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Article

Phosphorus Budget for a Forested-Agricultural Watershed Influenced by East-Asian Summer Monsoon

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Abstract: Despite increased awareness of and attention to the need for sustainable agriculture, fertilizers and compost application in excess of crop requirements remain common agricultural practices in South Korea, causing eutrophication of freshwater and coastal ecosystems. In this study, a phosphorus (P) budget was developed to quantify P inputs, outputs, and retention in a forested-agricultural watershed. The P budget showed that chemical fertilizers and organic compost were the largest source of P (97.6% of the total) followed by atmospheric deposition (2.1% of the total P), whereas forest export (0.2% of the total) and sewage treatment plants (STPs) (0.1% of the total) were negligible. The dominant P outputs were crop harvesting and hydrologic export to surface water. The P balance showed a significant accumulation of P in the watershed; approximately 87% of the total P input was retained in the soils within the watershed. However, P concentrations in drainage water were still high enough to cause eutrophication of downstream reservoirs. The results provide useful information on the proportion of P export and retention in soils and will help support efforts to improve water quality and design better management of agricultural non-point source pollution.

Keywords: Phosphorus; nutrient budget; non-point source pollution; Korea; monsoon climate

1. Introduction

Anthropogenic impacts on the global phosphorus (P) cycle have been a major research topic in the field of P biogeochemistry, especially in agricultural ecosystems. Because of the increase in P fertilizer use during the last few decades, global P inputs from terrestrial to aquatic ecosystems have doubled and eutrophication remains a global issue [1,2].

Eutrophication is a serious environmental challenge in Korea and P export from agricultural fields has been identified as major contributor to non-point source (NPS) nutrient pollution [3]. The characteristic intense rainfall during the East-Asian summer monsoon dramatically influences the export of NPS derived nutrients from highland agricultural croplands in Korea [4]. Some studies have shown that P export from agricultural fields in Korea is higher than in other regions [3,4]. To ensure short-term productivity as well as long-term sustainability, minimizing P losses and achieving a balance between P inputs and P outputs in agricultural systems is important. P budget studies can

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help to identify the sources and fates of P, which are important for regional water quality issues. Improved knowledge of watershed P budgets can also help evaluate the impacts of agricultural practices on P accumulation and losses.

Using a mass balance approach to calculate P budgets is a commonly used approach in agricultural systems [5-8]. Continued accumulation of P in agricultural land beyond crop requirements may well become a long-term concern in Korea. Although there are many watersheds with mixed (forested and agricultural) land use distributed throughout most areas of Korea [9], no research has focused on constructing P budgets for these mixed land use watersheds. The current study was conducted in the Haean watershed, a sub-watershed located at the upper reaches of Lake Soyang (the largest reservoir in South Korea). The study area is an advantageous location for studying the watershed P budget because it has only a single outlet (Mandae Stream). Previous studies on NPS of sediment and nutrient have conducted in the Haean watershed and the watershed is known as a hot spot for soil erosion and export of NPS pollution to Lake Soyang [4].

The aim of this study was to construct a P budget for the 2013 growing season to quantify P inputs, outputs, and retention for the Haean watershed.

2. Materials and Methods

2.1. Study site and land use

The Haean watershed (longitude 128°50′ to 128°11′E and latitude 38°13′ to 38°20′N) is located in the Gangwon Province in the eastern region of Korea (Figure 1). The physical characteristics of the study watershed are shown in Table 1. The hydrologic characteristics of the watershed are strongly influenced by the East-Asian summer monsoon climate. Nearly 70% of the annual precipitation occurs in July and August [10]. Approximately 90% of the annual rainfall occurs during the April to October cropping season [11]. The 10 year (2004-2013) mean annual temperature in the Haean watershed is 10.9°C with a mean annual precipitation of 1506 mm.

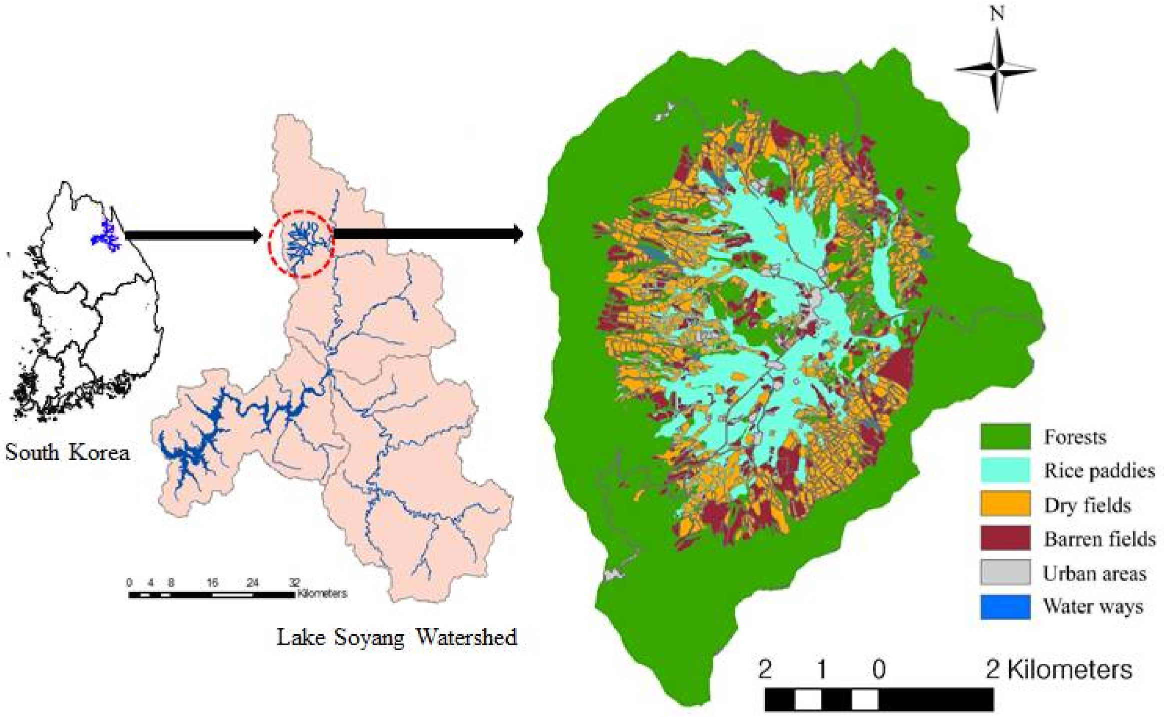

Figure 1. Location of the Haean watershed in eastern Korea and map showing the land use in the mixed-use watershed.

Table 1. Characteristics of the study watershed.

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Watershed	**Area (ha)**	**Population density (person/ha)**	**Elevation (m)**	**Slope (°)**	**% Coverage**				
					Forest	Crop	Urban	Other[1]	Total
Haean	6,174	0.23	340-1320	5-20	61.1	29.6	0.62	8.68	100

[1] Barren fields and water ways

The soils in the watershed are classified as Cambisols but most agricultural soils are Anthrosols due to the long-term use of soil amendments with sandy soil as a top dressing [12]. The study area is one of the largest highland agricultural areas in the Lake Soyang watershed [10]. Generally, in highland agricultural fields high value horticultural row crops such as potato, radish, cabbage and soybean are preferred over other crops [9]. In the study area, rice fields account for more than 30% of the agricultural land, while dryland crops (cabbage, potato, radish, soybean) account for approximately 52% of the agricultural land (Table 2) [13].

Table 2. Agricultural land use in the Haean watershed (2012) [13].

Croplands	**Area (ha)**	**Percent of the total (%)**
Annual		
Rice paddy	569	31.1
Cabbage	142	7.77
Potato	225	12.3
Radish	213	11.7
Soybean	163	8.92
Maize	52	2.84
Pumpkin	34	1.86
Perennial		
Orchard	85	4.65
Ginseng	82	4.49
Codonopsis	28	1.53
Peach	19	1.04
Grape	18	0.98
Others	198	10.8
Total	1828	100

A summary of local agricultural practices in the Haean watershed is shown in Table 3 [14]. Conventional tillage and seedbed preparation without surface cover are common agricultural practices in the Haean watershed. Some crops are planted with plastic sheets used as a mulch.

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Table 3. Local agricultural practices for the five most common crops accounting for about 72% of the total agricultural area in the Haean watershed and comparison between recommended fertilizer application rates by RDA (Rural Development Administration) and fertilizer applied by farmers [14].

Crop	**Cultivation period**	**Number of applications**	**Fertilizer application rates (kg P/ha/yr)**		
			Types	RDA Recommended	Applied
Rice paddy	Mid May – End October	1-2	Chemical	20	*78*
			Compost	-	*30*
Cabbage	End July – End October	1-2	Chemical	26	*64*
			Compost	19	*83*
Potato	End April – Mid August	1	Chemical	14	*55*
			Compost	13	*103*
Radish	End July – End September	1-3	Chemical	13	*37*
			Compost	19	*91*
Soybean	End May – End October	1	Chemical	13	*51*
			Compost	19	*92*

2.2. Sampling and chemical analysis

Crop (5-8 replicates from 1m^2 area for each crop) and soil (3-5 samples from 0-20 cm depth) samples were collected from randomly selected crop fields within the watershed at the time of final harvest. Immediately after separating the plant parts, the fresh weight (FW) of leaves, stems, roots, and grains were measured. Dry matter (DM) of plant parts was measured after oven drying at 80°C for 72 hours. A finely ground aliquot of each sample was analyzed for total phosphorus (TP) concentration [15]. Soil P concentration was measured using the modified Lancaster method [16]. Rainfall data were collected from a weather station maintained by the Korean Meteorological Administration (KMA). Twelve rainfall samples were collected using tipping buckets near a long-term monitoring site in a forested sub-watershed during the study period. TP concentration in rain water samples was measured using the ascorbic acid method [17].

2.3. Budget methodology

A mass balance approach was used to compare P inputs and P outputs and estimate annual P storage in the watershed in 2013 (Figure 2). To develop a more realistic budget, information on local agricultural practices and crop production were collected using a farm census. A total of 52 farmers involved in cultivating the major crops in the study watershed were interviewed during the study period. Data from the results of the farm census together with data from field and literature values were used to develop the P budget. Conceptually, P inputs to the Haean watershed were separated into two groups considered as anthropogenic (fertilizer application, sewage treatment plants) and background sources (atmospheric deposition, forest loading). P outputs from the Haean watershed were calculated using data on P concentrations from the crop harvest and hydrologic export to surface water.

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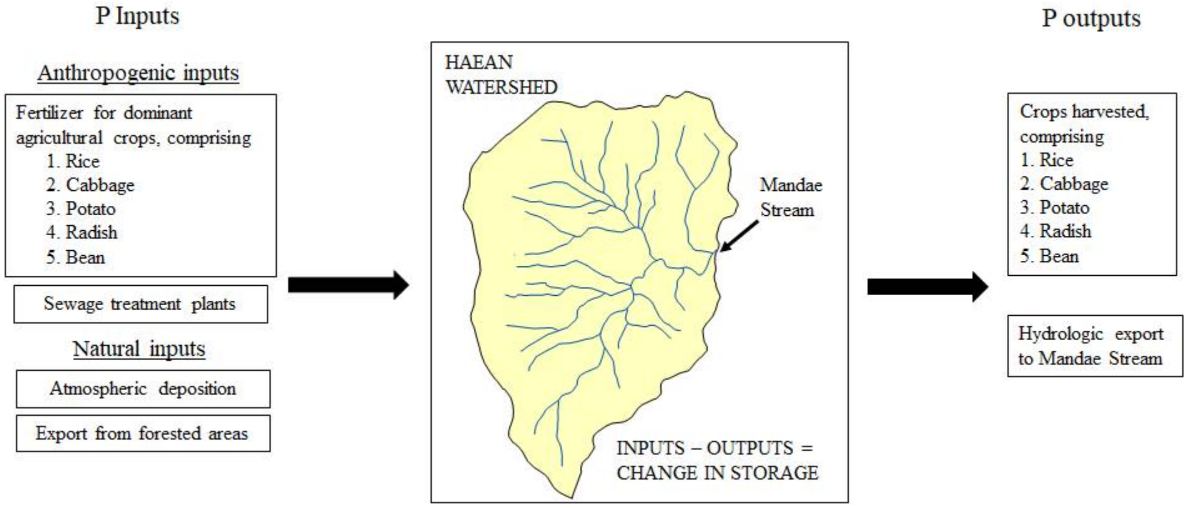

Figure 2. Schematic diagram of P inputs and outputs used to calculate the phosphorus budget for the Haean watershed.

2.3.1. P inputs to the Haean Watershed

- Inputs from fertilizer application

Interviews with farmers were conducted to collect information on fertilizer (chemical and organic compost) application rates. Fertilizer P content was obtained from data provided by the RDA and from previous studies [14, 18]. The total amount of P in fertilizer used in the Haean watershed was calculated by multiplying the rate of fertilizer application by the fertilizer P content and the agricultural land area for each crop and expressed as:

$$P_{Fert} = FA \times C_{Fert} \times A \qquad (1)$$

where P_{Fert} is the P input from the fertilizer (kg/yr); FA is the rate of fertilizer application (kg/ha/yr), C_{Fert} is the P content in fertilizer (chemical and organic compost) (%) and A is the agricultural land area for each crop (ha).

- Inputs from sewage treatment plants

Sewage treatment plants (STPs) are an obvious point source of P inputs. Though most of the study area is rural, three small STPs discharge treated wastewater in the Haean watershed. The outflow and TP concentrations were obtained from the managing authority [13]. The amount of P from STPs was calculated using the following equation:

$$P_{STP} = C_{STP} \times FR \qquad (2)$$

where P_{STP} is the P input from the STPs (kg/yr); C_{STP} is the average P concentration (mg/L) and FR is the average annual flowrate of the effluent (m^3/yr).

- Inputs from atmospheric deposition

In regions with sufficient rainfall, P inputs in through wet deposition is more important than dry deposition of P [19]. Therefore, P input from dry deposition was not considered in this study; input in wet deposition was estimated by the following approach [6]:

$$P_{Rain} = A\ \Sigma\ C_{Rain} \times V_{Rain} \qquad (3)$$

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where P_{rain} is P input from wet deposition (kg/yr), A is the watershed area (ha), C_{rain} is the average P concentration in wet deposition during the study period (mg/L) and V_{rain} is the 10 year (2004-2013) mean annual rainfall (mm/yr).

- Inputs from forested areas

The P input from forested land was considered as a background source. Due to the widely different sampling frequency for rain event and dry period samples, inputs from forested areas were estimated by summing the inputs during sampled and non-sampled rain events and dry period [20].

2.3.2. P outputs from the Haean Watershed

- Removal through crop harvesting

Crop production data were obtained from a local farm census. P removal from the Haean watershed was calculated by multiplying the measured P content in crop samples and the crop harvest estimated for each crop and expressed as:

$$P_{CH} = CP \times C_{CH} \times A \quad (4)$$

where P_{CH} is the P output through crop harvesting (kg/yr); CP is the crop production (kg/ha/yr), C_{CH} is the P content (%) and A is the agricultural land area for each crop (ha).

- Hydrologic export to Mandae Stream

To obtain an estimate of P export in surface water to Mandae Stream (the watershed outlet), the hydrologic export from an earlier intensive monitoring study conducted by the authors (2009-2013) was used [4].

3. Results

3.1. P inputs

3.1.1. Fertilizer application

The calculated annual P input from chemical fertilizer was 81,779 kg P/yr (47.8% of total P inputs). Organic compost supplied 86,640 kg P/yr (50.7% of total P inputs) to the Haean watershed. Among the five most common crops, fertilizer used in rice fields was found to be the largest contributor of P in the watershed followed by potato, radish, soybean and cabbage (Table 4). The P input from fertilizer use for rice, potato, radish, soybean, and cabbage was 61,447, 35,461, 27,297, 23,347, and 20,867 kg P/yr, respectively.

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Table 4. P inputs from fertilizer (chemical and organic matter) for the five most common crops in the Haean watershed.

Crop	Fertilizer input (kg P/yr)		P content (%)[1]		P input (kg P/yr)		
	Chemical	Compost	Chemical	Compost	Chemical	Compost	Total
Rice	441,981	1,437,443	10	1.20	44,198	17,249	61,447
Cabbage	303,188	980,915	3		9,096	11,771	20,867
Potato	308,306	1,927,391	4		12,332	23,129	35,461
Radish	261,072	1,622,053	3		7,832	19,465	27,297
Soybean	64,005	1,252,168	13		8,321	15,026	23,347
Total					81,779	86,640	168,418

[1] P content was calculated from values in published sources [14, 18]. Pig manure is the main raw material of compost used in the study watershed; rice hulls, crushed wood and saw dust were used as bedding materials.

3.1.2. Fertilizer application

P input from STPs accounted for a small fraction of the total P input to the Haean watershed. With the limited human population and little industrial development in the study area, STPs accounted for only 196 kg P/yr (0.1% of total P inputs) in the Haean watershed (Table 5).

Table 5. Summary of phosphorus inputs in the Haean watershed.

Phosphorus inputs	Amount (kg/yr)	Percent of the total (%)
Anthropogenic		
Chemical Fertilizer	81,779	47.4
Organic matter	86,640	50.2
Sewage treatment plants	196	0.1
Natural		
Atmospheric deposition	3,719	2.1
Export from forested areas	274	0.2
Total	172,607	100

3.1.3. Atmospheric deposition

The mean P concentration of the wet deposition samples was 0.04 mg/L. In 2013, the annual rainfall was 713 mm, less than half of the 10 years (2004-2013) average annual rainfall (1,506 mm) in the study area. Therefore, the annual P input from wet deposition was only 3,719 kg P/yr (Table 5). Atmospheric inputs accounted for about 2.1% of total P inputs.

3.1.4. Export from forested areas

Though forest land covers more than half of the Haean watershed, the P input from surface runoff was small. The calculated amount of P from surface runoff from forest areas was 274 kg P/yr (0.2% of total input; Table 5) [20].

3.1.5. Summary of P inputs

Our inventory of the P inputs showed considerable variation in the P content among the five most common crops in the watershed (Table 5). The total P inputs to the watershed were approximately 172,607 kg/yr for the 2013 growing season. Agricultural P inputs in the form of organic

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compost were the largest source of P, accounting for 50.2% of total P inputs. Chemical fertilizers were the second largest P source, accounting for 47.4% of the total P inputs. P inputs from STPs added only 0.1% of all the P entering the watershed. Background P inputs such as wet atmospheric deposition and export from forested area accounted for only 2.3% of the total P inputs. Overall, anthropogenic P inputs (chemical fertilizer and organic compost applications) were the largest P inputs in the Haean watershed (Table 5).

3.2. P outputs

3.2.1. P removal through crop harvesting

Crop production in the Haean watershed is solely commercial. We assumed that all the harvested crops left the watershed and none of the crops were consumed within the watershed. P output as harvested crops was 13,216 kg P/yr, accounting for 58.9% of total P outputs (Table 6).

Table 6. Phosphorus outputs from the watershed through crop harvesting.

Crop	Yield (kg/yr)	Water content (%)	Dry weight (kg/yr)	P content (%)	Harvested P (kg P/yr)
Rice paddy	3,218,833	11.3	2,855,105	0.22	6,281
Cabbage	6,882,456	91.8	564,361	0.35	1,975
Potato	3,578,850	77.2	815,978	0.23	1,877
Radish	6,184,242	94.0	371,055	0.40	1,484
Soybean	261,126	10.0	235,013	0.68	1,598
				Total	13,216

3.2.1. Hydrologic export to surface water

Hydrologic export of P to the Mandae stream was estimated to be 9,215 kg/yr in 2013 (Figure 3; Table 7) [4]. This P export in surface water accounted for 41.1% of total P outputs.

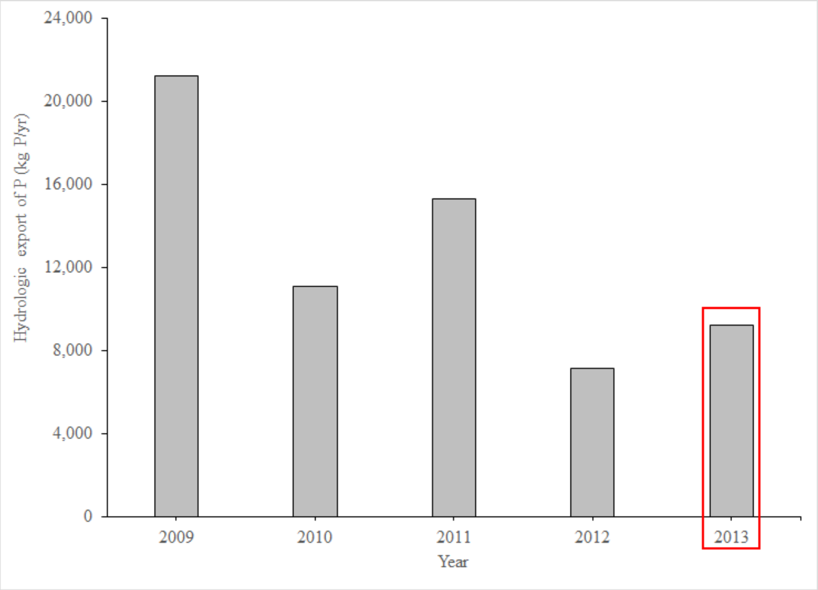

Figure 3. P output from the watershed in hydrologic export to the Mandae Stream (2009-2013)

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Table 7. Summary of phosphorus outputs in the Haean watershed

Phosphorus outputs	Amount (kg/yr)	Fraction of total output (%)
Crop harvesting	13,216	58.9
Hydrologic export	9,215	41.1
Total	22,431	100

3.2.3. Summary of phosphorus outputs

We calculated a net export of P in harvested crops of 58.9 % of the total P output compared to export in surface water of 41.1 % of the total P output (Table 7). Thus, P export through crop harvesting was identified as the main pathway for P outputs.

3.3. Summary P budget

We found that fertilizer use (including chemical fertilizer and organic compost application) is the largest P input to the Haean watershed. Secondary P inputs are wet deposition and surface runoff from forested land. P input from STPs accounted for only a small portion of P inputs. Hydrologic export in the watershed outlet and crop harvesting were the most important P outputs. Based on the current study, a net positive P balance was indicated for the Haean watershed (Table 8). We found that approximately 87% of the total P inputs were retained in the watershed (Table 8).

Table 8. Summary of the annual phosphorus budget of the Haean watershed

Phosphorus	Amount (kg/yr)
Inputs (I)	172,607
Outputs (O)	22,431
Net (I - O)	150,177
% Retained	87.0

4. Discussion

4.1. Fertilizer application and fate of P in soils

We have identified fertilizer use as the major P input in the Haean study watershed. Specifically, organic compost was the biggest contributor to the total P input for most of the common crops except rice. For the case of rice, chemical fertilizer was found to be the largest P input. Although the RDA has not recommended any organic compost application in rice fields, most farmers in the Haean watershed do apply organic compost in their rice fields. The estimated fertilizer consumption in Korea is 3.6 times higher than the global average [21]. Furthermore, application rates in the study watershed for chemical fertilizers and organic compost application rates have been 2.5 to 4 and 4.5 to 8 times higher than the recommended application rates (kg/ha/yr) by the RDA, respectively.

As part of this study, our interviews with local farmers showed that fertilizer application rates for rice, cabbage, potato, radish, and soybean surpassed the RDA recommended P fertilizer application rates by 5.7, 3.4, 6, 4 and 4.6 times, respectively. Farmers in the Haean watershed generally applied all the P fertilizer in a single dose at the beginning of the growing season and did not use additional applications of P fertilizer later in the year. At the beginning of the growing season, plant growth is thought to be slow with relatively low P uptake. Thus, excess P fertilizer application early in the growing season combined with substantial rainfall could result in enhanced loss of P from soils. Therefore, splitting P fertilizer applications into two or three separate fertilizer applications based on crop P requirement could be a useful measure to reduce harmful P losses. While annual chemical fertilizer consumption in the Haean watershed has been decreasing in recent years [13],

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there are still considerable opportunities to reduce P fertilizer inputs and eventually decrease P surpluses in the watershed.

The detailed inventory of P inputs and outputs in this study has shown that P inputs are higher than surpass the outputs (Table 8). Approximately 150,177 kg P/yr (Table 8) is retained in soils in the Haean watershed, signifying the potential for contributing to eutrophication and leaching into ground water. This finding is further supported by the increase in soil P concentration in the watershed. An increase in average soil test P concentrations in the dry fields from 76.3 mg/kg (estimated in 2009) [22] to 95.9 mg/kg (this study) suggests that the excess P is being held in the soil. Based on the calculation method used by Bennet et al [1], if farmers in the watershed immediately stop applying excess P fertilizer and apply the same amount of P that is exported from the watershed (assuming that agricultural production and P export will not decline with reduced fertilizer application), more than 22 years would be required for P in the soil to reach equilibrium P concentrations. Therefore, achieving reductions in soil P concentrations in the Haean watershed is a goal with long-term benefits.

P sequestered in soil is often considered a ‘chemical time bomb’ [23]. Excessive P stored in soils can result in increased water-soluble P concentrations in soils, thus amplifying the potential for hydrologic export [24]. The general soil texture of soils in the Haean watershed is sandy loam; these soils are susceptible to erosion during the summer monsoon season [25]. Related to this, observations from other monitoring studies show that most (>83%) of the P exported from the Haean watershed in surface water is in particulate form [26]. Even if P fertilizer applications are reduced, soil P will continue to be available for hydrologic export to Lake Soyang. Soil P can be desorbed by changes in soil chemistry which might be related to changing inputs of acidic precipitation [5]. With continued climate change, the number of tropical and subtropical cyclones is likely to increase in summer monsoon regions [27,28]. Future efforts focused on the design and implementation of revised P management programs should consider the importance of P retained in highland agricultural soils in the study area.

In this study, we measured P inputs in wet deposition of 3,719 kg P/yr. This estimate is similar to P inputs in wet deposition in other studies [29, 30]. Although forested land covers more than 61% of the total watershed area, only a small amount of P was lost from forests in the Haean watershed (274 kg P/year). This estimate is within the range of measurements of P lost in surface runoff from forested land in other regions [31, 32]. Forested-agricultural watersheds can be found throughout Korea and future research directed at understanding P retention in mixed forested-agricultural systems would provide insight on how to better manage P losses at long-term scales.

Our study was not focused on identifying the biogeochemical processes controlling specific pathways of P sequestration or export. Generally, P losses from agricultural land are related to soil erosion [33, 34]. In the Haean watershed, hydrologic export of P is influenced by meteorological factors including rainfall amount, rainfall intensity, and the number of antecedent dry days.

4.1. P input and output budgets from other studies

Studies on the global P cycle confirm that the average P accumulation rate in the world’s soil has increased along with the dramatic increase in P consumption observed since 1960 [35, 36]. P accumulation in agricultural soils has been documented in most areas of Korea [37, 38]. The amount of P retained in the Haean watershed, 24.4 kg P/ha/yr, is similar to P retention in countries with intensive agricultural practices such as the Netherlands [39]. To understand the magnitude of P retention in a regional context, we compared P retention in the Haean watershed with P retention in watersheds in other locations (Table 9). The Haean watershed shows high P retention and has a larger area of forest land use compared to the other watersheds. Changing crop types in the watershed from annual crops to perennial crops with lower recommended fertilizer P applications is a possible management strategy that would lower the amount of P sequestered in the watershed. However, perennial crops cannot replace the economic value of annual crops in Korea, and this strategy might be limited to only certain fields. In addition to P input and output budgets, more studies on the biogeochemical processes controlling P dynamics are needed. Developing more efficient and sustainable fertilization strategies will be useful to minimize long-term P sequestration in the Haean watershed.

Table 9. Comparison of the P budget in this study with P budgets for other watersheds

Watershed	Area (ha)	Land use (%)			Phosphorus flux (kg/ha/yr)			Retention (%)	Ref.
		Forest	Agri.	Others	Input	Output	Balance		
Haean, Korea	6,174	61.1	29.6	5.45	28.0	3.63	24.4	87.0	This study
EAA, South Florida	191,198	-	93.3	7.70	3.32	0.82	2.50	75.2	[8]
Lake Okeechobe*, Florida	1,392,987	30.3	55.2	14.5	5.99	0.88	5.11	85.3	[40]
Lake Okeechobe**, Florida	1,392,874	29.5	56.2	14.3	4.59	0.97	3.62	78.9	[41]
Bui SB, Vietnam	2,751	13.6	45.8	40.6	5.7	0.90	4.80	84.1	[42]
Cuyahoga, Ohio	182,300	41.6	31.0	27.4	12.1	2.43	9.47	79.9	[43]
Grand, Ohio	182,500	44.2	38.8	17.0	7.42	1.81	5.61	75.6	
Guayaquil, Ecuador	136,000	6.40	39.8	53.8	4.36	0.93	3.43	78.7	[7]
Liuchahe, China	732	17.9	70.1	12.0	53.4	5.46	47.9	89.8	[6]
Roanoke, North Carolina	2,194,756	60.4	33.3	6.30	2.55	0.46	2.09	81.9	[44]

5. Conclusions

The P budget approach used in this study represents the first comprehensive attempt to identify the origin and fate of P in highland forested-agricultural watersheds in Korea. The P budget in the Haean watershed is highly influenced by agricultural activities. P inputs to the watershed are dominated by fertilizer inputs, while crop harvesting and hydrologic export are almost equally important in the P outputs. There is a net accumulation of P in the system even though nutrient loss and soil erosion occurs during the summer monsoon season in areas with intensive agriculture. Comparing the balance between P inputs and outputs of the present study with a number of diverse watersheds throughout the world shows common patterns with the Haean watershed, despite the significant differences in site specific soil characteristics, agricultural practices, geologic, and meteorological factors among the watersheds. Comparing the P retention in the Haean watershed in the present study with other studies shows that amount of P retained in the Haean watershed is much higher than for many watersheds. This study also confirmed that even if all the P inputs in the watershed were eliminated, soil P concentrations may not drop immediately because of the high P accumulation in agricultural soils. The P budget in this study provides a useful analysis tool to design better management practices to mitigate NPS-derived P pollution problems in mixed land use watersheds in Korea.

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