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Article

Rice-Residue Management Practices of Smallholder Farms in Vietnam and Their Effects on Nutrient Fluxes in the Soil-Plant System

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Abstract: In Vietnam, approximately 39 million tons of rice (*Oryza sativa*) residues accrue every year. In this study, we quantified soil nutrient balances of paddy rice fields under different crop-residue management practices in northern Vietnam. On twelve farms, we calculated nutrient balances for the four prevalent rice-residue management practices, i.e., (1) direct incorporation of rice residues into the soil, (2) application of rice-residue compost, (3) burning of rice residues on the field, and (4) the use of rice residues as fodder for livestock. Soils under practices (1) to (3) showed a positive nutrient balance, which indicates that soil fertility can be maintained under these practices and that the amounts of chemical fertilizers can be considerably reduced. If not, there is a risk of eutrophication in the surrounding surface waterbodies. Practice (4), in contrast, resulted in a negative nutrient balance, which indicates the need for returning nutrients to the soils. From our findings we conclude that knowledge about the effects of rice-residue management practices on nutrient cycles may help to optimize the use of fertilizers, resulting in a more sustainable form of agriculture.

Keywords: paddy-rice farming; crop-residue management; nutrient balance; smallholders; fertilizer use; Vietnam

1. Introduction

Rice is the most important food crop in Asia. In Vietnam, annual rice consumption amounts to 150–200 kg per capita, providing 60% of protein and 50–70% of calories of the dietary intake [1]. Furthermore, Vietnam is one of the largest rice producers and exporters in the world. Ninety percent of the arable land in Vietnam is used for rice cultivation, which corresponds to 11.5 million ha, with a median landholding size of 0.65 ha [2]. As such, smallholders are the backbone of the country's agriculture.

The cultivation of rice involves the accrual of large amounts of straw and stalk. On average, one hectare of rice generates about five tons of residues, equaling to approximately 39 million tons per year [3]. The major portion of rice residues is burned on the field in Vietnam, like in many countries [4–6]. The burning of crop residues however results in a loss of nutrients, including the major macronutrients nitrogen (N), phosphorus (P), and potassium (K) [7–10]. In contrast, incorporating crop residues into the soil can increase soil organic carbon (SOC) stocks, improve soil structure, and substantially contribute to maintaining appropriate levels of nutrients such as N, P, and K in the

soil [7,11,12]. Incorporating crop residues into the soil has the potential to increase crop yields and reduce the need for chemical fertilizers. As such, crop residues may serve as a potential partial substitute for chemical fertilizers in agriculture [12–15]. Vietnam relies heavily on the import of chemical fertilizers. In the case of K fertilizers, 100% is imported. In 2017, Vietnam imported 4.64 million tons of chemical fertilizers at an estimated cost of 1.23 billion US\$ [16]. From 1992 to 2015, the average amount of total N, P, and K fertilizers applied in agricultural production in Vietnam doubled. At the same time, fertilizer-use efficiency was low, resulting in the loss of several hundreds of millions of US dollars annually for the national economy, and causing eutrophication and greenhouse gas emissions [16–18]. Against this background, the increased use of readily available, cost-efficient, and domestically produced organic fertilizer, such as crop residues, may reduce the need for costly imported chemical fertilizer and improve the national trade balance [19,20]. This would also increase farmers' net income by reducing their investments for chemical fertilizers [19,21].

Soil nutrient balances are the overall net result of the various nutrient flows of a farming system [22,23]. Nutrient balances have been quantified in Africa and Asia [24–27]. However, these studies focused on urban agriculture and aquaculture, but not on rice-farming systems. Moreover, most of the studies were limited to one year of observation, thus capturing only short-term effects, which limits the possibility to quantify the main factors that control the element balances. In this study we analyzed the relationship between crop-residue management practices and nutrient flows in the soil-plant system in paddy rice fields of selected areas of northern Vietnam. The specific objectives were (i) to analyze agricultural inputs and outputs of N, P, and K in different crop-residue management systems, and (ii) to evaluate the obtained soil nutrient balances with respect to the prospective potential of partially substituting imported chemical fertilizers by rice residues. The overall aim of the study was thus to evaluate the potential of crop-residue management to contribute to a more sustainable agriculture in Vietnam in the future.

2. Materials and Methods

2.1. Study Areas

We selected two study areas in contrasting rice-production regions of northern Vietnam. One study area was in Luong Phong Commune (Hiep Hoa District, Bac Giang Province; 106°01' E, 21°20' N), 60 km East of Hanoi (Figure 1, bottom).

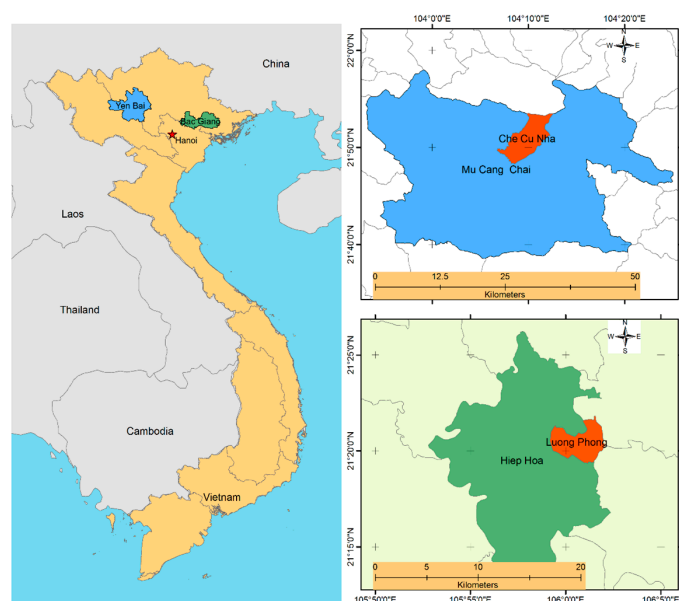


Figure 1. Study sites in northern Vietnam.

It is characterized by a subtropical monsoon climate with a mean annual temperature of 23.5 °C and mean annual rainfall of 1620 mm, with more than 80% of the rainfall occurring between May and October. The soils are Plinthic Acrisols according to World Reference Base WRB (2014), corresponding to “gray degraded soils” in the Vietnamese soil classification. Acrisols are among the main soils used for agriculture in Vietnam, occupying 1.4 million hectares (4.5% of the total land, and 12% of the agricultural land of Vietnam). In northern Vietnam, these soils are concentrated in Bac Giang, Vinh Phuc, Bac Ninh, Thai Nguyen Province, and Hanoi city, which are known for the most intensive agricultural production [28–30]. The texture of the soils is predominantly sandy loam. Their fertility is generally low [31].

The other study area was located in Che Cu Nha Commune (Mu Cang Chai District, Yen Bai Province; 104°10' E, 21°51' N), 320 km Northwest of Hanoi (Figure 1, top). The climate there is humid-tropical with a mean annual temperature of 22.8 °C and a mean annual precipitation of 1337 mm, influenced by the Northeast monsoon. The average air moisture is 81%. Maximum daytime temperature is 38–40 °C, occurring in June and July, while minimum daytime temperature is 2–5 °C, occurring from December to February. The predominant soils are Stagnic Acrisols, and paddy rice is the major crop on these soils [32].

Incorporation of crop residues into the soils is a widespread practice in Luong Phong Commune (Bac Giang Province), accounting for 51% of the total volume of crop residues. Another 38% of the crop residues are burned on the field, and about 10% are used as fodder for cattle [13]. The proportion of rice residues that are burned on the field is lower in Bac Giang Province than in Thai Binh Province [33] and in the Mekong Delta [5], where similar studies have been conducted. For comparison, in the Mekong Delta, 98% of the rice residues of the winter-spring season, 90% of rice residues of the summer-autumn season, and 54% of the rice residues of the autumn-winter season are burned. In Yen Bai Province, all crop residues are used as fodder for cattle.

2.2. Characterization of the Cropping Systems

The types of cropping systems that are common in a certain region depend on the climatological conditions, irrigation/precipitation patterns, and topography. Five cropping systems were identified in the two study areas (Table 1).

Table 1. General characteristics of the cropping systems in the two study areas.

Characteristics	Luong Phong Commune	Che Cu Nha Commune
Topography	Rainfed lowland paddy rice	Terraced paddy rice fields
Mean precipitation (mm)	1620	1337
Water source	Irrigation	Rainfall
Cropping systems	Spring rice–summer rice; spring rice–summer rice–maize (sweet potatoes)	Summer rice; summer maize grown on sloping land

In Luong Phong Commune (Bac Giang Province), spring rice is usually planted in February and harvested in late May. Summer rice is planted in late June and harvested in late December. Some farmers also plant maize and sweet potatoes in October that are harvested in January. Our study focused on the spring rice–summer rice cropping system only, because the farms that grow maize or sweet potatoes in the two study areas amounted to only 13% and 15% of the total number of farms, respectively. In Che Cu Nha Commune (Yen Bai Province), summer rice is planted in May and harvested in September. Maize is also planted in May but harvested in October [13].

2.3. Monitoring of Element Balances

We monitored quantitative nutrient inputs and outputs of each plot over two subsequent years. Based on the mentioned four types of rice residue management in the two study areas [13], we selected twelve farms for further in-depth analysis (Table 2).

Table 2. Rice-residue management in the study areas.

Study Area	Rice-Residue Management
Luong Phong Commune (Bac Giang Province)	Complete rice-residue incorporation before transplanting of spring rice (incorporation 1) and summer rice (incorporation 2)
Luong Phong Commune (Bac Giang Province)	Application of composted rice residues before transplanting of spring rice (compost 1) and summer rice (compost 2)
Luong Phong Commune (Bac Giang Province)	Application of ash from burned rice residues before transplanting of spring rice (burn 1) and summer rice (burn 2)
Che Cu Nha Commune (Yen Bai Province)	Collection of all rice residues (collect) for use as fodder for cattle, subsequent application of manure to maize grown on sloping lands

We collected data on rice-residue management practices from September 2015 to September 2017. For this purpose, we established nine plots in Luong Phong Commune (Bac Giang Province), including the following practices: (1) Incorporation of crop residues into the soil, (2) application of composted rice residues, (3) application of ash from burned rice residues. In addition, we established three plots in Che Cu Nha Commune (Yen Bai Province), where all rice residues were collected and used as fodder for cattle. For each of the plots, the exact amounts of inputs (i.e., fertilizers, crop residues, manure, and ash) and outputs (harvested crops) were recorded for each crop season. After harvest, we analyzed nutrient concentrations of rice grains, rice residues, manure, and soils. The composition of the chemical fertilizers was provided by the manufacturers. Nutrient fluxes through rain, irrigation, ash, N fixation, leaching, and volatilization were estimated based on the data of references [7,34,35].

2.4. Sampling and Analysis

Samples of topsoil, crop residues, rice grains, chemical fertilizers, and manure were collected at all plots, to monitor element fluxes of the four types of rice residue management, with three replicates per management practice (Figure 2).

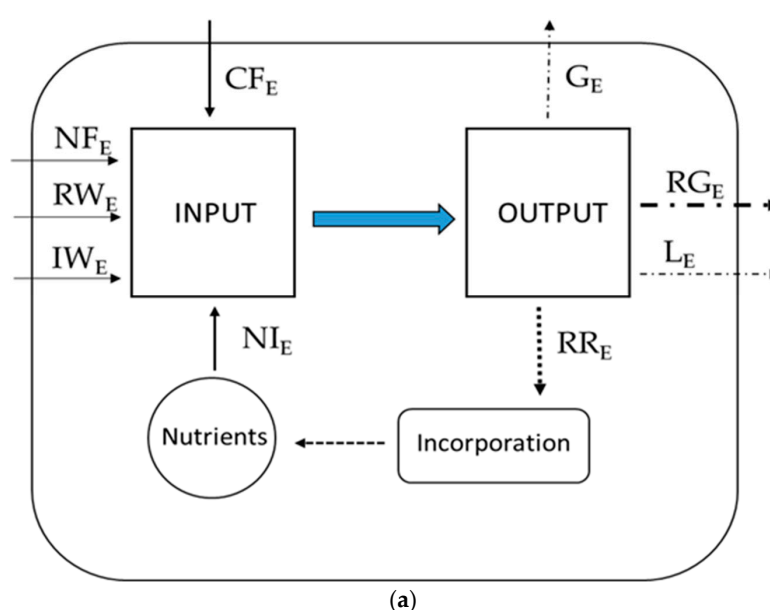
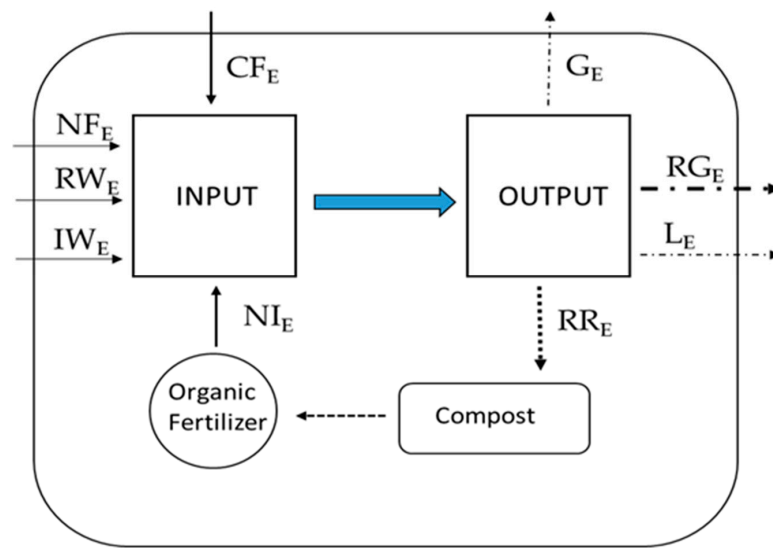
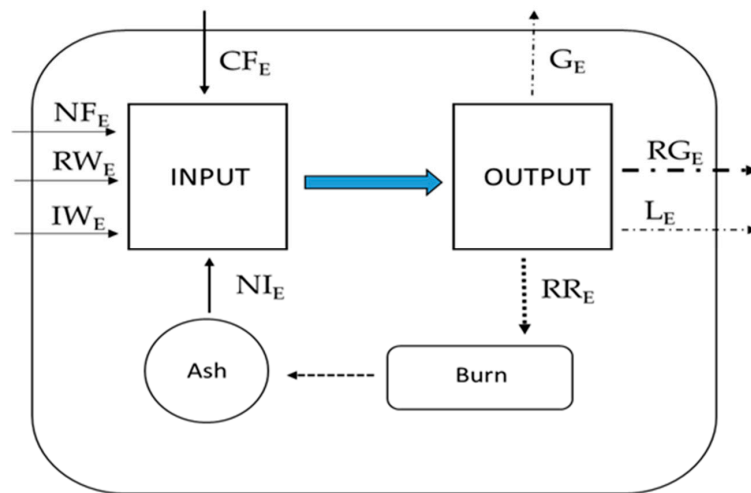


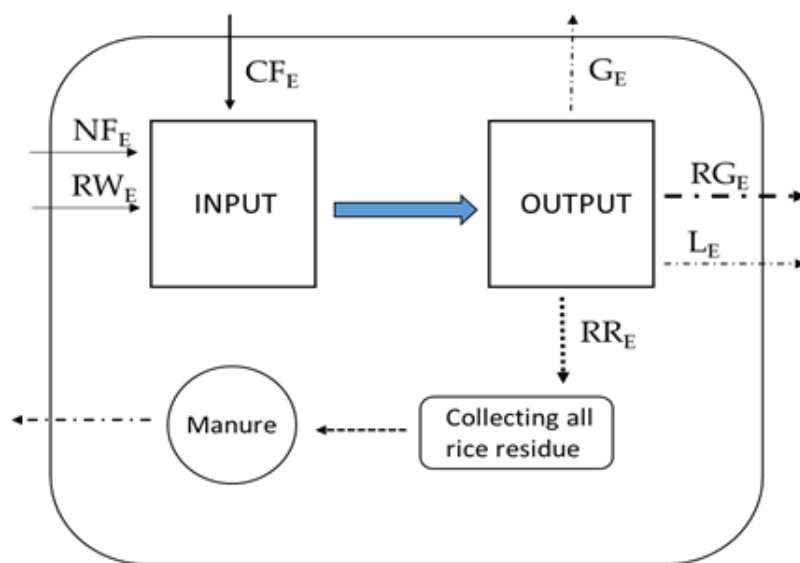
Figure 2. Cont.



(b)



(c)



(d)

Figure 2. Schematic representation of nutrient fluxes in the four types of rice-residue management practices. CF_E : Chemical fertilizers; G_E : Gaseous losses of N; RR_E : Rice residues; NF_E : Nitrogen fixation; RG_E : Harvested rice grain; RW_E : Rain water; L_E : Leaching; IW_E : Irrigation water; NI_E : Nutrients input as rice residue incorporation, compost or ash; (a) incorporation of rice residues into the soil; (b) application of rice-residue compost; (c) application of ash from burned rice residues; (d) collection of all rice residues for use as fodder for cattle.

The topsoils were sampled at a 0–20 cm depth, using a stainless-steel trowel. Five topsoil samples, taken within an area of 5 m × 5 m, were mixed in the field. Samples of crop residues and rice grains were collected at the time of harvesting from an area of 2 m × 2 m within the area from which topsoil samples had been taken. The crop residues were weighed. Subsamples for chemical analysis were air-dried, cut into small pieces, dried at 60–70 °C to constant weight, and ground to pass a 0.4 mm nylon sieve. Samples of chemical fertilizers and manure were collected either from the fields or obtained from the farm households. The samples were air-dried, ground, and sieved for chemical analysis. Nutrient analysis was carried out at the laboratory of the Soils and Fertilizers Research Institute (SFRI) in Hanoi, Vietnam. Soil pH (KCl and H₂O) was measured at a soil: solution ratio of 1:5, using a pH electrode (ISO 10390: 2005). Concentrations of total organic carbon were determined by the Walkley-Black method (ISO-22003: 2008), and concentrations of total N were analyzed by semi-micro-Kjeldahl (ISO 11261: 1995). The available P was extracted by the Bray 2 method and analyzed colorimetrically (by use of the vanadomolybdophosphoric acid colorimetric method). The total contents of P and K were analyzed after digestion with H₂SO₄ + HNO₃ (1:1, *v:v*). The total contents of P were determined colorimetrically, and those of K were determined by using a photoelectric flame photometer (Corning 410-UK). The texture was analyzed using the sieve and pipette method, and particle density was determined by use of a pycnometer (ISO 11277:2009). Cation exchange capacity (CEC) was determined using ammonium acetate at pH 7.

2.5. Calculation of Nutrient Balances

Nutrient balances of N, P, and K were calculated as the difference between inputs and outputs. Changes in soil nutrient status were evaluated using the following element balance equation [24,26]:

$$\Delta P_E = I_E - O_E \quad (1)$$

where ΔP_E represents changes in the soil pool, I_E comprises all inputs, and O_E includes all outputs of the element E. Element inputs I_E considered in this study were through irrigation water from rivers IW_E , rainwater RW_E , chemical fertilizers CF_E , nutrient input as rice residue incorporation, compost or ash NI_E , and biological N₂ fixation N_E . Considered element outputs O_E were through harvested rice grain RG_E , rice residues RR_E , gaseous losses of nitrogen G_E , and leaching L_E . The net changes in the soils' stocks of the element E $\Delta Soil_E$ were calculated as:

$$\Delta Soil_E = (IW_E + RW_E + CF_E + NI_E + N_E) - (RG_E + RR_E + G_E + L_E) \quad (2)$$

2.6. Statistical Analysis

A one-way ANOVA was performed to test the significance of the effects of applying chemical fertilizer, rice residues, compost, and ash at the two study sites. Significance was defined as $p < 0.05$ using the Duncan test.

3. Results

The soils of the investigated farms in Luong Phong Commune (Bac Giang Province) were characterized by low fertility (Table 3).

They had low pH (average pH KCl = 4.5) and light textures, typically varying from sand to silt. They showed low CEC and low concentrations of SOC, N, and K, but high contents of plant-available P. The soils were highly porous, making soil preparation easy [30,36]. The fields were in flat topography with shallow groundwater that is readily exploitable for irrigation [13]. Soils of the farms in Che Cu Nha Commune (Yen Bai Province) were even somewhat more acidic (average pH KCl = 4.0). They had a heavier texture (33% clay), higher CEC (13.9 cmolc kg^{−1} CEC), and higher total nutrient contents, but lower contents of plant-available P (1.6 mg 100g^{−1} versus 16.2–23.7 mg 100g^{−1}), compared to the soils of Luong Phong Commune.

Table 3. Topsoil (0–20 cm depth) characteristics under four rice-residue management practices.

Parameter	Rice-Residue Management			
	Luong Phong			Che Cu Nha
	Incorporation	Compost	Burn	Collect
pH (KCL)	4.50 (0.50)	4.70 (0.40)	4.60 (0.40)	4.00 (0.10)
pH (H ₂ O)	5.10 (0.40)	5.20 (0.50)	5.30 (0.50)	4.90 (0.20)
Bulk density (g cm ⁻³)	1.31 (0.09)	1.35 (0.03)	1.33 (0.10)	1.11 (0.05)
Coarse sand (%)	2.50 (1.90)	0.50 (0.10)	2.60 (2.10)	3.90 (1.80)
Fine sand (%)	62.9 (13.6)	57.8 (8.00)	54.7 (0.80)	31.5 (7.90)
Silt (%)	21.9 (2.80)	32.0 (5.80)	31.5 (1.40)	31.4 (9.40)
Clay (%)	12.7 (8.80)	9.70 (2.30)	11.2 (1.40)	33.2 (12.30)
CEC (cmol _c kg ⁻¹)	6.77 (2.03)	8.30 (3.39)	6.71 (1.99)	13.90 (3.04)
SOC (g kg ⁻¹)	1.30 (0.33)	1.26 (0.20)	1.25 (0.15)	1.50 (0.51)
Total N (g kg ⁻¹)	0.12 (0.03)	0.12 (0.02)	0.12 (0.03)	0.14 (0.04)
Total P (g kg ⁻¹)	0.05 (0.02)	0.06 (0.02)	0.05 (0.01)	0.10 (0.03)
Total K (g kg ⁻¹)	0.03 (0.03)	0.05 (0.02)	0.03 (0.02)	0.40 (0.13)
Available P (mg 100g ⁻¹ soil)	16.74 (4.02)	23.74 (11.81)	16.15 (3.76)	1.64 (0.82)
Available K (mg 100g ⁻¹ soil)	3.78 (2.29)	4.33 (1.99)	2.93 (0.72)	8.43 (0.96)
Total N stock (t ha ⁻¹)	3.14	3.24	3.19	3.11
Total P stock (t ha ⁻¹)	1.31	1.62	1.33	2.22
Total K stock (t ha ⁻¹)	0.79	1.35	0.80	8.88

Note: Numbers represent means (standard deviation) of selected soil properties over the 24 months of monitoring ($n = 6-9$).

Nutrient inputs were mainly through chemical fertilizers, rice-residue compost, and rice residues. The use of chemical fertilizers in the intensive rice-cropping systems of Luong Phong Commune exceeded the recommendations by the Agriculture Extension Department [37,38]. N inputs through chemical fertilizers were higher for the burning plots and incorporation plots than for the other plots (Table 4).

Table 4. Mean N, P, and K inputs from chemical fertilizers at plot level.

Rice Residue Management	Spring Rice (kg ha ⁻¹)			Summer Rice (kg ha ⁻¹)		
	N	P	K	N	P	K
Incorporation	114.21 ^c	28.09 ^{bc}	97.79 ^{bc}	101.01 ^{abc}	32.66 ^c	75.99 ^b
Compost	86.11 ^a	24.82 ^{ab}	81.46 ^b	88.59 ^{ab}	21.29 ^a	86.34 ^b
Burning	96.67 ^{abc}	27.40 ^{bc}	125.11 ^{cd}	109.26 ^{cb}	31.94 ^{bc}	132.95 ^d
Collect	0	0	0	96.66 ^{abc}	20.29 ^a	12.27 ^a

Note: a, b, c, and d represent data that are statistically different ($p < 0.05$).

Nevertheless, the burning plots showed a negative N balance for spring rice (Figure 3).

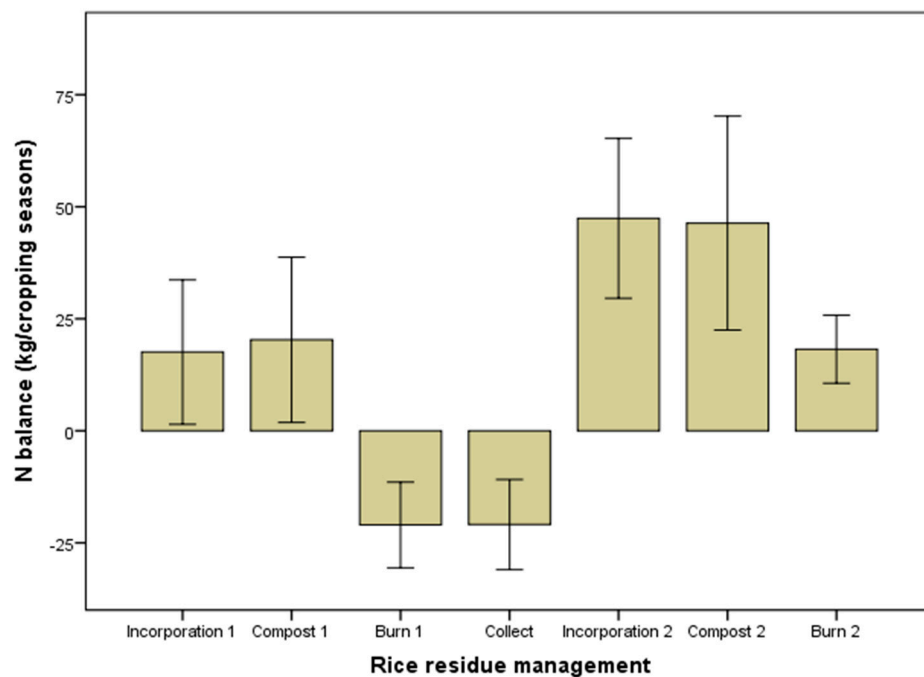


Figure 3. Mean balance of N per cropping season under the selected rice-residue management practices. The columns show arithmetic means ($n = 6$) and the bars represent standard deviations.

The burning plots received the highest total K ($125/133 \text{ kg ha}^{-1}$) and P inputs ($27/32 \text{ kg ha}^{-1}$) through chemical fertilization of spring and summer rice, respectively. K and P inputs to the compost and incorporation plots were high, too, leading to positive K and P balances (Figures 4 and 5).

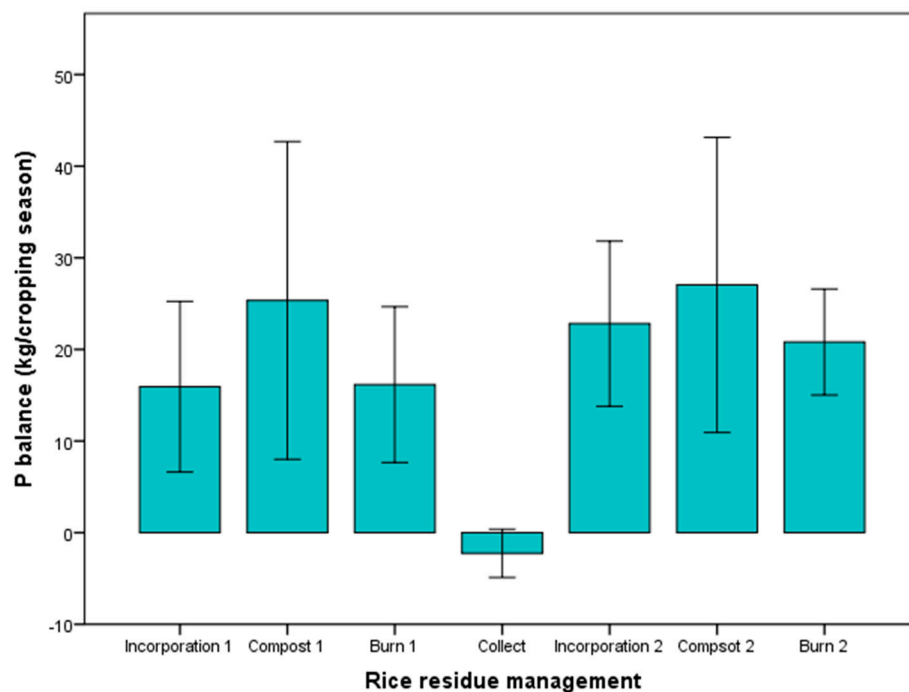


Figure 4. Mean balance of P per cropping season under the selected rice-residue management practices. The columns show arithmetic means ($n = 6$) and the bars represent standard deviations.

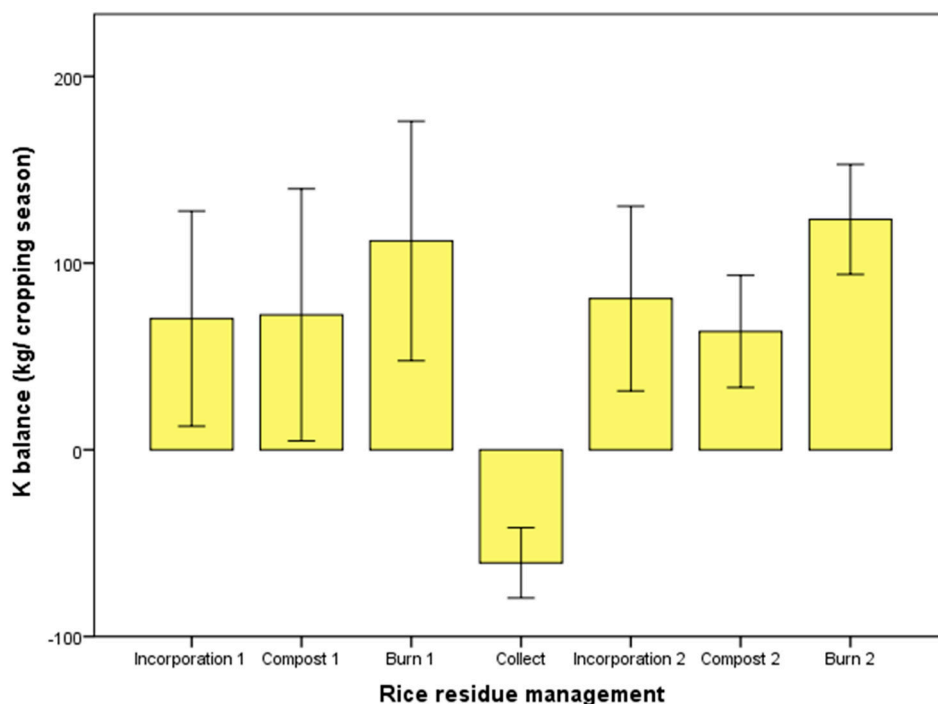


Figure 5. Mean balance of K per cropping season under the selected rice-residue management practices. The columns show arithmetic means ($n = 6$) and the bars represent standard deviations.

In contrast, nutrient inputs through chemical fertilizers were lowest in collection plots in the Che Cu Nha Commune, especially for K. Fertilizer application in the collection plots in Che Cu Nha Commune did not match the nutrient requirements of the rice, which resulted in negative N, P, and K balances for these plots (Figures 3–5).

Additional nutrient inputs through the different rice-residue management practices differed considerably. For the compost and incorporation plots, their contributions to the total nutrient inputs amounted to 21–35% N, 20–53% P, and 29–45% K (Table 5).

Table 5. Mean N, P, and K inputs from the incorporation of rice residues into the soils, application of compost from rice residues, and burning of rice residues at plot level.

Rice Residue Management	Spring Rice (kg/ha)				Summer Rice (kg/ha)			
	C	N	P	K	C	N	P	K
Incorporation	2057 ^c	31 ^b	8 ^a	34 ^a	2246 ^d	42 ^c	8 ^a	61 ^b
Compost	788 ^b	46 ^c	19 ^b	48 ^{ab}	831 ^b	44 ^c	24 ^c	35 ^a
Burning	53 ^a	0 ^a	7 ^a	46 ^a	56 ^a	0 ^a	7 ^a	45 ^a

Note: a, b, c, d represent data that are statistically different ($p < 0.05$).

For the collection plots (where rice residues were collected to feed cattle), all management-related nutrient inputs were calculated as 0 kg ha⁻¹ per cropping season. For the burning plots, only the management-related N inputs were calculated as 0 kg ha⁻¹ (accounting for gaseous loss of N through burning of the crop residues), whereas the management-related K inputs to the burning plots (45–46 kg ha⁻¹ per cropping season) were similar to those of the compost plots (35–48 kg ha⁻¹) and incorporation plots (34–61 kg ha⁻¹). Compost application was associated with the largest management-related P (19–24 kg ha⁻¹) and N (44–46 kg ha⁻¹) inputs per cropping season.

C inputs per cropping season related to the different management practices decreased in the following order: Incorporation of rice residues (~2.1–2.2 t ha⁻¹) > application of compost from rice

residues ($788\text{--}831\text{ kg ha}^{-1}$) > burning of rice residues ($53\text{--}56\text{ kg ha}^{-1}$), whereby total C loss through crop-residue burning was high ($\sim 2.0\text{--}2.1\text{ t ha}^{-1}$).

For the collection plots in the Che Cu Nha Commune, all nutrient balances were negative, amounting to $-21\text{ kg ha}^{-1}\text{ a}^{-1}$ for N, $-3\text{ kg ha}^{-1}\text{ a}^{-1}$ for P, and $-60\text{ kg ha}^{-1}\text{ a}^{-1}$ for K. The other three management practices on the plots in Luong Phong Commune generally led to positive nutrient balances, whereby the surplus of N was $18\text{--}47\text{ kg ha}^{-1}\text{ a}^{-1}$, that of P was $16\text{--}27\text{ kg ha}^{-1}\text{ a}^{-1}$, and that of K was $63\text{--}123\text{ kg ha}^{-1}\text{ a}^{-1}$. The only exception was spring rice with burning of crop residues (Burn 1 in Figure 3), which resulted in a negative N balance.

4. Discussion

4.1. Effects of Rice-Residue Management on Nutrient Balances of Rice-Cropping Systems

This study showed that considerable amounts of nutrients in paddy-rice systems can be recycled within the system through appropriate rice-residue management. Direct incorporation of the rice residues into the soils after harvest returned $31\text{--}42\text{ kg N ha}^{-1}$, 8 kg P ha^{-1} , and $34\text{--}61\text{ kg K ha}^{-1}$ per cropping season to the soil. Application of rice-residue compost returned significantly more P and somewhat more N to the soils, whereas the amounts of recycled K were similar in both management practices. In detail, compost application in our study involved the return of $44\text{--}46\text{ kg N ha}^{-1}$, $19\text{--}24\text{ kg P ha}^{-1}$, and $35\text{--}48\text{ kg K ha}^{-1}$ per cropping season to the soil. Thus, compared to the two other rice-residue management practices investigated in this study, burning and use as fodder for cattle, the two management practices (1) application of rice-residue compost and (2) direct rice-residue incorporation into the soils after harvest can considerably reduce the need of chemical fertilizers in paddy-rice cultivation [13,14]. In addition, high amounts of C were also added to the soils through the incorporation of rice residues ($2.1\text{--}2.2\text{ t C ha}^{-1}$ per cropping season) and rice-residue compost ($788\text{--}831\text{ kg C ha}^{-1}$ per cropping season). Thus, compared to burning (adding $53\text{--}56\text{ kg C ha}^{-1}$ per cropping season) or use as fodder (not calculated in this study), incorporation of rice residues and rice-residue compost may also increase SOC contents of paddy soils. The combined effect of nutrient cycling and SOC accumulation associated with these two practices has the potential to enhance soil quality [39,40], ensure appropriate plant nutrition, and correspondingly high crop yields, and at the same time reduce the use of chemical fertilizers. In this way, these practices may contribute to an economically and ecologically more sustainable food-crop production. Thus, they can help to meet the food demands of a growing population [41–43]. In contrast, several studies have shown that burning of crop residues can result in a loss of almost 100% N, 25% P, and 20% K from the system [7,10]. Applying these figures to the situation of our study, we estimate that the practice of burning rice residues on the field, resulted in nutrient returns of about 0 kg N ha^{-1} , 7 kg P ha^{-1} , and 46 kg K ha^{-1} to the soil per season. As no or very little N is returned from rice residues to the soil under the practice of crop-residue burning, large amounts of chemical N fertilizers are required under this management. The negative N balance, which we identified for spring rice cultivation on the burning plots of our study, points to this problem. In Che Cu Nha Commune (Yen Bai Province), as well in the upland areas of rice cultivation in Vietnam, removal of rice residues is the most common management practice at present. The rice residues are used as fodder for cattle. Farmers then collect the manure of their cattle and produce compost out of it. The compost is, however, not returned to the rice fields but is applied to maize fields. This practice leads to the loss of nutrients from the rice fields. Our results suggest that this loss is much greater for K than for P, as shown by the comparison of the K and P balances of the collect plots in Figures 4 and 5. This outcome of our study agrees with the data reported by the authors in reference [34].

The K balance was positive for all rice-residue management practices except for the collection of the rice residues to feed cattle (Figure 5). This result is a consequence of the considerable amounts of K that were returned to the soils through the three other rice-residue management practices, direct incorporation, compost application, and burning. The amounts of K that were returned through these

three practices were in the same order of magnitude, amounting to 34–61 kg K ha^{−1} per cropping season. It can be concluded that these three rice-residue management practices all are suitable for maintaining a high K use efficiency in rice-cropping systems.

In addition, the P balance was positive for all rice-residue management practices except for the collection of rice residues to feed cattle (Figure 4). The greatest positive P balance was obtained for the plots with compost application, although less chemical P fertilizers were used on these plots (21–25 kg P ha^{−1} per cropping season), compared to the incorporation and burning plots (27–33 kg P ha^{−1} per cropping season). This large P surplus resulted from the high quantities of P that were returned to the soils through the compost (19–24 kg P ha^{−1} per cropping season), compared to the amounts of P that were returned through the direct incorporation of rice residues (8 kg P ha^{−1} per cropping season) or burning (7 kg P ha^{−1} per cropping season). It can be concluded that, among the investigated management practices, compost application has the greatest potential to increase P use efficiency in rice-cropping systems.

In general, organic fertilizers have been recognized as an important source of nutrients. In addition to the nutrients N, P, and K that were in the focus of this study, organic fertilizers also supply other macro- and micronutrients that are not contained in commercial chemical NPK fertilizers [34,44]. Moreover, organic fertilizers help improving soil fertility by increasing CEC and SOC contents. Farmers in Vietnam have used organic fertilizers for a long time [45,46], whereby the amounts and application methods vary between regions as well as between individual farms, depending on crops, soils, and available types of manure. Bui [44] reported that farmyard manure was usually applied before crop planting. The amounts of applied manure varied between 9.7 t ha^{−1} and 14.9 t ha^{−1}, differing between individual households. However, these data on manure application were collected two decades ago. In more recent surveys [20,45] a decreased application of manure was found. This decline is related to (1) a decrease in the availability of manure from pig farms, because most of the pig manure in northern Vietnam is nowadays used for biogas production, (2) insufficient knowledge of farmers about the management of manure in an efficient and at the same time environmentally sustainable way [47], and (3) the ready availability of chemical fertilizers that seem to provide an easy substitution of manure [48].

Results of recent investigations by the authors of references [20,42], and ourselves (obtained 2015, unpublished), showed that farmers would prefer to apply more organic fertilizers, especially to rice, maize, and peanuts, but that the amounts of organic fertilizers produced on their own farms is not enough to supply their fields. In all three provinces, where these studies were carried out, no or low application of organic fertilizers to rice was found. This trend was due to an increase in the practice of burning harvest residues, lack of labor force, and reduction of livestock per hectare in the course of specialization of rice farms. Vu [45] and Hoang [42] identified logistic constraints (workload, volume of manure, distance to field, availability of labor force) as the most important reasons why the majority of farmers hesitated to apply manure to crops. Most of the farmers knew about the benefits of organic fertilizers for crop yield and soil fertility. However, the effects of crop-residue incorporation into soils on plant yield and its potential for partial fertilizer substitution were less known [13].

The outcomes of our study supported previous investigations, which suggested that rice-residue incorporation into soils can reduce the required amounts of fertilizers and therefore the costs related to the purchase of fertilizers [13,42]. In addition, it has the potential to increase SOC contents of soils, thus positively affecting soil physical, chemical, and biological properties. Our study under laid these assumptions through quantitative data. In conclusion, we propose that rice-residue incorporation into soils can be a suitable alternative management practice for farms that do not produce sufficient amounts of farmyard manure [14,15].

4.2. Environmental Risks Related to Nutrient Management in Paddy-Rice Cultivation

Our analysis showed that the total application of N, P, and K through chemical fertilizers and organic materials (rice residues, compost) to the soils was high (Tables 4 and 5), leading to

a considerable surplus of these nutrients in the soils (Figures 3–5). The continued accumulation of excessive N, P, and K in rice-cropping systems involves a risk of nutrient leaching and potential eutrophication of adjacent surface-water bodies and groundwater [25,26,49]. The risk of eutrophication is particularly high in regions with paddy-rice cultivation, as the nutrient pathways from over fertilized soils to surface- and groundwater are extremely short and straightforward in paddy-rice systems. In the context of eutrophication, P deserves particular attention. Plinthic Acrisols, which are widely used for rice cultivation in Vietnam, and on which this study was performed, are generally considered infertile because of P fixation, low pH and CEC, advanced stage of nutrient leaching, and consequently low nutrient contents [50,51]. Compared to the low P contents reported by Mi [51], in our study, we found increased contents of plant-available P in the soils, especially with compost application (Table 3). An increase was also reported in other studies [30,36]. Therefore, due to the high risk of eutrophication related to paddy-rice cultivation, application of P, both in chemical and organic form, requires particular caution.

Another environmental aspect related to crop-residue management is the emission of fine ash particles from burning crop residues into the atmosphere. These emissions do not only affect the climate, but they also threaten human health in rural communities, as they may cause severe respiratory diseases [52,53]. For instance, burning one ton of rice straw releases 3 kg of particulate matter, 60 kg of CO, 1460 kg of CO₂, 2 kg of SO₂, and 199 kg of ash [4]. In our study, the average amount of rice residues in Luong Phong Commune (Bac Giang Province) was 5.3–5.6 t ha^{−1} per cropping season. Thus, burning the rice residues on all study plots in Luong Phong Commune would release 7.7–8.2 tons of CO₂. This CO₂ release also clearly exceeds the CO₂ release from the decomposition of incorporated rice residues [54], which is relevant in the context of greenhouse-gas balances of rice-cultivation systems.

This study in which we established nutrient balances for paddy-rice fields under different rice-residue management practices, showed that there is an urgent need for improving the nutrient management of paddy-rice cultivation in Vietnam. Three rice-residue management practices were tested in the Luong Phong Commune (Bac Giang Province), (1) direct rice-residue incorporation into the soils after harvest, (2) application of rice-residue compost, and (3) burning of rice residues on the field. All three, together with non-adapted chemical fertilization, led to a surplus of P in the range of 37–52 kg P ha^{−1} and of K in the range of 136–235 kg K ha^{−1}. These positive nutrient balances indicate a risk of excess nutrient accumulation in the soils. Such accumulation may potentially lead to eutrophication of adjacent water bodies. Surface- and groundwater around paddy-rice fields are especially at risk of eutrophication because the groundwater is often very close to the soil surface, and the temporary flooding of the rice fields provides a very direct nutrient pathway from the paddy fields to nearby surface-water bodies. Only for the rice fields in Che Cu Nha Commune (Yen Bai Province), from which rice residues were collected after harvest to be used as fodder for cattle, our study showed a risk of nutrient depletion. It was the only management that resulted in negative N, P, and K balances (−21 kg N ha^{−1}, −2 kg P ha^{−1}, −61 kg K ha^{−1}).

5. Conclusions

Based on these outcomes of our study, we draw two main conclusions for optimized rice-residue and fertilizer management:

- I. We advise against the burning of rice residues. Given the limited availability of manure and labor force in the study regions, we recommend incorporating rice residues into the soils. This management technique is not very labor-intensive, and it has multiple benefits, as it returns nutrients to the soils, thus allowing for reducing the use of chemical fertilizers, and it adds organic matter to the soils, thus potentially increasing SOC contents.
- II. Nutrient inputs need to be better adapted to the crop needs, as demonstrated by the unbalanced nutrient budgets of all the investigated systems in most of the studied cases resulting in nutrient accumulation and in one case resulting in nutrient depletion. Knowledge about (1) soil nutrient contents prior to planting, (2) expected harvest and corresponding nutrient uptake by plants, (3)

nutrient concentrations in the rice residues, and nutrient balances resulting from the different rice-residue management practices, may help to optimize the fertilization practices to obtain high yields from paddy-rice fields without risking eutrophication of adjacent water bodies.

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