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Estimating the gross budget of applied nitrogen and phosphorus in tea plantations

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ABSTRACT

To increase crop yield, high fertilizer application rates have generally been used. The residual fertilizers potentially become a source of diffused pollution, and degrade soil and water quality. Such nonpoint source pollution is a major threat to reservoir eutrophication. The best management practices (BMPs) are usually used to prevent eutrophication; however, the environmental distribution of the applied fertilizers has not been understood properly. This could lead to a biased assessment of the rational quantity of nitrogen and phosphorous applied and the selection of BMPs. A field investigation of 32 plantations and 4 forests in the Feitsui Reservoir watershed, Taiwan, was conducted. Storm runoff water and soils were sampled, and a mass balance was used to demonstrate the gross nutrient budget. The results showed that when applying fertilizers of 2700 kg ha^{-1} in tea plantations only 18.3% of applied nitrogen and 5.5% of applied phosphorus were utilized by tea plants. Less than 5% of applied phosphorus was released in storm runoff, and more than 90% remained in the field. Approximately 30% of the nitrogen was lost through storm runoff, and 52% was stored in the soil mass. Therefore, reducing fertilizer application was recommended as the principal BMP, and collecting and treating storm runoff was suggested for controlling nitrogen pollution. The current management of soil erosion is an efficient measure for controlling phosphorus pollution.

1. Introduction

Nonpoint source pollution control is a key issue in watershed management, especially for avoiding eutrophication in reservoirs and lakes. Nonpoint source pollution is diffuse pollution and is dominated by type of land use. Storm events trigger nonpoint pollution, as pollutants accumulate during dry days are flushed away and transported to the receiving water body by surface runoff. The characteristics of accumulated pollutants are dependent on the type of land use. For example, heavy metals might accumulate on urban roads, sediment from soil erosion of construction sites, and nutrients are flushed from agricultural and urban lands. Among the different types of land, croplands where fertilizers are applied are of particular concern [1–3].

To increase crop yield, high fertilizer application rates have generally been used. However, a high fertilizer application rate does not always increase crop yield proportionally, and residual nutrients might accumulate in soil and distribute in the environment [4]. Frequent fertilization can lead to the excessive application of nutrients, which either flow out with runoff or remain as surplus in the soil, potentially leaching into the groundwater. Nutrient leaching can degrade soil and water quality [5–9]. Tea requires a particular growth environment that includes acidic soil and high moisture [10]. In Taiwan, tea plantations are located in the upper regions of watershed, and some are located in areas that are a drinking water source. Therefore, the impact of nonpoint source pollution from tea plantation on water quality must be taken into consideration.

Many studies have confirmed the relationship between the use of fertilizers on tea plantations and polluted water and soils. For example, Nagumo et al. [8] studied cases in Japan and concluded that increasing the area devoted to tea resulted in a significant increase in the total nitrogen (TN) concentration in the basin. In China, Liu et al. [7] suggested replacing conventional chemical

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fertilizers with organic or slow-release fertilizers in the tea fields to reduce N and P losses. In Kenya, Maghanga et al. [9] also verified that fertilizer application on tea plantations contributed to high nitrate levels in the receiving river. In addition to surface water, Han et al. [6] tested tea soils and found high nitrogen application is the cause of nitrate in tea soils. Sainju et al. [4] reviewed studies and concluded that nitrogen fertilization can increase soil organic carbon and nitrogen concentration. Both surface runoff pollution and land or soil pollution present significant potential for damaging water quality. However, such associated sampling is always neglected and the base data are still rare [5,11]. The causal relationship between fertilizer application and surface water or soil pollution is realized, but the complete picture of the distribution of the fertilizer nutrients is not understood. The fraction of applied nitrogen and phosphorus in storm runoff, soil, or plants has not been estimated. Owing to the lack of information, nonpoint source pollution cannot be controlled completely. The performance of best management practices (BMPs), especially the structural BMPs, is often assessed solely by the improvement in quality of runoff, and the residual pollutants remaining in the environment are ignored. This assessment might be biased and not accurately reflect the actual situation.

Nonpoint source pollution contributes to more than half of the pollution in most upstream watersheds in Taiwan [12–14]. The Feitsui Reservoir supplies drinking water to more than 5 million people in Taipei, the capital city of Taiwan. The primary objective in managing the quality of its water is to avoid eutrophication, and in this watershed, potential pollution from tea plantations is the target [11,13,14]. This study aimed to clarify the water and soil quality affected by tea plantations and to capture the distribution of nitrogen and phosphorus fertilizers. A large-scale sampling scheme was implemented, and the use of fertilizers, the amount of tea yields, and tea leaf analysis were surveyed to clarify the mass flow. The understanding of pollution distribution of applied nitrogen and phosphorus should be beneficial in assisting and advancing the efficiency of nonpoint pollution BMPs.

2. Materials and methods

2.1. Study area

Over the past several years, the water quality in Feitsui Reservoir has been controlled to eliminate eutrophication. However, increasing levels of total phosphorus (TP) imply that nonpoint source pollution remains a challenge that needs to be overcome. Nonpoint source pollution from tea plantations is of particular concern because the tea industry is important to the economy in this area [14,15]. Approximately 6.6% of the land is dominated by tea plantations [16], and most of these plantations are located in 3 subwatersheds: the Baishin, Jingualiao, and Daiyujue watersheds, where export TP loadings are high [17]. The land use in the 3 subwatersheds is listed in Table 1. The most prevalent type of land use in the 3 subwatersheds is forest, with agricultural lands occupying less than 10%, and 75% of the agricultural lands are tea plantations. The subsequent sampling tasks in this study were performed in these subwatersheds.

Table 1
The land use of major subwatersheds in the Feitsui Reservoir watershed.

Land use	Subwatershed		
	Baishin (ha)	Jingualiao (ha)	Daiyujue (ha)
Forests	10,638 (77.9%)[a]	2164 (89.5%)	4658 (91.0%)
Waterbodies	900 (6.6%)	11 (0.4%)	57 (1.1%)
Crop land	1317 (9.6%)	182 (7.5%)	258 (5.0%)
Tea plantations	1135 (8.3%)	145 (6.0%)	157 (3.1%)
Urban	258 (1.9%)	20 (0.8%)	52 (1.0%)
Grassland	546 (4.0%)	41 (1.7%)	94 (1.8%)
Total area	13,658 (100%)	2418 (100%)	5119 (100%)

[a] Percentage of land area.

In this area, tea is harvested twice a year and usually in spring and winter and the total harvest amount is approximately 2700 kg ha^{-1}. The nitrogen, phosphorus, and potassium contents in tea leaves are 4–6, 0.25–0.4, and 1.5–2.1%, respectively [18]. Several fertilizers are applied in this area; No. 1 (Taiwan Fertilizer Co.) and No. 42 (Taiwan Fertilizer Co.) compound fertilizers are the most commonly used. The percentages of nitrogen, phosphorus, and potassium in No. 1 and 42 compound fertilizers are 20, 5, 10% (20-5-10) and 23, 5, 5% (23-5-5), respectively. In addition to the compound chemical fertilizers, organic fertilizers have been promoted in recent years.

2.2. Sampling methods

2.2.1. Soil sampling and analysis

Forty soil samples were collected from 32 tea plantations, and four from 4 forests. Fig. 1 depicts the sampling site locations. The samples from forests were used as background data. Among the 32 tea plantations sampled, storm water was also sampled at 4 sites. All soil samples were collected after the application of fertilizers in May and August, 2009.

The soil sampling procedure followed the standard operating procedure provided by Council of Agriculture (COA), Executive Yuan, Taiwan. One soil sample was collected from each site; it was taken from the center of the diagonals of a tea plantation assuming soil homogeneity in the site. However, in sites where storm water also was simultaneously sampled, 3 soil samples were collected, i.e., two additional samples were taken along the diagonal line. One kg of soil was collected at a depth of 0–10 cm, and > 500 g of soil was sampled to a depth of 0–20 cm. All soil samples were sealed and delivered to a certified laboratory on the same day. Eleven soil parameters were analyzed: pH, cation exchangeable capacity, organic content, texture, water content, available phosphorus (PO_4^{3-}), TP, ammonia (NH_4), nitrate (NO_3), TN, and exchangeable potassium.

2.2.2. Sampling and analysis of storm water runoff

Runoff from four tea plantations were sampled in 2009, and each site collected a total of 5 storm events and 1 dry day event. In the four tea plantations, soils were sampled as well. In order to increase the runoff sample data, the results of water quality monitoring in 2008 was complemented to the runoff analysis. In 2008, 8 tea plantations were sampled; in each field, samples were collected on 5 storm days and on 4 dry day events. The dry day samples were used as contrast data. Storm runoff was collected when the cumulative rainfall reached 5 mm. Random sampling of storm water runoff was conducted during rainfall periods at the outlet of the onsite drainage channel. Because the tea plantations are private properties, it is difficult to set up equipment to measure runoff flow. When calculating the mass flow of nitrogen and phosphorus, runoff is obtained from rainfall data and the rational equation is used. The details are explained in Section 2.3.

Several properties of the collected water samples were analyzed, including suspended solids (SS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and different types of nitrogen and phosphorus compounds. The pH of the runoff was tested in the 2009 program to assess acidification. Because our experience in 2008 indicates that BOD was less in runoff, we retained COD analysis but excluded BOD analysis in the 2009 samples.

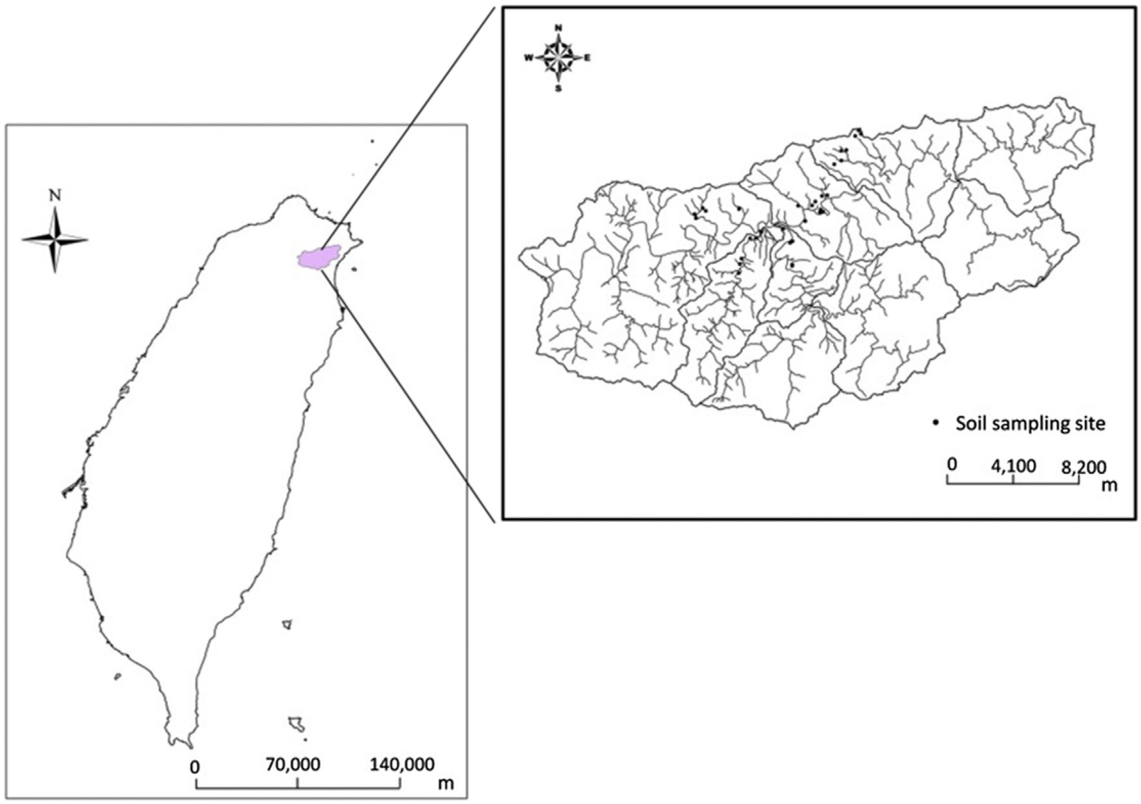

Fig. 1. Soil sampling sites in the tea plantation in the Feitsui Reservoir watershed.

2.3. Gross nutrient budget analysis

Following sampling, a gross nutrient budget analysis based on mass balance was conducted to understand the distribution of applied fertilizers among tea, soil, and runoff. The first task in the mass balance calculation was unit conversion, since the units for the water parameters and soil content are different (mg L^{-1} and mg kg^{-1}, respectively). All units were converted to kg ha^{-1} yr^{-1} representing the pollutant mass per area per year. This conversion would facilitate the demonstration of the extent of pollution distribution.

To transform water parameter concentration into expression of mass, the runoff discharge is required. Because runoff measurement equipment was not allowed to be set up on the private tea plantations, the rational equation $Q = C_eIA$ was used to estimate flow data, where Q is peak flow, C_e is runoff coefficient, I is rainfall intensity, and A is area. The watershed areas of the 4 sampling tea plantations are 0.4, 0.1, 0.2, and 0.4 ha, respectively. The sampling area is less than 1 ha, the concentration time for the runoff should be less than the rainfall duration, and the estimated peak flow can be regarded as the runoff flow. Rational equation is suggested to be used in nongauge station by Taiwan COA and the recommended runoff coefficient for flat crop land is 0.45–0.6. In addition, the runoff coefficient of tea plantation was suggested as 0.3 [18], and the other report suggested 0.53–0.90 for this study watershed [19]. In this study, we assumed that the runoff coefficient was a moderate value, 0.5, for the studied tea plantations. Combining the estimated flow discharge and the sampled water concentrations provides the mass of pollutants per hectare at each site and each event. Finally, transforming the time unit to year produces the unit kg ha^{-1} yr^{-1} (Eq. (1)).

$$M_r = \frac{Q \times C_r \times TF}{A} \tag{1}$$

where M_r is mass of pollutant in runoff, kg ha^{-1} yr^{-1}, Q is runoff rate calculated from the rational equation, C_r is the pollutant concentration in runoff, and TF is unit transform factor. However, this unit transformation might overestimate the mass because runoff is produced only in rainfall events.

The concentrations of substances in soil samples are measured in mg kg^{-1}. To transform these values to kg ha^{-1}, the soil density is needed. Two assumptions are made for the soil sample calculation. One assumption is that the surplus pollutant is limited in topsoil, and the depth of the topsoil is determined as 10 cm, which is the depth for soil sampling. With this assumption, we can confine the soil volume to the sampling sites. The other assumption is that the soil concentration is uniform at the tea plantation, so that we can apply the sample result to represent the whole tea plantation. Based on these two assumptions, the mass of pollutants per hectare can be obtained by multiplying the sampled pollutant content by the soil weight (Eq. (2)).

$$M_s = D \times V \times C_s \times TF \tag{2}$$

where M_s is the mass of the pollutant in the soil, kg ha^{-1}, D is the soil density and the value 1.32 g cm^{-3} is used, V is soil volume in a 1 ha area, C_s is the pollutant concentration in the soil, and TF is the unit transform factor.

In order to obtain data on the amount of fertilizers applied in the tea plantations, the tea farmers were interviewed. Next, data from Wenshan Branch of the Taiwan Tea Research and Extension Station, a local department for tea research, was consulted. The average amount of fertilizer applied in this watershed was 3200 kg ha^{-1} yr^{-1}, and the most commonly used fertilizer was No. 42 compound fertilizer (23-5-5).

Next, the amount of nutrients utilized by the tea plants was studied. The annual tea harvest was approximately 2700 kg ha^{-1} in the area. However, the nutrient content of tea leaves was highly variable and this could be due to differences in tea species, age, season, and sampled parts of leaves [20]. An average value was therefore used in the present study. According to the report of the Taiwan Tea Research and Extension Station [20], the tea leaves contained 4–6% nitrogen and 0.25–0.40% phosphorus. Fig. 2 shows the estimation approach that was used to obtain the nutrient budget, combining field data from soil and runoff samples and data from references and calculations.

3. Results and discussion

3.1. Soil analysis

The results of the soil analysis are listed in Table 2. The total of 43 soils from tea plantations was sampled. The soil texture was classified as either clay or clay loam. The median pH of the soil at the tea plantations was less than 4, indicating obvious soil acidification. The pH in the surrounding forests was relatively higher, ranging from 4 to 5. The TP at the tea plantations was significantly greater than the TP in forest land ($F(1,42) = 6.333$, $p < 0.05$). The average TP content in forests was 314 mg kg^{-1}, and the maximum was not greater than 500 mg kg^{-1}. However, the average TP in tea plantations was 925 mg kg^{-1}, 75% of samples were more than 500 mg kg^{-1} TP, and some were as high as 2000 mg kg^{-1}. The differences in PO_4^{3-} content between tea plantations and forest lands was higher than the TP content recorded previously. The average PO_4^{3-} content in tea plantations (135 mg kg^{-1}) was 6 times more than that recorded in forest lands (19 mg kg^{-1}).

There were no distinct differences between tea plantations and forest land in terms of TN ($F(1,42) = 0.027$, $p = 0.871$). The average TN in tea plantation and forest soils was 1499 mg kg^{-1} and 1525 mg kg^{-1}, respectively. However, both NH_4 and NO_3 content was much greater in tea plantation soil than in the soils of forest land. The average value of NH_4–N at tea plantations was 14.7 mg kg^{-1}, which is 7 times greater than that of NH_4–N in forests, which was 1.9 mg kg^{-1}. The results confirm that the application of nitrogen fertilizer causes high NH_4 and NO_3 content at tea plantations. Comparing with the TN content, the NH_4–N and NO_3–N content was relatively low. It implied that most of TN was organic nitrogen, which is one component of TN but not estimated in the analysis.

Potassium is 1 of the 3 key components of fertilizers. There is no significance between tea plantations and forest lands ($F(1,42) = 2.835$, $p = 0.100$). Surprisingly, the content of exchangeable potassium was low in tea plantation soil. The average values of exchangeable potassium were 91 and 147 mg kg^{-1} at tea plantations and forests, respectively. Two reasons were speculated to explain this phenomenon: (1) the potassium output and the original potassium are taken up completely by tea trees, or (2) the exchangeable potassium is being leached away from soils or is lost through eroded soil.

3.2. Runoff water quality

The quality of storm water runoff was analyzed for a total of 12 tea plantations in two years. During the 2-yr monitoring period, 10 storm events and 5 dry day events were recorded. The results are summarized in Table 3. Unsurprisingly, the water quality was worse in storm water than in dry day samples. Although samples were taken in 2 different years, the mean water quality did not vary. Storm runoff results in soil erosion and therefore increased the mean SS to 24 mg L^{-1}, which is 2 times greater than the mean SS of the contrast groups, 12 mg L^{-1}. Following the storm water flow and high SS concentration, the attached organic substances were washed away, and the COD concentration in storm runoff also increased.

The mean TP concentration in runoff and dry day samples was 0.07 and 0.02 mg L^{-1}, respectively. No obvious differences were observed with respect to TN; TN concentrations were 3.5 and 3.1 mg L^{-1} in runoff and dry day samples, respectively. We also

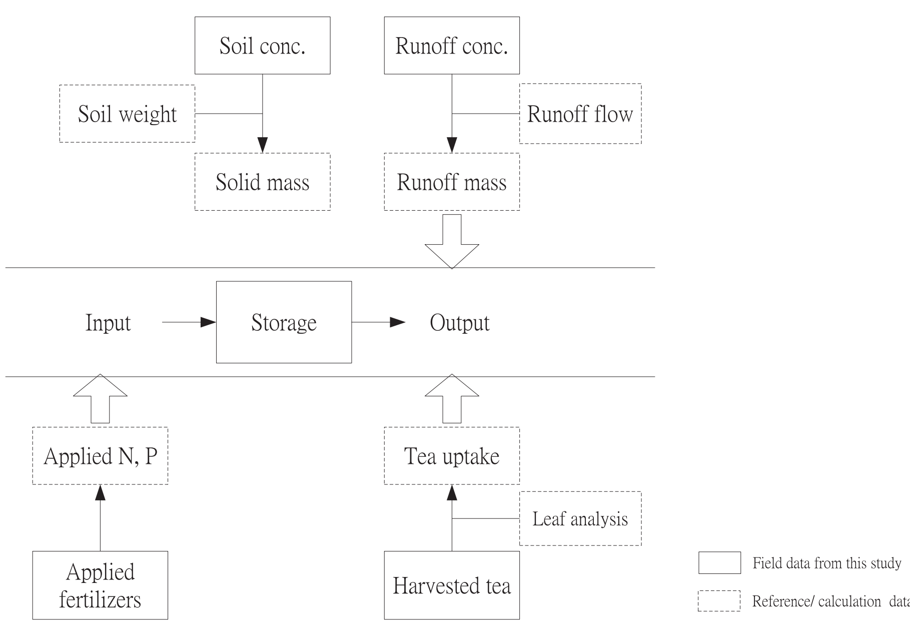

Fig. 2. Estimation process used to obtain nutrient balance budget. The budget was determined by combining field data from soil and runoff samples, and surveyed collected data of the amount of fertilizer applied and tea harvested. Runoff flow rate and soil weight were calculated.

Table 2
Characteristics of soil in tea plantations and forest lands.

Site	Water quality	pH	CEC (cmol kg^{-1})	OM (%)	PO_4^{3-} (mg kg^{-1})	TP (mg kg^{-1})	NH_4–N (mg kg^{-1})	NO_3–N (mg kg^{-1})	TN (mg kg^{-1})	K (mg kg^{-1})
Tea plantation (40)[a]	Average	3.2–4.8	14.1	2.4	135	925	14.7	16.4	1499	91
	S.D.[b]		4.6	0.9	139	465	18.8	13.0	402	59
Forest (4)	Average	4.2–5.4	12.4	3.4	19	314	1.9	6.7	1525	147
	S.D.		3.6	2.8	19	128	2.3	2.8	571	64

[a] Number of samples is indicated in the parentheses.
[b] S.D. refers to standard deviation.

Table 3
Characteristics of regular and runoff water in tea plantations.

Year	Type of water	pH	BOD (mg L^{-1})	COD (mg L^{-1})	SS (mg L^{-1})	PO_4^{3-} (mg L^{-1})	TP (mg L^{-1})	NH_4–N (mg L^{-1})	NO_2–N (mg L^{-1})	NO_3–N (mg L^{-1})	Organic nitrogen (mg L^{-1})	TN (mg L^{-1})
2008 (8[a])	Regular (4[b])	–	3.2	8	3	0.01	0.02	0.03	0.03	1.76	1.08	2.89
	S.D.[c]	–	0.9	5	2	0.01	0.01	0.03	0.06	1.90	1.75	
	Runoff (5)	–	4.3	13	20	0.04	0.09	0.20	0.05	2.17	0.68	3.09
	S.D.	–	1.6	8	24	0.04	0.08	0.29	0.07	2.47	0.32	
2009 (4)	Regular (1)	4.5–7.6	–	5	21	0.01	0.01	0.01	< 0.01	2.72	0.50	3.23
	S.D.		–	3	–	0.00	0.00	0.00	–	1.64	0.27	
	Runoff (5)	4.2–7.0	–	17	29	0.02	0.06	0.11	< 0.01	3.01	0.70	3.82
	S.D.		–	9	26	0.01	0.11	0.17	–	2.17	0.45	
Average	Regular	4.5–7.6	3.15	7	12	0.01	0.02	0.02	0.03	2.24	0.79	3.06
	Runoff	4.2–7.0	4.26	15	24	0.03	0.07	0.15	0.05	2.59	0.69	3.46

[a] Number of tea plantations sampled.
[b] Number of events sampled.
[c] S.D. refers to standard deviation.

assessed the distribution of dissolved and particular types of nutrients. Dissolved phosphorus (PO_4^{3-}) had a mean concentration of 0.03 mg L^{-1} in storm water and contributed approximately 30–40% of TP in storm runoff. However, the situation was not the same for nitrogen. Dissolved nitrogen in the form of nitrate and nitrite comprised 72 and 79% of TN in 2008 and 2009, respectively. The majority of the dissolved nitrogen is in nitrate form and has a mean concentration of 2.59 mg L^{-1}. The nutrient distribution in storm runoff reveals that particulate phosphorus makes up 60–70% of TP, whereas dissolved nitrogen comprises 70–80% of TN.

3.3. *Nutrient budget of tea plantation nonpoint source*

Storm runoff and soil were sampled simultaneously from 4 tea plantations in 2009 so that the data for assessing the nutrient budget were determined from the observations at the 4 tea plantations, designated sampling sites A, B, C, and D. The TP and TN mass in storm runoff and soil is summarized in Table 4. They were calculated using Eqs. (1) and (2), and the average levels recorded in each site are presented. There were 5 storm water and 3 soil samples for each sites and Table 4 showed the average results. The export coefficients of TP and TN from each tea plantation were obtained; their average values were 3.4 and 219 kg ha^{-1} yr^{-1}, respectively. The average TP and TN content in tea plantation soil at a depth of 10 cm was 1097 and 2019 kg ha^{-1}, respectively. The observed soil content cannot be presented using a time scale because the accumulation period is unknown. Therefore, the expression of observed soil data lacks time scales. Compared with the nutrient quantity in the soil, the release by the storm runoff flush was relatively low. However, these observed data were obtained from samples taken in an area with a daily rainfall of 10–60 mm. If a strong storm occurs and induces violent soil erosion, the quality of the runoff water will be quite different from these observations.

Table 4
Average mass of TP and TN in soil and export runoff in tea plantations. The results were obtained by Eqs. (1) and (2), in which 5 storm samples and 3 soil samples were used for each site.

Sample site	Subject	TP	TN
A	Storm runoff (kg ha^{-1} yr^{-1})	3.2	171
	Soil content (kg ha^{-1})	857	2105
B	Storm runoff (kg ha^{-1} yr^{-1})	2.1	369
	Soil content (kg ha^{-1})	1084	1636
C	Storm runoff (kg ha^{-1} yr^{-1})	6.9	229
	Soil content (kg ha^{-1})	1281	2325
D	Storm runoff (kg ha^{-1} yr^{-1})	1.4	108
	Soil content (kg ha^{-1})	1166	2010
Average	Storm runoff (kg ha^{-1} yr^{-1})	3.4	219
	Soil content (kg ha^{-1})	1097	2019

The mass balance is designed to define the distribution of nutrients from a nonpoint source. The inputs of nitrogen and phosphorus are assumed to be only from applied fertilization, and the transmission routes include tea uptake, storm runoff flushing, and storage in soil. Storage is regarded as a "black box" that consists of all possible physical, chemical, and biological interactions among soil and groundwater. The detailed processes of nitrogen and phosphorus transformation in soil can be found in Reuss and Johnson [21] and Frossard et al. [22]. The leaching of pollutants into groundwater was assumed to be black box action (i.e., storage) due to non-availability of data on groundwater monitoring. Mass balance was calculated using the following equation:

$$\frac{dS}{dt} = Input - Output$$
$$= Input\ Fertilizers - (Plant\ Uptake + Runoff\ loss) \quad (3)$$

On the basis of field investigations and the statistical data from the Wenshan Branch of the Taiwan Tea Research and Extension Station, the average amount of fertilizer applied in this watershed is 3200 kg ha^{-1} yr^{-1}, and the content of commonly used fertilizers is 5% phosphorus and 23% nitrogen (i.e., No. 42 compound fertilizer).

The inputs of phosphorus and nitrogen from the fertilizer are therefore 160 and 736 kg ha^{-1} yr^{-1}, respectively. The annual tea harvest per hectare is approximately 2700 kg and tea leaves contain 0.25–0.4% phosphorus and 4–6% nitrogen [20]. Thus, the quantities of phosphorus and nitrogen taken up by the tea plants are 6.8–10.8 and 108–162 kg ha^{-1} yr^{-1}, respectively. Mean values of TP and TN, i.e., 8.8 and 135 kg ha^{-1} yr^{-1}, respectively, were used to calculate the gross nutrient budget. The loss of nutrients in runoff was obtained from sample data. The storage change was calculated from the mass balance equation (Eq. (3)).

Fig. 3 shows the results of mass balance, which is the nutrient distribution in tea plantation nonpoint sources. The applied phosphorus released by storm runoff and taken up by tea trees is only 5.5 and 2.1%, respectively. Most phosphorus amounts (92.4%) are in the underground environment. This result suggests that less than 5% of the applied phosphorus is lost in storm water runoff, which is consistent with previous studies [1,23]. The mass of phosphorus lost in runoff was relatively low, implying that the collection and treatment of storm runoff with structural BMPs might have fewer benefits because a surplus of approximately 150 kg P ha^{-1} yr^{-1}would remain. The transport of phosphorus depends mainly on solid movement [24], indicating that surplus phosphorus will occur with soil erosion. In addition to the reduction of excess phosphorus fertilization, the improvement of soil erosion is crucial for effectively controlling phosphorus pollution [25]. Zehetner et al. [11] analyzed the sediment in the Feitsui Reservoir and found very high levels of inorganic phosphorus; the authors speculated that the source of the phosphorus came from tea plantations in the watershed.

The distribution of nitrogen is quite different from the distribution of phosphorus. Almost 30% of the nitrogen is washed away with runoff, 18% is utilized by the tea trees, and 52% is stored. More than half of the TN exists in a dissolved form that is easily washed away with runoff or leaches into groundwater. The majority of TN in sampled runoff is composed of nitrate, implying that nitrification in this area is active. A high nitrification rate was also found in Han et al. [6], where nitrogen fertilizer containing ammonium would stimulate soil nitrification. Approximately 50% of the nitrogen surplus in soil might be a threat to groundwater, soil, and even human health. The surplus nitrate might leach into the surrounding groundwater or accelerate soil acidification. Nitrate is subsequently reduced to nitrite. Because nitrite exposure is harmful to human health, the problem of nitrate leaching is of great concern in sustainable agricultural development [26]. The increasing nitrate concentration in surface water and groundwater has also been observed in high-density tea plantations in Japan [5,27]. Hirono et al. [5] discovered that reducing nitrogen fertilization from 1000–600 kg ha^{-1} results in large decreases in nitrate levels in stream water and groundwater.

The annual remaining P and N is approximately 150 and 380 kg ha^{-1}, respectively. Compared to the soil investigation in this study, where the average P and N content in tea soil is 1097 and 2019 kg ha^{-1} (Table 4), the fertilizers are assumed to have been applied for at least 5–7 yr.

The resultant gross balance of TP and TN in tea plantations was based on onsite observed data and some assumptions. Therefore, the nutrient distributions contained certain uncertainty. Quantifying the level of uncertainty is another issue but it is necessary to address the possible impacts. The two major uncertainties of this resultant distribution are the use of runoff coefficient and the nutrients taken by tea trees. The use of runoff coefficient influences the runoff flow and the final nutrient mass in the runoff. The reference range of this value by COA is 0.45–0.6, which means the maximum 20% difference might exist if 0.5 is used for flow prediction. The amount of nutrients utilized by tea growth cannot be measured, so that the contents of nutrients in tea leaves were used as substitutions. The uncertainty level of the tea uptake is 0.15% for phosphorous and 2% for nitrogen according to the reference range. Therefore, the results of the gross nutrients budget might contain a level of uncertainty of 22%. In addition to the calculation uncertainty, it should be noted that the input from atmospheric deposition is regarded as background and is not accounted for in the distribution. Liao [28] investigated the nitrogen budget in the forest system in Taiwan and demonstrated that the wet deposition of atmospheric nitrogen is 80 kg ha^{-1} yr^{-1}, approximately 10% of the applied nitrogen fertilizer. If considering the wet deposition of TN in the nutrient budget (Fig. 3), the increment TN was added into the storage component because runoff loss and tea uptake are fixed and the percentage of TN storage rose from 52 to 57%.

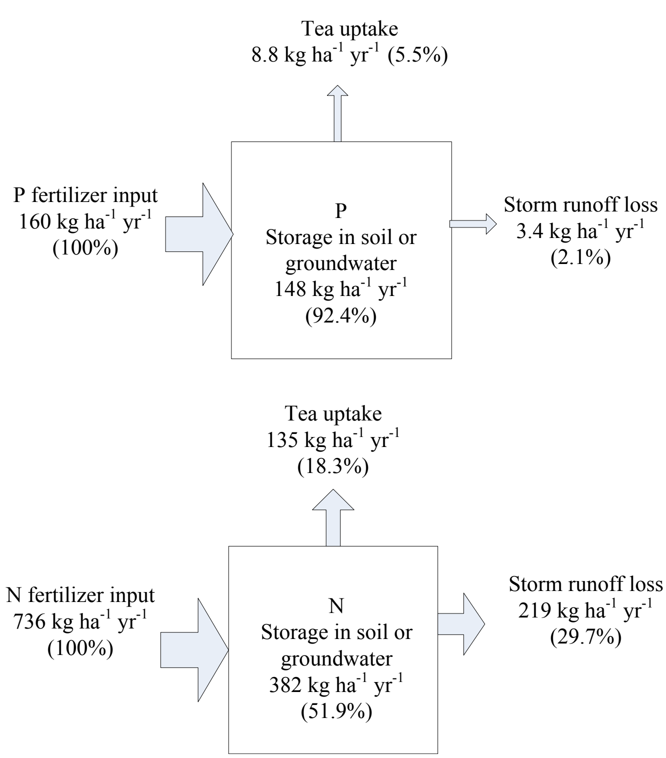

Fig. 3. Gross phosphorus (P) and nitrogen (N) budget in tea plantation from nonpoint sources. Percentages are shown in parentheses. Applied P and N are budget inputs, excluding wet deposition. Two output routes, including tea uptake and runoff loss, were considered. Leaching into groundwater, and possible physical, chemical, and biological interactions were assumed as black box action, i.e., storage.

4. Conclusions

Many water bodies worldwide have experienced eutrophication problems, and the use of excess fertilizers in croplands has been shown to be the primary cause. Understanding the environmental distribution of these applied fertilizers helps control nitrogen and phosphorus levels. In the present study, the quality of soil and runoff water from tea plantations and forest lands was studied. The gross nutrient budget of applied fertilizers was worked out from (1) tea yields and amounts of fertilizer applied collected by survey, (2) calculated runoff flow rate, and (3) tea leaf contents obtained from references. Wet deposition, groundwater leaching, and interactions among soils and groundwater were considered in the “black box” storage component of the nutrient budget. The study revealed that only 18.3 and 5.5% of applied nitrogen and phosphorus was taken up by the tea plants. These values implied that the utilization of applied fertilizers was very low, and hence, could result in cutting the current rate of use of fertilizers in half. The distribution of nitrogen and phosphorus was different, indicating that the objective pollutant ought to be considered when determining BMP measures.

Nitrogen exists mainly in dissolved forms, such as nitrate and nitrite, which are easily washed out or leached. Nearly 30% of the nitrogen is found in storm runoff. The phosphorus exists mostly as specific types; less than 5% is washed out and more than 90% remains in the soil or groundwater. On the basis of the resultant nutrient distribution, collecting and treating storm runoff from tea plantations would be a satisfactory solution for reducing nitrogen levels, e.g., measures such as bioretention ponds and constructed wetlands. However, structural BMPs that focus on infiltration mechanisms are not recommended for nitrogen removal because they may accelerate nitrate and nitrite pollution in groundwater. The effective way to control excess applied phosphorus is to avoid soil erosion. In addition to the structural BMP methods, reducing the use of applied fertilizers is suggested for the main BMP. In addition to reducing the fertilization rate, the use of a mixture of legumes or slow-released fertilizers might be good alternatives [4,7,8].

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