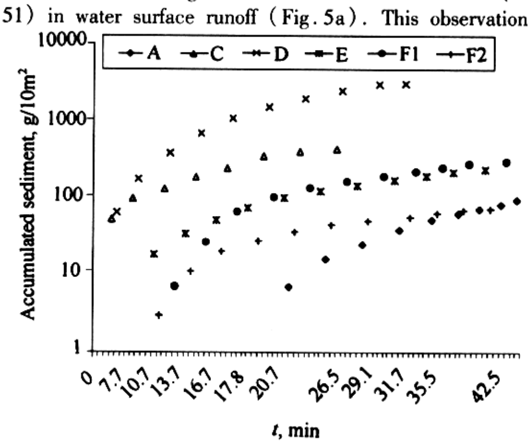

Fig.4 Accumulated sediment loss from each plot, sediment from plot B was not measured

Table 3 Rainfall-runoff information for all the plots

Plot No.	Mean rainfall intensity, mm/min	Total rainfall, mm	Time when runoff occurs	Rainfall time	Runoff time	Runoff volume, mm	Sediment load, g/10m^2
A	1.37a*	61.1	17′5″	44′50″d	44′50″g	23.7n	93.2
B	1.75b	76.4	10′37″	43′47″d	45′20″g	25.6n	
C	1.75b	46.6c	1′50″	26′50″e	31′15″h	30.5	425.9
D	1.28a	37.4	2′10″	29′5″e	31′h	18.0s	2989.5
E	1.25a	44.7c	5′40″	35′40″f	39′40″m	18.5s	233.2
F1	1.17a	45.0c	8′30″	38′30″f	42′30″m	17.6s	294.3
F2	0.60	22.5	7′40″	37′40″f	40′50″m	8.5	71.5

* No significant difference at 0.05 level with the same letter

Table 4 Mean concentration of P in surface runoff

Plot No.	TP, mg/L	DP, mg/L	PP, mg/L	DRP, mg/L	DOP, mg/L	DP/TP, %	DRP/DP, %
A	0.159	0.063	0.096	0.025	0.038	40.0	39.7
B	3.693	2.992	0.701	2.635	0.357	81.0	88.1
C	0.971	0.052	0.919	0.016	0.036	5.4	30.8
D	9.463	0.029	9.434	0.006	0.023	0.3	20.7
E	0.735	0.032	0.703	0.007	0.025	4.4	21.9
F1	1.160	0.058	1.106	0.012	0.046	5.0	20.7
F2	1.326	0.066	1.260	0.020	0.046	5.0	30.3

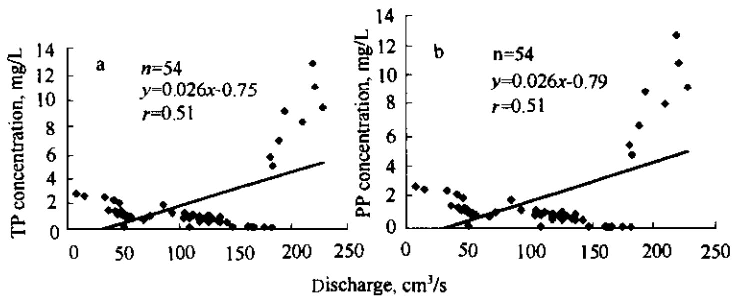

Fig.5 Relationship between the concentration of a(TP), b(PP) and discharge of runoff

The proportions of P forms in runoff also varied with different plots. DP concentration accounted for 40% of the TP lost from plot A, and DRP accounted for 40% of the DP in the runoff. However, DP accounted for 81% of the TP lost from plot B, and DRP was 88.1% of the DP in the runoff. In contrast with plot B, DP concentration accounted for less than 6.0% of the TP lost from cropland plots, demonstrating that most of P loss happened to the particulate P form during the runoff period. DRP accounts for 20% – 30% of DP, showing that dissolved organic P dominates dissolved P in runoff from cropland fields (Table 4). The higher yield of dissolved organic P (more than 70% of DP) from cropland plots was largely derived from organic fractions of P in the soil and most inorganic P was strongly adsorbed by Fe oxides and Ca minerals (Fig.1). The TP and PP concentrations had close relationships with sediment concentration (for both TP and PP, $r = 0.97$) (Fig.6a and 6b), which is consistent with the results of Kronvang (Kronvang, 1992) and Ng *et al*. (Ng, 1993). The close correlation between sediment and PP suggests that P loss in particulate form (more than 90% of TP) is the major way of P transport method in agricultural runoff for most cropland in the watershed (Fig.7). One explanation is that iron-bound P constitutes a large portion of inorganic P in the cropland soil (Fig.1), and the Fe-P is very difficult to desorb and thus is carried away with the sediment by runoff. In addition, for all the plots, concentrations of TP, DP and PP are much higher than 0.02 mg/L, which is the critical concentration for lake waters (Hakanson, 1983; Schindler, 1977; Vollenweider, 1968). This result shows that agricultural surface runoff may potentially cause eutrophication of receiving waters such as Lake Taihu.

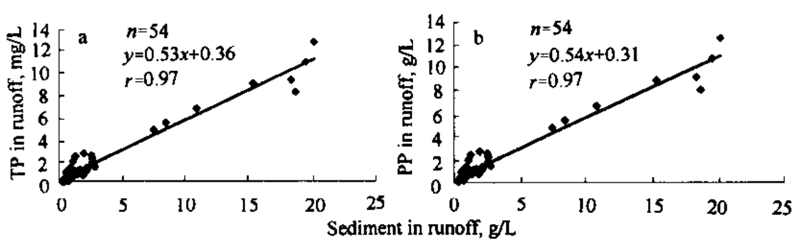

Fig.6 Relationship between a(TP), b(PP) and sediment of runoff

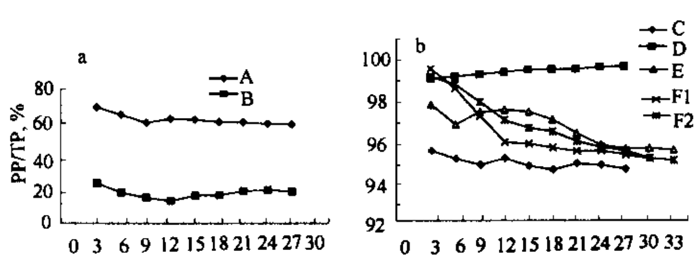

Fig.7 Yield of PP as a percentage of TP during the rainfall simulation experiment for each plot

Accumulated DP (Fig.8) and PP (Fig.9) losses varied greatly from plot to plot. Mean DP yields were 1.5, 64.8, 1.6, 0.5, 0.6, 1.0 and 0.6 mg/m^2 for the 7 plots (plot A-F2), respectively, under simulation rainfall conditions. Mean PP yields were 2.3, 15.9, 28.0, 174.8, 13.0, 19.5 and 10.7 mg/m^2 for the 7 plots, respectively. Compared with DP, PP loss was much greater for all the plots except for plot A2. The highest yield of TP was from plot D, which was related to the greatest sediment yields (300 g/m^2) in runoff and higher runoff coefficients (48.1%) of the plot. The total loss of 175.3 mg TP m^{-2} is about 35.8% of the available-P in the surface 10 mm of soil planted with cotton. This result showed that soil and P are more readily lost by runoff from cropland with slope > 7% than from other croplands with a smaller slope. The TP yield (80.7 mg/m^2) in runoff from plot B was 0.51% of added fertilizer P. However, TP yield in runoff from plot A was 3.8 mg/m^2, much lower than that from plot B, accounting for 1% of the $NaHCO_3$-extractable P in the surface 10 mm of the ricefield soil. The higher yield of TP from plot C resulted from higher P concentrations in runoff and the highest runoff coefficients (65.4%), as compared with other plots. The total loss of 29.6 mg TP m^{-2} is 6.1% of the available-P in the surface 10 mm of the fallow field soil, suggesting that soil and P are readily lost by runoff from the fallow lands. The relatively lower yield from plot F2 was due to the least runoff and the lowest sediment yields (7.1 g/m^2), despite its higher DP and PP concentrations in runoff (Table 4). The average TP yields for cropland plots (except for plot D) were 18.8 mg/m^2. Our rainfall simulations were performed during the summer season when rainstorms with a similar duration and intensity to the simulated rainfall (70 – 110 mm/hm^2 for 30 – 40 min) are very frequent in the watershed. To estimate annual loss of P from the croplands, we suppose an annual precipitation of 1100 mm under normal hydrological conditions and one fourth producing runoff similar to the simulation rainfall experiments. The calculated TP loss was 0.74 kg/(hm^2·a) for the croplands, which is 11.8% of the available-P in the surface 10 mm of soil in the watershed. Our data are consistent with the results of many researches obtained from other lake watersheds in Southern and Eastern China (Peng, 1988; Yan, 1998; Zhang, 1993). Equally high TP loss (0.9 and 1.15 kg/(hm^2·a)) was reported by Kronvang (Kronvang, 1992) from two agricultural basins in Denmark whereas appreciably lower TP loss was observed in a number of agricultural watersheds of Canada (0.047 – 0.46 kg/(hm^2·a); Dillon, 1975). Fig.7 shows the ratio of PP to TP at 3 min intervals throughout the rainfall simulation experiments. This ratio was consistently higher for cropland plots (mean > 90% of TP) than ricefield plots (mean < 60% of TP). For all the plots, this ratio tended to decrease slightly during the course of the experiments. Therefore, most of P lost from croplands was PP, which potentially constitutes a long-term source of bioavailable P in Taihu Lake.

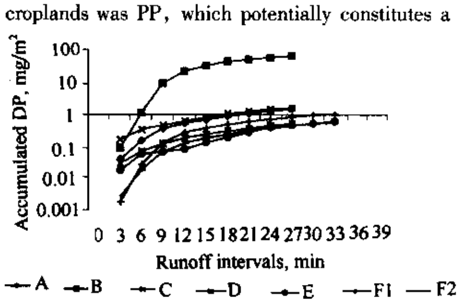

Fig.8 Accumulated DP in surface runoff from each plot

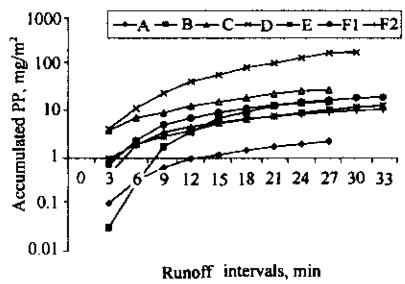

Fig.9 Accumulated PP yield of each plot

Sediment enrichment ratios (ER), defined as the ratio of sediment nutrient content to source soil nutrient content (Sharpley, 1980), were 1.23, 2.07, 1.70, 1.74, 1.52 for plot A, C, D, E, F1, respectively. The values of P ER were little variable among different cropland plots. The values of P ER were larger than 1, indicating that P enrichment occurred for sediment from all the plots. These P ratios are similar to P ER ratios reported by Sharpley (Sharpley, 1980), who used simulated rainfall (6 and 12 cm/h application rates) on Houston (fine, 4% and 8% slope) and Kirkland (fine, 4% slope) soils with 0 – 100 kg fertilizer P/hm^2. However, these values are much lower than those observed by Douglas, *et al*. (Douglas, 1998) from a 5 year (1980 – 1984) study of wheat-pea rotation in Northeast Oregon.

4 Conclusions

The rainfall simulation experiments showed that more runoff is generated from the fallow soils with less crop cover and more sediment is generated from croplands with slope > 7%. Accumulated sediment yields varied from 7.1 to 300 g/m^2 for the croplands. Accumulated TP losses were 3.8 and 18.8 mg/m^2 for ricefield and cropland, respectively. We estimated an annual loss of 0.74 kg/(hm^2·a) P for croplands under normal hydrological conditions. For all the plots, weighted average concentrations of TP, DP and PP in runoff were much higher than the critical concentration of 0.02 mg/L in lake waters, indicating that agricultural surface runoff has a great potential to cause lake eutrophication. Most P loss (more than 90% of TP) was associated with sediment, which had a P ER greater than 1. The large amount of PP may constitute a long-term source of potentially bioavailable P in Taihu Lake.

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