Management options for optimizing nutrient cycling and reducing greenhouse gas emissions from smallholder rice farms in Vietnam

Dissertation

for the award of the degree

"Doctor rerum naturalium" (Dr.rer.nat.)

of the Georg-August-Universität Göttingen

within the doctoral program of Geoscience/Geography

of the Georg-August University School of Science (GAUSS)

Submitted by

Dao Trong Hung

Ha tinh, Vietnam

Göttingen, 2019

Thesis Committee

Prof. Dr. Daniela Sauer, Department of Physical Geography, Institute of Geography, University of Göttingen

Dr. Markus Keck, Department of Human Geography, Institute of Geography, University of Göttingen

Members of the Examination Board

Reviewer: Prof. Dr. Daniela Sauer, Department of Physical Geography, Institute of Geography, University of Göttingen

Second Reviewer: Dr. Markus Keck, Department of Human Geography, Institute of Geography, University of Göttingen

Further members of the Examination Board:

Prof. Dr. Heiko Faust, Department of Human Geography, Institute of Geography, University of Göttingen

Prof. Dr. Christoph Dittrich, Department of Human Geography, Institute of Geography, University of Göttingen

Prof. Dr. Martin Kappas, Department of Cartography, GIS and Remote Sensing, Institute of Geography, University of Göttingen

Dr. Daniel Wyss, Department of Cartography, GIS and Remote Sensing, Institute of Geography, University of Göttingen

Date of the oral examination: 30.10.2019

Dedication

This thesis is dedicated to my mother Mai Thị Vỹ

You will always be missed.

Acknowledgements

I have received great help from many people. Here, I would like to take this opportunity to gratefully thank them.

First and foremost I would like to express my deepest appreciation and thanks to my academic supervisors, Prof. Dr. Daniela Sauer and Dr. Markus Keck, for all their support, inspiring encouragement, tireless guidance and helpful comments and suggestions throughout the PhD project. I would like to express my gratefulness to Dr. Felix Heitkamp, who accepted me as a PhD student in the Department of Physical Geography.

Great thanks to everybody in the Department of Physical Geography, Georg-August University Göttingen for inspiration, assistance and enjoyable times during my stay in Germany. Many thanks go to Dr. Harold J. Hughes, Dr. Maxim Dorodnikov, and Dr. Callum C. Banfield for helping me with the lab-study.

My grateful thanks also go to Nguyen Ba Phuong, Tran Thi Nguyet, Cao Thi Hai, Mai Van Long, Nguyen Toan Thang and my colleagues in the Soils and Fertilizers Research Institute for their help and support with my field work. Many thanks to the technicians in the Midland Centre of Soils and Fertilizers Research, who help in taking care of my field experiment. My deepest thanks goes to the people in Che Cu Nha Commune (Yen Bai Province), Luong Phong Commune (Bac Giang Province), and Yen Dong (Nam Dinh Province) for gladly inviting me into their houses and sharing me their knowledge, worries, and dreams of the fortune.

I would like to thank the Vietnamese government for granting me a scholarship to undertake this research. I would like to also acknowledge the Open Access Publication Fund of the University of Göttingen, for supporting me in publishing open access papers through MDPI publisher. I would like to thank the GAUSS family-oriented bridging fund for financially supporting me during the time I was writing this thesis.

Finally, I would like to say thanks to my family for their support and encouragement, and in particular to my wife and my two daughters, Dao Chau Anh and Dao Nguyet Anh, for the happiness they have brought me.

Preface

The present dissertation entitled “Management options for optimizing nutrient cycling and reducing greenhouse gas emissions from smallholder rice farms in Vietnam” has been submitted in partial fulfilment of the requirements for the PhD degree at the Faculty of Geoscience and Geography, University of Göttingen (Germany). The main supervisor was Prof. Dr. Daniela Sauer and the second supervisor was Dr.Markus Keck.

This dissertation is a compilation of six chapters. Besides the Introduction and the Conclusions, the four remaining chapters are based on papers or manuscripts that have been published in, submitted to ISI-indexed journals.

The study was conducted at the Department of Physical Geography, from April 2015 to September 2019.

Göttingen, September 2019

Dao Trong Hung

Summary

Rice is the most important food crop in Asia. However, rice production in Asia is facing tremendous challenges in the 21st century. Fast-growing populations are demanding larger rice supplies under the increasingly difficult production conditions of declining water availability and quality. Furthermore, rice cultivation produces large amount of rice residues. With currently increasing trends in cropping intensity, the amounts of residues that are burned on the field are expected to increase dramatically, unless crop residues are managed more sustainably. Comparative research on the effects of different water and rice residue management practices on nutrient balances and greenhouse gas emissions are needed. They will provide information on the environmental and agronomic consequences of choices in rice residue management practices, including direct incorporation of rice residues into the soil, application of rice-residue compost, burning of rice residues on the field, and use of rice residues as fodder for livestock. The outcome of such studies can then be used to find the best option for rice residue management.

In a survey of rice residue management in northern Vietnam, we examined the present cropping systems and the patterns of crop residue management prevalent in three different ecological zones of northern Vietnam. We compared the farmers' practices of either burning or incorporating the residues of their rice crops, and furthermore, calculated involved costs and benefits. Our data demonstrate that the burning of crop residues might be an erroneous trend from an ecological perspective, but is rational from an economic point of view. Based on this finding, we argue that a change of the prevalent burning practice cannot be achieved without the farmers getting their extra expenses refunded.

A field study was therefore conducted to quantified soil nutrient balances of paddy rice fields under different crop-residue management practices in northern Vietnam. All plots received mineral N, P, and K fertilizer in addition. We found that soils with (1) direct incorporation of rice residues into the soil, (2) application of rice-residue compost, and (3) burning of rice residues on the field showed a positive nutrient balance, which indicates that soil fertility can be maintained under these practices and that amounts of chemical fertilizers can be considerably reduced. Without fertilizers reduction, there is a risk of eutrophication in surrounding surface waterbodies. In contrast, use of rice residues as fodder for livestock, resulted in a negative nutrient balance in paddy soils, which indicates the need for returning nutrients to the soils. From these 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 in northern Vietnam.

Silicon (Si) is known to have beneficial effects for plants, in particular for rice, which is a strong Si accumulator. It helps mitigate environmental stresses and soil nutrient depletion. In some regions plant available Si in soil might be limited and have detrimental effect on rice agriculture. Here we study the impact of three rice residue management practices (burying, burning and manure production for use on the field) in Si-depleted rice fields from northern Vietnam. The different Si reservoirs in soils and the plants Si content were measured under these different practices. Our results show a strong correlation between the different soil Si reservoirs and plants Si content. Our results show no significant difference between the different management practices in terms of Si bio-availability and Si uptake by plants. These new data also suggest also raise the question whether Si-depleted environment may proportionally lose Si faster through grain harvest than other less Si-depleted environment.

In order to compare the fluxes of methane (CH_4) and Nitrous oxide (N_2O) from rice paddy fields managed by differently treated crop residue inputs (direct incorporation of rice residues into the soil (I), application of rice-residue compost (CR), burning of rice residues on-site burning of rice residues (B)) under two water management systems, a field experiment was performed in Bac Giang Province in northern Vietnam. The field experiment was carried out on spring rice and summer rice seasons. The results indicate that water management is a major factor in reducing CH_4 emissions. The alternate wetting and drying (AWD) management led to a reduction of CH_4 emissions by 15-42% for the CR treatment, by 27-47% for the B treatment, and by 36-45% for the I treatment. Similarly, AWD management resulted in a reduction of global warming potential (GWP) by 16-36% (CT), 15-39% (CR), 27-40% (B), and 35-40% (I), respectively. The treatment I led to the highest CH_4 emissions, while the control (CT) showed the lowest CH_4 emissions under both water management systems. Rice yields were slightly higher for treatments including with mineral and organic fertilizers compared to only mineral fertilizer (CT). In conclusion, we recommend a combination of treatment I with AWD water management, as this combination resulted in reduced greenhouse gas emissions while ensuring high rice yields.
Key words: Agricultural, Crop residues, Fertilizers use, Mitigation of methane emissions, Nutrient balance, Smallholder, Vietnam, Water management.

List of manuscripts and publications

Chapter 2	Keck, M.; **Hung, D.** Burn or bury? A comparative cost-benefit analysis of crop residue management practices among smallholder rice farmers in northern Vietnam. *Sustainability Science*. **2019**, *14* (2): 375-389. doi.org/10.1007/s11625-018-0592-z
Chapter 3	**Hung, D.;** Hughes, H.; Keck, M.; Sauer, D. Rice-residue management practices of smallholder farms in Vietnam and their effects on nutrient fluxes in the soil-plant system. *Sustainability*. **2019**, *11* (6): 1641. doi:10.3390/su11061641
Chapter 4	Hughes, H.; **Hung, D.;** Sauer, D. Silicon recycling through rice-residue management does not prevent silicon depletion in paddy rice cultivation *(Under Review in Nutrient Cycling in Agroecosystems)*
Chapter 5	**Hung, D.;** Callum, C.B.; Dorodnikov, M.; Sauer, D. Improved water and rice-residue management may reduce greenhouse gas emissions from paddy soils and increase rice yields *(Under Review in Soil & Tillage Research)*

Table of Contents

List of Figures

List of Tables

Abbreviations

ANOVA	Analysis of Variance
AWD	Alternate Wetting and Drying
B	Burning of rice residues
CCF	Conventional continuous flooding
CF_E	Chemical fertilizers
CEC	Cation exchange capacity
CH_4	Methane
CO_2	Carbon dioxide
CR	Composted rice residues
CT	Control
DAT	Day of transplanting
EE	Environmental Economics
FAO	Food and Agriculture Organization of the United Nations
G_E	Gaseous losses of N
GHG	Greenhouse gas
GHGI	Greenhouse gas intensity
GWP	Global warming potential
I	Incorporation of rice residues into the soil
IW_E	Irrigation water
K	Potassium
L_E	Leaching
N	Nitrogen
NF_E	Nitrogen fixation
NI_E	Nutrients input as rice residue incorporation, compost or ash
N_2O	Nitrous oxide
OC	Organic carbon
P	Phosphorous
PRA	Participatory Rural Appraisal
RG_E	Harvested rice grain
RR_E	Rice residues
RW_E	Rain water

Si	Silicon
SOC	Soil organic carbon
SO_2	Sulfur dioxide
VND	Vietnam dong
SWOT	Strengths Weaknesses Opportunities Threats
WRB	World Reference Base

Chapter 1

1.1 General 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 accruement 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]. Traditionally, rice farming by-products were removed from the fields to be applied as cooking fuel and fodder for ruminants, and after composting, as organic fertilizer. Unfortunately, this form of rice residue management has changed in Vietnam in recent times, as it has in many other Asian countries. Today, an increasing proportion of crop residues is burned in the field directly after harvesting [4–6]. This practice depletes valuable nutrients such as nitrogen (N), phosphorus (P), and potassium (K), and exhausts soils of organic matter [7–9]. Soil nutrient degradation as a result of crop residue burning can be characterized by a decreased nitrate (NO_3) content of 46%, declined N uptake by 29%, and crop yields of only 39% of the possible yield as compared to soils with non-removed crop residues [10]. The burning of rice residue leads to greenhouse gas emissions such as carbon mono- and dioxide (CO, CO_2), nitrous oxide (N_2O), sulfur dioxide (SO_2), and nitrogen oxides (NOx). For instance, burning 1 ton of rice straw releases 3 kg of particulate matter, 60 kg of CO, 1460 kg of CO_2, 2 kg of SO_2, and 199 kg of ash [11], which negatively affects not only the climate but also the human health in rural communities, as it causes severe respiratory diseases [12, 13]. In summary, these research findings show that burning of rice residue often leads to negative nutrient balance and potentially causes pollution.

To solve these problems, incorporation of rice residues into the soil is recommended in Vietnam. Incorporation of 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 mineral fertilizers in agriculture [14–17]. Unfortunately, relatively little research has been published on the effect of rice residue management practices on the involved costs and benefits, and the associated changes that will occur in the nutrient flows of farms in Vietnam with and without incorporation of rice residue. Therefore, a field survey was conducted to determine whether financial benefits arise to farmers when rice residues are incorporated into their fields instead of being burned. Our purpose was to see, if there is an economic incentive for farmers to change their residue management practices from burning to burying, which would have a positive effect on soil health, human health and the climate. Based on our findings, policy recommendations are formulated that best fit the economic conditions of smallholder rice farmers in Vietnam.

Vietnam relies heavily on the import of mineral fertilizers. In the case of K fertilizer, 100% is imported. In 2017, Vietnam imported 4.64 million tons chemical fertilizers at an estimated cost of 1.23 billion US$ [18]. From 1992 to 2015, the average amount of total N, P, and K 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 dollar annually for the economy and causing eutrophication and greenhouse gas emissions [18–20]. Against this background, the use of readily available, cost-efficient and domestically produced organic fertilizer, such as crop residues, may reduce the need of costly imported mineral fertilizers and improve the national trade balance [21, 22]. This would also increase farmers' net income by reducing their investment for mineral fertilizers [21, 23]. Soil nutrient balances are the overall net result of the various nutrient fluxes of a farming system [24, 25]. Nutrient balances have been quantified in Asia and Africa [26–29]. 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 limited the possibility to quantify the main factors that control element balances. Therefore, we studied on rice-residue management practices of smallholder farms in Vietnam and their effects on nutrient fluxes in the soil-plant system. In this study we analyzed the relationship between crop-residues management practice and nutrient flow in the soil-plant system in paddy fields. The aim of the study was to evaluate the potential of crop-residues management to contribute to a more sustainable agriculture in Vietnam in the future.

Silicon (Si) is now broadly recognized as a beneficial substance for plants and a quasi-essential nutrient [30, 31]. Many studies highlight its strong beneficial effects for a variety of plants, particularly under stressful conditions. Si can enhance plant resistance in a large variety of circumstances, which includes for example nutrient depletion, drought stress, pathogens and pest attacks. Evidence suggests multiple combined effects of Si rather than one single effect [32]. The fundamental functioning of these beneficial effects is, however, far from being understood and is still subject for debate [33]. This beneficial effect of Si has been particularly studied for rice due to both its importance as a food source and its strong tendency to accumulate Si. The quantity of Si taken up and accumulated by plants varies according to the species [34]. Rice straw residue management practices may also have an influence on the bio-availability of Si in rice fields [35, 36]. Si cycle and Si bio-availability in rice agriculture have already been the subject of several articles [37, 38]. These studies showed evidence of a strong Si limitation in local rice agriculture, with a possible impact on yields. These studies also emphasized the importance of recycling crop residues for the Si supply to paddy rice in the area, and in regions with low Si availability in general. They pointed to the lack of knowledge on the effect of agricultural practices, in particular straw management, on Si availability and called for more studies. However, most studies focused on comparing the impact straw export with straw residues fertilization. To the best of our knowledge, no study specifically focused on comparing the efficiency of different crop residue management practices in regards to Si recycling.

Rice production in Asia is facing tremendous challenges in the 21st century. The fast-growing population is demanding larger rice supplies under the increasingly difficult production conditions of declining water availability and quality [1, 39, 40]. Rice cultivation accounts for nearly 20% of global anthropogenic methane (CH_4) emissions [41], whereby the magnitude of CH_4 emissions depends on organic matter application, soil organic matter (SOM) contents, and anaerobic soil conditions [42–45]. Another greenhouse gas (GHG) emissions is nitrous oxide (N_2O). Emissions of N_2O from paddy soils depend on soil nitrogen (N) stocks and quality, and on water management [46, 47]. Carbon dioxide (CO_2) fluxes are a source of GHG emissions, too, but at global scale they are estimated to contribute less than 1% to the global warming potential (GWP) of agriculture [48]. Vietnam is one of the largest rice producers and exporters in the world, with more than seven million hectares of paddy rice [49]. Paddy rice production is the largest source of GHG emission in Vietnam's agriculture, contributing about 44.7 Tg CO_2 equivalents, accounting for more than 50% of the total agricultural GHG emissions [50]. Paddy rice fields have a high potential to emit CH_4, because flooding leads to anaerobic CH_4 production [51]. Especially the combination of organic resource fertilizer application, the nitrogen and water management by flooding in paddy rice generating high GHG emissions. Hence, there is a conflict between irrigation water management, rice residue management and GHG emissions in rice production.

Vietnamese farmers have been using organic fertilizer for a long time [52, 53]. Organic fertilizers not only supply macro-nutrient as N, P, and K but also micronutrients that are not contained in commercial chemical NPK fertilizers [54, 55]. Moreover, organic fertilizers help improving soil fertility by increasing cation exchange capacity (CEC) and soil organic carbon (SOC) content. However, there is a decreasing trend of organic fertilizer application [53, 56, 22, 22]. Farmers would prefer to apply more organic fertilizers, especially to rice, maize, and peanuts, but the amounts of organic fertilizers produced on their own farms is not enough to supply their fields [22, 57, 57, 57], as revealed by interviews that we carried out in 2015 Ourselves(obtained 2015, unpublished). This decline of organic fertilizers 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 [58], and (3) the ready availability of chemical fertilizers that seem to provide an easy substitution of manure [59].

As a common practice in paddy rice cultivation in Vietnam, the paddy fields are continuously flooded Water apply continuously throughout the growing season, which is a common practice in Vietnam [60]. Alternate wetting and drying (AWD) is a water-saving technique that has been developed for rice cultivation in Asia [39, 61]. By this practice, the amount of water can be reduce by 30–40% compare to the conventional continuous flooding (CCF) without adversely affecting their yields and/or profitability [62]. Furthermore, application of AWD does not only reduce CH_4 emissions but also increases in rice yields compared to CCF [63–65].

However, there has been little research to date on the effect of different rice residue management practices, as open burning on the field, application of composted rice residues, direct incorporation of rice residues into the soil on CCF and AWD under water management. Therefore, we conducted a field experiment to determine the effects of different rice residue management practices and water management on rice yields and GHG emissions from paddy rice fields on smallholder farms in norther Vietnam.

We hypothesized that incorporation of rice residues or composted of rice residues in combination with AWD can reduce CH_4 emissions without increasing N_2O emissions. The benefit of AWD is the reduction in water use, whereas the advantages of rice residue incorporation compared to burning include the build-up SOC, soil N, P, K nutrition and the improvement of soil-water holding capacity, and bulk density.

1.2 Objective

The main objective of this study was to develop strategies for optimizing rice residue, water management for improving plant nutrition and reducing greenhouse gas.

Therefore, I investigated the effects of different rice residue management options, including application of composted rice residues, burning of rice residues on the field, and direct incorporation of rice residues into the soil, with and without AWD water management, on plant nutrition as well as greenhouse gas emissions from the fields. The outcomes provide information on the environmental and agronomic consequences of choices made in rice residue management on smallholder farms and can consequently be used to identify the optimal rice residue management.

The specific objectives were:

i) to investigate the current practices of rice residue management on smallholder farms in northern Vietnam,

ii) to evaluate agricultural inputs and outputs of nitrogen, phosphorous, and potassium in different rice-residue management systems, and to identify potentials and problems in each of the crop-residue management systems with respect to the prospective potential of partially substituting imported chemical fertilizers by rice residues,

iii) to assess how the different rice residue management practices affect the different soil Si pools in a system that is potentially Si-depleted, as rice is a Si accumulator and tropical soils are usually poor in Si,

iv) to examine the effects of rice residue management (open burning on the field, application of composted rice residues, direct incorporation of rice residues into the soil) and water regimes (conventional continuous flood, alternate wetting and drying) on greenhouse gas emissions.

1.3 Research questions

This research seeked to address the following questions:

- ✓ What are currently the most common practices of rice residue management on smallholder farms in northern Vietnam?
- ✓ What are the fertilizer values of different rice residue management practices (incorporation, application of composted rice residues, burning rice residues on the fields, using rice residues as fodder for cattle) when applied to rice in the field?
- ✓ How does different rice residue management affect nutrient fluxes in the plant-soil system?

- ✓ What are the effects of different rice residue management on silicon-depleted soils and silicon bio-availability?
- ✓ How does different rice residue management (incorporation, application of composted rice residues, burning rice residues) and water management affect on greenhouse gas emissions and rice yield?

1.4 Overview of the study

This dissertation comprises six chapters. Apart from the Introduction and Conclusion, the four main chapters are based on two papers and two manuscripts that have been published in or submitted to ISI-indexed journals.

The six chapters include:

Chapter 1: This chapter presents a basic background of the research. It gives an overall introduction of the research problems and specific objectives.

Chapter 2: This chapter introduces the present rice-cropping systems and crop residue management practices prevalent in three different ecological zones of northern Vietnam. I compare the farmers' practices of either burning or incorporating the residues of their rice crops, and furthermore, calculate involved costs and benefits. The burning of crop residues might be an erroneous trend from an ecological perspective, but is rational from an economic point of view. I argue that a change of the prevalent burning practice cannot be achieved without refunding the farmers for their extra expenses.

Chapter 3: This chapter presents and discusses quantified soil nutrient balances of paddy rice fields under different crop-residue management practices in northern Vietnam. Soils under direct incorporation of rice residues into the soil and burning of rice residues on the field practices 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 surrounding surface waterbodies. Use of rice residues as fodder for livestock resulted in a negative nutrient balance, which stresses the need for returning nutrients to the soils. I 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 agricultural practice.

Chapter 4: This chapter presents and discusses the effects of three rice residue management practices (incorporation into the soil, burning and manure production for use on the field) in Si-depleted rice fields of northern Vietnam. We analyzed the different Si reservoirs in soils and plants under these different practices. The results show a strong correlation between the different soil Si reservoirs and plant Si contents. We found no significant difference between the different management practices in terms of Si bio-availability and Si uptake by plants.

Chapter 5: This chapter presents and discusses the effects of water and rice-residue management on greenhouse gas emissions and rice yields. The results indicate that water management is a major factor in reducing CH_4 emissions. Alternate wetting and drying (AWD) management led to a reduction of CH_4 emissions by 15-42% for the application of composted rice residues (CR) treatment, by 27-47% for the on-site burning of rice residues (B) treatment, and by 36-45% for the incorporation of rice residues into the soil (I) treatment. Similarly, AWD management resulted in a reduction of global warming potential (GWP) by 16-36% (CT), 15-39% (CR), 27-40% (B), and 35-40% (I), respectively. The treatment I led to the highest CH_4 emissions, while the control (CT) showed the lowest CH_4 emissions under both water management systems. Rice yields were slightly higher for treatments including organic fertilizers compared to only mineral fertilizer (CT). In conclusion, we recommend a combination of treatment I with AWD water management, as this combination resulted in reduced greenhouse gas emissions while ensuring high rice yields.

Chapter 6: This chapter summarizes the results obtained from Chapters 2 – 5 and answers the research questions listed in Chapter 1. Finally, I provide recommendations and point out future research directions.

References

1. (GRiSP) Global Science Partnership. *Rice almanac*, 4th; International Rice Research Institute: Philippines, 2013.
2. FAO. Smallholders data portrait. *Available online: http://www.fao.org/family-farming/data-sources/dataportrait/farm-size/en/ (05/19/2017). 2017. Available online: http://www.fao.org/family-farming/data-sources/dataportrait/farm-size/en/.*
3. (GSO) General Statistics Office of Vietnam. *Statistical Summary Book of Vietnam;* Statistical Publishing House: Hanoi, Vietnam, 2017.
4. Hai, H.T.; Tuyet, N. *Benefit of the 3R Approach for Agricultural waste Management (AWM) in Vietnam*: Hayama, Japan, 2010.
5. Hoang, A.L.; Nguyen, T.; Le, T.L. Estimated gas emissions from burning rice straw in open fields in Thai Binh Province. *J Sci* **2013**, *29*, 26–33.
6. Tran, S.N.; Nguyen, T.; Nguyen, H.C.; Nguyen, V.; Le, H.V.; Ingvorsen, K. To quantify the seasonal rice straw and its use in different provinces in the Vietnamese Mekong Delta. *J. Sci.* **2014**, *32*, 87–93.
7. Fairhurst, T.; Witt, C.; Buresh, R.; Dobermann, A. *Rice: a practical guide to nutrient management.* International Rice Research Institute, International Plant Nutrition, International Potash Institute: Metro Manila, Philippines, 2007.
8. Kumar, K.; Goh, K.M.; Scott, W.R.; Frampton, C.M. Effects of 15 N-labelled crop residues and management practices on subsequent winter wheat yields, nitrogen benefits and recovery under field conditions. *J Agric Sci Camb* **2001**, *136*, 35–53.

9. Prabhat, K.G.; Shivraj, S.; Nahar, S.; Dixit, C.K.; Singh, D.P.; Sharma, C.; Tiwari, M.K.; Raj, K.G.; Garg, S.C. Residue burning in rice-wheat cropping system: causes and implications. *Curr Sci* **2004**, *87*, 1713–1717.
10. Krishna, G.M.; Arun, K.M.; Kuntal, M.H.; Kali, K.B.; Prabir, K.; Bandyopadhyay, P.; Manoranjan, M. Rice residue-management options and effects on soil properties and crop productivity. *Food Agric Environ* **2004**, *2*, 224–231.
11. Gadde, B.; Bonnet, S.; Menke, C.; Garivait, S. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. *Environ Pollut* **2009**, *157*, 1554–1558.
12. Cancado, J.; Saldiva, P.; Pereira, L.; Lara, L.; Artaxo, P.; Martinelli, L.A.; Arbex, M.A.; Zanobetti, A.; Braga, A. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. *Environ Health Perspect 114(5):* **2006**, *114*, 725–729.
13. Awasthi, A.; Singh, N.; Mittal, S.; Gupta, P.; Agarwal, R. Effect of agriculture crop residue burning on children and young on PETs in North West India. *Sci Total Environ 408:4440–4445.* **2010**, *408*, 4440–4445.
14. Hoang, N.T.; Tran, T.T.; Dao, T.H.; Nguyen, N.M.; Pham, T.N.; Nguyen, T.N.; Nguyen, H.T.; Vu, D. Q.ö Ho, C.T. *Effect of Agricultural Residues Incorporation into Soils on Increasing Crops Yield, Reducing Mineral Fertilizers Applied and Improving Soil Properties*. The Rsults of Soils and Fertilizers Research; Agricultural Publishing: Hanoi, Vietnam, 2014.
15. Keck, M.; Hung, D.T. Burn or bury? A comparative cost–benefit analysis of crop residue management practices among smallholder rice farmers in northern Vietnam. *Sustain. Sci.* **2018**, *14*, 375–389.
16. Tran, T.T.; Hung, T.D. Effect of crop by-product on yield and possibility of reducing potassium application rate for crops under rice-based cropping systems on marine sandy soils and grey-degraded soils. *Vietnam Soil Sci. J.* **2010**, *33*, 89–95.
17. Zhao, Y.; Wang, P.; Li, J.; Chen, Y.; Ying, X.; Liu, S. The effects of two organic manures on soil properties and crop yields on a temperate calcareous soil under a wheat–maize cropping system. *Eur. J. Agron.* **2009**, *31*, 36–42.
18. (MARD) Ministry of Agriculture & Rural Development. *Annual Report 2017 of Fertilizers Sector*: Hanoi, Vietnam, 2018.

19. FAO. FAOSTAT Database. Available online: http://www.fao.org/faostat/en/#data/EF (accessed on 24 April 2018).
20. Pham, Q.H.; Nguyen, V.B. *Fertilizer and Mitigation of Greenhouse Gas Emission*. *National Workshop on Measures for Improving Fertilizer Use Efficiency in Vietnam (March 28, 2014);* Agricultural Publishing: Hanoi, Vietnam, 2014.
21. Bui, H.H. *Assessing the Present Use of Chemical Fertilizers and Promoting Methods to Improve the Use of Fertilizers for Crop Production in Vietnam;;* Soils and Fertilizers Research Institute: Hanoi, Vietnam, 2008.
22. Nguyen, V.B.; Tran, M.T.; Nguyen, V.C.; Le, T.; Bui, H.A.; Nguyen, T.T.; Chu, V.H.; Nguyen, H.; Bui, H.D.; Nguyen, D. et al. *Study on Determination of Limited Factors of Soils in Red River Delta, Mekong River Delta and Recommended Solutions;*: Hanoi, Vietnam, 2014.
23. Baumann, L. *Insights into Vulnerability of Smallholder Farming Systems in the Upland Region of North Vietnam;* Swiss Federal Institute of Technology: Zurich, Switzerland, 2014.
24. Cobo, J.G.; Dercon, G.; Cadisch, G. Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. *Agric. Ecosyst. Environ.* **2010**, *136*, 1–15.
25. Stoorvogel, J.J.; Smaling, E. *Assessment of Soil Nutrient Depletion in Sub-Saharan Africa;*: Wageningen, The Netherlands, 1990.
26. Abdalla, S.B.; Predotova, M.; Gebauer, J.; Buerkert, A. Horizontal nutrient flows and balances in irrigated urban gardens of Khartoum, Sudan. *Nutr. Cycl. Agroecosyst.* **2012**, *92*, 119–132.
27. Huang, B.; Shi, X.; Yu, D.; Öborn, I.; Blombäck, K.; Pagella, T.F.; Wang, H.; Sun, W.; Sinclair, F.L. Environmental assessment of small-scale vegetable farming systems in peri-urban areas of the Yangtze River Delta Region, China. *Agric. Ecosyst. Environ.* **2006**, *112*, 391–402.
28. Khai, N.M.; Ha, P.Q.; Öborn, I. Nutrient flows in small-scale peri-urban vegetable farming systems in Southeast Asia—A case study in Hanoi. *Agric. Ecosyst. Environ.* **2007**, *122*, 192–202.
29. Phong, L.T.; Stoorvogel, J.J.; van Mensvoort, M.; Udo, H. Modeling the soil nutrient balance of integrated agricultural aquaculture systems in the Mekong Delta, Vietnam. *Nutr. Cycl. Agroecosyst.* **2011**, *90*, 33–49.

30. Coskun, D., Deshmukh, R., Sonah, H., Menzies, J.G., Reynolds, O., Ma, J.F., Kronzucker, H.J., Bélanger, R.R. The controversies of silicons role in plant biology. *New Phytol* **2019**, 221.
31. Epstein, E. SILICON. Annu. Rev. Plant Physiol. *Plant Mol. Biol.* **1999**, 641–664.
32. Guntzer, F.; Keller, C.; Meunier, J.-D. Benefits of plant silicon for crops: a review. *Agron. Sustain. Dev.* **2012**, 201–213.
33. Coskun, D.; Deshmukh, R.; Sonah, H.; Menzies, J.G.; Reynolds, O.; Ma, J.F.; Kronzucker, H.J.; Bélanger, R.R. The controversies of silicons role in plant biology. *New Phytol.* **2019**, 67–85.
34. Hodson, M.J.; White, P.J.; Mead, A.; Broadley, M.R. Phylogenetic Variation in the Silicon Composition of Plants. *Ann. Bot.* **2005**, 1027–1046.
35. Klotzbücher, T.; Leuther, F.; Marxen, A.; Vetterlein, D.; Horgan, F.G.; Jahn, R. Forms and fluxes of potential plant-available silicon in irrigated lowland rice production (Laguna, the Philippines). *Plant Soil* **2015**, 177–191.
36. Savant, N.K.; Datnoff, L.E.; Snyder, G.H. Depletion of plant-available silicon in soils: A possible cause of declining rice yields. *Commun. Soil Sci. Plant Anal.* **1997**, 1245–1252.
37. Klotzbücher, Thimo, Marxen, A., Vetterlein, D., Schneiker, J., Türke, M., van Sinh, N., Manh, N.H., van Chien, H., Marquez, L., Villareal, S., Bustamante, J.V., Jahn, R. Plant-available silicon in paddy soils as a key factor for sustainable rice production in Southeast Asia. *Basic Appl. Ecol.* **2015**, 665–673.
38. Klotzbücher, T.; Marxen, A.; Jahn, R.; Vetterlein, D. Silicon cycle in rice paddy fields: insights provided by relations between silicon forms in topsoils and plant silicon uptake. *Nutr. Cycl. Agroecosystems* **2016**, 157–168.
39. Bouman, B.; Tuong, T. Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management* **2001**, *49*, 11–30, doi:10.1016/S0378-3774(00)00128-1.
40. Tuong, T.; Bouman, B. *Water Productivity in Agriculture: Limits and Opportunities for Improvement. Rice production in water scarce environments,*, J.W. Kijne, R. Barker, D. Molden,, 2003.
41. Yan, X.; Akiyama, H.; Yagi, K.; Akimoto, H. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the

2006 Intergovernmental Panel on Climate Change Guidelines. *Glob. Biogeochem. Cyscles* **2009**, *23*, 1–15.
42. Sass, R.L.; Fisher, F.M.; Harcombe, P.A.; Turner, F.T. Mitigation of methane emission from rice fields: possible adverse effects of incorporated rice straw. *Glob. Biogeochem. Cycles* **1991**, *5*, 275–287.
43. Mosier, A.; Wassmann, R.; Verchot, L.; King, J.Palm, C. Methane and nitrogen oxide fluxes in tropical agricultural soils: sources, sinks and mechanisms. *Enviton Dev Sustain* **2004**, 11–49.
44. Wassmann, R.; Latin, R.S.; Neue, H.U.; Buendia, L.V.; Corton, T.; Lu, Y. Characterrization of methane emissions from rice fields in Asia: Mitigation options and future research needs. *Nutr Cycl Agroecosyst.* **2000**, 23–26.
45. Yagi, K.; Minami, K. Effect of organic-matter application on methane emission from some Japanese paddy fields. *Soil Sci Plant Nutr* **1990**, 599–610.
46. Skinner, C.; Gattinger, A.; Muller, A.; Mäder, P.; Flieβbach, A.; Stolze, M.; Ruser, R.; Niggli, U. Greenhouse gas fluxes from agricultural soils under organic and non-organic management—a global meta-analysis. *Sci. Total Environ.* **2014**, *468*, 553–563.
47. Wang, J.; Zhang, X.; Xiong, Z.; Khalil, M.; Zhao, X.; Xie, Y.; Xing, G. Methane emissions from rice agroecosystem in South China: effect of water regime, straw incorporation and nitrogen fertilizer. *Nutr. Cycl. Agroecosyst.* **2012**, *93*, 103–112.
48. Smith, P.; Martino, D.; Cai, Z. et al. *Agriculture. In: Climate Change 2007: Mitigation. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change,*, Metz, B.; Davidson, O.R.; Bosch, P.R.; Dave, R.; Meyer, L.A.;; Cambridge University Press: Cambridge, UK and New York, NY, USA.,, 2007.
49. FAO. *The database of FAOSTAT. http://www.fao.org/faostat/en/#data/QC. (Accessed 13 August 2018)* 2016.
50. (MoNRE) Ministry of Natural Resources and Environment. *The second biennial updated report of Vietnam to the United Nations framework convention on climate change;;* Vietnam Publishing House of Natural Resources, Environment and Cartography: Hanoi, Vietnam, 2017.
51. Corton, T.M.; Bajita, J.B.; Grospe, F.S.; Pamplona, R.R.; Asis Jr, C.A.; Wassmann, R.; Lantin, R.S.; Buendia, L.V. Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines). *Nutr. Cycl. Agroecosyst.* **2000**, *58*, 37–53.

52. (SFRI) Soils and Fertilizers Research Institute. *Fertilizers Handbook;* Agriculture Publishing House: Hanoi, Vietnam, 2005.
53. Vu, T.; Tran, M.T.; Dang, T.A. survey of manure management on pig farms in Northern Vietnam. *Livest. Sci.* **2007**, *112*, 288–297.
54. Bui, D.D. An overview on fertilizer use in Vietnam. *Vietnam Soil Sci. J.* **1996**, *6*, 21–25.
55. Doberman, A.; Fairhurst, T.H. *Rice Nutrient Disorders & Nutrient Management;* International Rice Research Institute: Los Baños, Philippines, 2000.
56. Nguyen, V.B.; Tran, M.T.; Nguyen, V.C.; Le, T.; Bui, H.A.; Nguyen, T.T.; Chu, V.H.; Nguyen, H.; Bui, H.D.; Nguyen, D.*; et al. Study on Determination of Limited Factors of Soils in Red River Delta, Mekong River Delta and Recommended Solutions;;;* Soils and Fertilizers Research Institute: Hanoi, Vietnam, 2014.
57. Hoang, N.; Tran, T.T.; Dao, T.H.; Vu, D.Q. Effect of crop by-product on yield of rice and maize under Spring rice–Summer rice–Winter maize cropping system on Red river alluvial soils, grey degraded soils and marine soils. *Vietnam Soil Sci. J.* **2010**, *33*, 95–106.
58. Pillot, D.; Le Coq, J.F.; Hoa, N.T.; Porphure, V. *Stakeholders' Perception of Pig Effluent Management in Thai Binh Province*. *Pig Production Development, Animal Waste Management and Environment Protection: A case Study In Thai Binh Province, North Vietnam;* CIRAD-PRISE Publication: France, 2006.
59. Phuong, N.D.; Tuan, V.D.; Toan, T.D. *Farmers Practices in Organic and Inogarnic Fertilization on Crops, Trees and Vegetables*. *Pig Production Development, Animal Waste Management and Environment Protection: A case Study in Thai Binh Province, North Vietnam;* CIRAD-PRISE Publication: France, 2006.
60. van Trinh, M.; Tesfai, M.; Borrell, A.; Nagothu, U.S.; Bui, Thi Phuong Loan; Quynh, V.D.; Le Thanh, Q. Effect of organic, inorganic and slow-release urea fertilisers on CH4 and N2O emissions from rice paddy fields. *Paddy Water Environ* **2017**, *15*, 317–330.
61. Belder, P.; Bouman, B.; Spiertz, J.; Cabangon, R.; Guoan, L.; Quilang, E.; Li, Y.; Tuong, T.P. Effect of water and nitrogen management on water use and yield of irrigated rice. *Agricultural Water Management* **2004**, *65*, 193–210.
62. Rejesus, R.M.; Palis, F.G.; Rodriguez, Divina Gracia P.; Lampayan, R.M.; Bouman, B.A. Impact of the alternate wetting and drying (AWD) water-saving irrigation

technique: Evidence from rice producers in the Philippines. *Food Policy* **2011**, *36*, 280–288, doi:10.1016/j.foodpol.2010.11.026.
63. Lu, W.F.; Chen, W.; Duan, B.W.; Guo, W.M.; Lu, Y.; Lantin, R.S.; Wassmann, R.; Neue, H.U. Methane emissions and mitigation options in irrigated rice fields in Southeast China. *Nutr Cycl Agroecosyst* **2000**, *58*, 65–73.
64. Pandey, A.; Mai, V.T.; Vu, D.Q.; Bui, T.; Mai, T.; Jensen, L.S.; A. de Neergaard. Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. *Agric. Ecosyst. Environ.* **2014**, *196*, 137–146.
65. Triol-Padre, A.; Dang, H.T.; Nghia, H.T.; Hau, D.V.; Ngan, T.T.; An, L.V.; Minh, N.D.; Wassmann, R.; Sander, B.O. *Measuring GHG emissions from rice production in quang nam province (Central vietnam): emission factors of different landscapes and water management practices. Land Use and Climate Change Interaction in Central Vietnam, Water Resources Development and Management*, A. Nauditt, L. Ribbe (Eds); Springer Science + Business Media: Singapore, 2017.

Chapter 2

This chapter is based on the published paper: Keck, M.; Hung, D. **Burn or bury? A comparative cost–benefit analysis of crop residue management practices among smallholder rice farmers in northern Vietnam**. *Sustainability Science*. **2019**, *14* (2): 375–389.

Abstract

In Vietnam, approximately 39 million tons of rice (Oryza sativa) residues are produced every year. While a substantial quantity of these residues are used for animal feed, soil mulching, or fuel purposes, a large portion is burned on-farm. The burning of crop residues not only causes environmental pollution through greenhouse gas emissions adding to global warming but also results in the depletion of valuable nutrients such as nitrogen, phosphorus, and potassium. With current increasing trends in cropping intensities, the amounts of residues that are burned on the field are expected to increase dramatically, unless crop residues are managed more sustainably. In this study, we examine the present cropping systems and the patterns of crop residue management prevalent in three different ecological zones of Northern Vietnam. We compare the farmers' practices of either burning or incorporating the residues of their rice crops, and furthermore, calculate involved costs and benefits. Our data demonstrate that the burning of crop residues might be an erroneous trend from an ecological perspective, but is rational from an economic point of view. Based on this finding, we argue that a change of the prevalent burning practice cannot be achieved without the farmers getting their extra expenses refunded.

Keywords: Agricultural, Cost-benefit analysis, Crop residues, Economic incentives, Smallholder, Vietnam.

2.1 Introduction

Rice (*Oryza sativa*) is the most important food crop in Vietnam. Annual rice consumption amounts to 150–200kg per capita per year, providing inhabitants with 60% of protein and 50–70% of calories from dietary intake [1]. Currently, Vietnam is one of the largest rice producers in Asia, ranking third among rice exporting countries following India and Thailand [1]. While two crop seasons are considered in northern Vietnam, in some southern regions, three seasons are possible due to climate conditions and extensive irrigation systems. With a median landholding size of 0.65 ha [2] , smallholders are the backbone of the country's agriculture.

On average, one ha of rice generates about five tons of waste, equating to approx. 39 million tons of rice residue per year in Vietnam [3]. Traditionally, rice farming by-products were removed from fields to be applied as cooking fuel and fodder for ruminants, and following composting, as organic fertilizer. Unfortunately, this form of rice residue management has changed in Vietnam in recent times, as it has in many other Asian countries. Today, an increasing proportion of crop residues is burned in the field directly after paddy harvesting [4, 5].

In the last years, a significant body of literature has emerged addressing the negative environmental impacts of burning crop residues in the field [4–11] . This practice depletes valuable nutrients like nitrogen (N), phosphorus (P), and potassium (K), including depriving soils of organic matter [12–14] (12, 13, 14). Soil nutrient degradation as a result of crop residue burning can be characterized by a decreased nitrate (NO_3) content of 46%, declined N uptake by 29%, and crop yields of only 39% of the possible yield as compared to soils with non-removed crop residues[15]. (2) The burning of crop residues decreases the soil's microbial population involved in nitrification [15]. In the surficial 2.5cm of the soil, single burning activities lead to a slight decrease of bacterial and fungal populations, whereas repeated burning practices may diminish bacterial populations by more than 50%. (3) The burning of crop residues immediately increases the exchangeable ammonium (NH_4^+-N) and bicarbonate-extractable P content so that, ultimately, no nutrients can be built up in the profile [16]. (4) The burning of agricultural residues leads to greenhouse gas emissions like methane (CH_4), carbon mono- and dioxide (CO, CO_2), nitrous oxide (N_2O), sulfur dioxide (SO_2), and nitrogen oxides (NO_x). For instance, burning one ton of rice straw releases 3 kg of particulate matter, 60 kg of CO, 1460 kg of CO_2, 2 kg of SO_2, and 199 kg of ash (6), which affects not only the climate, but also the human health in rural communities negatively, as it causes severe respiratory diseases [17–18].

As compared to the burning of crop residues on the field, the practice of burying them can provide certain ecological advantages that improve the physical and chemical properties of the soils. These advantages include improving hydraulic conductivity, reducing soil bulk densities, decreasing average soil temperatures during hot seasons, increasing mean weight diameters, and raising water storage capacities. In sum, incorporating crop residues contributes substantially to soil health and thus to sustainable crop yields [19–23]. At that, altering agricultural practices from burning to burying would considerably contribute to the mitigation of global environmental change.

In this study, we examine the present cropping systems and the patterns of crop residue management prevalent in three different ecological zones of northern Vietnam. We compare smallholders' practices of either burning or burying the residues of rice crops in three communes, i.e. Yen Dong (Nam Dinh Province), Luong Phong (Bac Giang Province), and Che Cu Nha (Yen Bai Province), and calculate involved costs and benefits. The aim of this study is to determine whether financial savings arise to farmers when rice residues are incorporated into their fields instead of being burned. We do this to see if there is an economic incentive for farmers to change their residue management practices from burning to burying, which would have a positive impact on soil health, human health and the climate. Based on our findings, policy recommendations are formulated that best fit the economic conditions of smallholder rice farmers in Vietnam.

Theoretical frame

Cost-benefit analyses can be said to be part of the standard repertoire of Environmental Economics (EE), which had been chosen as theoretical frame for this study. EE is a sub-discipline of economics that studies the financial aspects of environment-friendly practices and policies on different analytic scales [24]. Environmental economists perform empirical studies that take into account the environmental costs and benefits of certain economic practices in order to help designing appropriate political measures for crafting more sustainable economies.

The fundamental argument underpinning EE is that economic growth involves environmental costs that go unaccounted in the standard market model. These negative externalities, if staying unaccounted, can result in market failure, which means that markets – under specific circumstances – are unsuccessful to allocate scarce resources to generate the greatest social welfare [25]. In their studies, environmental economists thus try to include the negative externalities of specific economic practices into their market models so that, eventually, market failure can be prevented. Equipped with the results of their calculations, environmental economists are able to provide policy advice. In general, there are two broad ways of how governments can deal with negative environmental impacts of their respective economies [24, 26]: For instance, if a state is trying to impose a transition to clean energy, it can legislate a law that forcibly limits companies' carbon emissions, or it can place taxes on carbon emissions that provide companies an incentive to adopt for renewable power sources. While the first of these two approaches would be a restriction-based approach, the second would be an incentive-based solution.

In our case study, we take the positive and negative externalities of two types of rice crop residue management into account (burning vs. burying) and translate them into economic figures. By doing so, we are able to determine whether financial savings arise to farmers when they incorporate the residues into their fields instead of burning them. If so, these savings could be advertised as an economic incentive for transforming agriculture in Vietnam towards a more sustainable way. If not, empirical evidence is provided on the extra expenses that farmers should be refunded if sustainable agriculture is the Vietnamese state's primary goal.

2.2 Material and methods

2.2.1 Study sites

Table 2.1 Key characteristic of the three provinces of interests

Province	Nam Dinh	Bac Giang	Yen Bai
Enviromental indicators			
Topogarphy	Lowlands	Hills	Mountains
Main soil type	Alluvial	Grey degraded	Acrisol
Mean temperature	24.0 ^{0}C	23.5 ^{0}C	22.8 ^{0}C
Mean precipitation	1790 mm	1620 mm	1337 mm
Socio-economic indicators			
Rural population	1.5 million	1.5 million	0.6 million
Area planted with rice (as propotion of are plated with cereal)	97 %	91 %	59 %
Average yield per ha	6.1 tons	5.6 tons	5.0 tons
Percentage of communes with local store for agricultural input	100 %	81 %	65 %

Source: [27–34]

For our study, we selected three provinces, i.e., Nam Dinh in the Red River Delta's lowlands bordering the Gulf of Tonkin, Bac Giang in the northern hill areas located 50 km to the East of Hanoi, and Yen Bai in the mountainous region of northern Vietnam (Figure 2.1). We selected these provinces as they fall in three ecological zones with varying key characteristics (Table 2.1). This selection enabled us to compare different systems of rice residue management, and to identify regions that allow for a transformation of prevalent practices from both economic and ecological standpoints.

2.2.2 Province level

Nam Dinh Province was selected as it exhibits the largest area under spring and summer rice in the Red River Delta [31], and as from all northern provinces it encompasses the largest area of alluvial soil [35]. The alluvial soils of the Red River Delta are suitable for the production of rice, maize, peanuts, soybeans, tomatoes, potatoes, vegetables, and fruit trees [27]. The climate in Nam Dinh is humid-tropical, the average air moisture is 83%, and the rainy season lasts from May to October (Table 2.1).

Bac Giang Province was selected as it exhibits the largest area under spring and summer rice in the midlands and northern mountains [31], and from all northern provinces it has the largest area of grey degraded soils [28–30]. The climate in the province is monsoon subtropical (Table 2.1) and more than 80% of the annual rainfall occurs between May and October. The grey degraded soil is often considered infertile. Nevertheless, such soils have been extensively exploited for agricultural purposes, especially in regions where rice, vegetables and other annual crops are cultivated intensively [37].

Yen Bai Province was selected as from all northern provinces it encompasses the largest areas of terraced rice fields (elevation >1,000 m) [38] as well as the largest area of Acrisol [27]. This soil type, which is distributed throughout the midland and mountainous provinces, is characterized by lower total and biologically available P and K nutrients as compared to alluvial soils [38–39]. The climate of the region is humid-tropical. The mean daily temperature ranges from 38–40°C during June and July to 2–5°C from December to February. The average air moisture is 81%.

2.2.3 District and commune level

In each province, we chose one district, and in each district, we studied one commune (Figure 1).

This study was conducted in Y Yen District (Nam Dinh Province), Hiep Hoa District (Bac Giang Province), and Mu Cang Chai District (Yen Bai Province) for two reasons: (1) Literally all farmers produce rice in these districts and thus all of these districts encompass large rice planted areas [30–33]. (2) All three districts feature the mentioned dominant soil types (alluvial, grey degraded, Acrisol) [28, 29, 35, 36, 37, 38]. In each of these three districts, one commune was chosen randomly for the collection of empirical data.

The inhabitants of Yen Dong Commune (Nam Dinh Province) and Luong Phong Commune (Bac Giang Province) belong to the Kinh ethnic group, which accounts for over 85% of the population in Vietnam. The residents of Che Cu Nha Commune (Yen Bai Province) belong to one of the country's ethnic minorities called H'Mong. In the past, H'Mong people practised a semi-nomadic lifestyle, but recently they have become mostly sedentary as a result of government policy on "settled agriculture and fixed residence" [40–41].

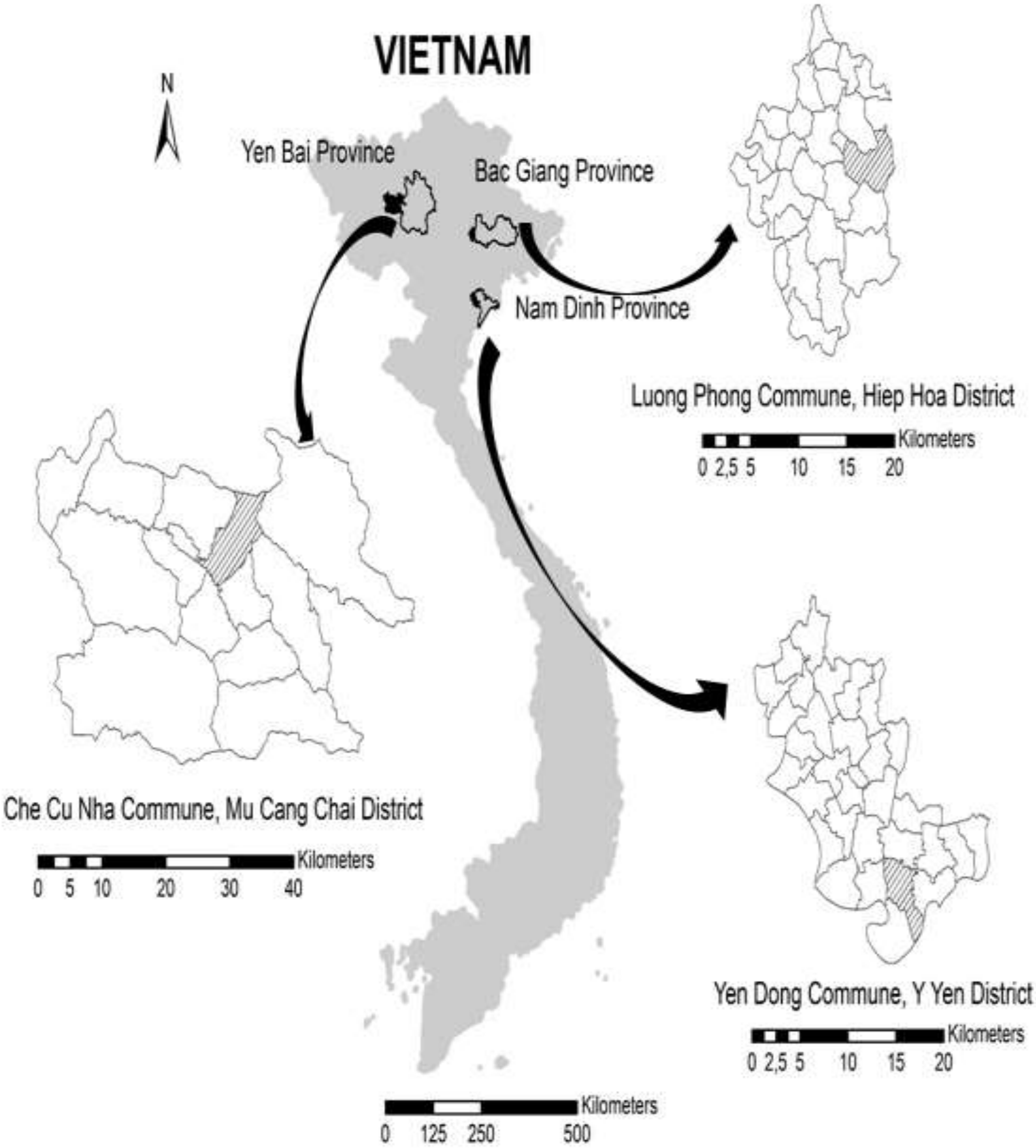


Fig. 2.1. Study sites in northern Vietnam

2.2.4 Data collection and analysis

The research process was divided into three phases. In the first phase, literature was reviewed on crop residue management patterns in rice farming countries worldwide, questions for qualitative and quantitative data collection were prepared, and logistical aspects of the fieldwork were clarified. The second phase comprised the data collection in

Vietnam. Expert interviews were conducted, selected tools of the social science package Participatory Rural Appraisal (PRA) were applied, a standardized survey was organized, and crop residue samples were taken. In the last phase, the collected data was organized, analyzed and interpreted in collaboration with colleagues in Vietnam and Germany.

2.2.5 Expert interviews

First of all, expert interviews were conducted with researchers in Hanoi and with staff of agricultural extension centers at the province, district and commune level. Afterwards, village leaders as representatives of the People's Committees at the commune level were met to introduce the team of researchers, to present the objectives of the study, and to gain valuable information about the settlements in terms of area, demography, and land use. Finally, problem-centered interviews [42] were conducted with village elders selected via snowball sampling (Table 2.2). All interviews were transcribed and analyzed by means of a case-specific and topic-related content analysis [43].

Table 2.2 List of experts on the interviews

No	Date of interview	Specialized	Position	Institutions/location
1	06 March 2015	Environment, greenhouse gases emission	Senior Researcher	Institute for Agricultural Environment, Hanoi
2	09 March 2015	Soils science, land use	Senior Researcher	Soils and Fertilizers Research Institute, Hanoi
3	11 March 2015	Plant nutrients, crop residues management	Senior Researcher	Soils and Fertilizers Research Institute, Hanoi
4	16 March 2015	Agriculture management	Office staff	Nam Dinh Department of Agriculture and Rural Development, Nam Dinh city
5	17 March 2015	Agriculture extension	Office staff	Y Yen Agriculture extension center, Lam
6	24 March 2015	Agriculture management	Office staff	Bac Giang Department of Agriculture and Rural Development, Bac Giang city
7	25 March 2015	Agriculture extension	Office staff	Hiep Hoa Agriculture extension center, Thang
8	30 March 2015	Agriculture management	Office staff	Yen Bai Department of Agriculture and Rural Development, Yen Bai city
9	First April 2015	Agriculture extension	Office staff	Mu Cang Chai Agriculture extension center, Mu Cang Chai
10	10 September 2015	Agriculture extension	Office staff	Yen Dong Agriculture extension, Yen Dong
11	11 September 2015	Village leader	Village leader	Village leader number 11, Yen Dong commune
12	12 September 2015	Experienced villagers	Village elder	Village number 10, Yen Dong commune
13	24 September 2015	Agriculture extension	Office staff	Luong Phong Agriculture extension, Luong Phong
14	25 September 2015	Village leader	Village leader	Chua Village leader, Luong Phong commune
15	26 September 2015	Experienced villagers	Village elder	Giua village, Luong Phong commune
16	19 September 2015	Agriculture extension	Office staff	Che Cu Nha Agriculture extension, Che Cu Nha
17	20 September 2015	Village leader	Village leader	Trong Tong village leader, Che Cu Nha commune
18	21 September 2015	Experienced villagers	Village elder	De Thang village, Che Cu Nha commune

2.2.6 Participatory Rural Appraisal

Table 2.3 List of PRA session

No	Date of interview	PRA tools applied	Location
1	13 October 2015	Seasonal calendar, SWOT analysis	Village number 11, Yen Dong Commune
2	14 October 2015	Seasonal calendar, SWOT analysis	Village number 10, Yen Dong Commune
3	15 October 2015	Seasonal calendar, SWOT analysis	Village number 12, Yen Dong Commune
4	1 November 2015	Seasonal calendar, SWOT analysis	Giua Village, Luong Phong Commune
5	2 November 2015	Seasonal calendar, SWOT analysis	Chua Village, Luong Phong Commune
6	3 November 2015	Seasonal calendar, SWOT analysis	Chop Village, Luong Phong Commune
7	16 November 2015	Seasonal calendar, SWOT analysis	De Thang Village, Che Cu Nha Commune
8	17 November 2015	Seasonal calendar, SWOT analysis	Trong Tong Village, Che Cu Nha Commune
9	18 November 2015	Seasonal calendar, SWOT analysis	Hang Chua Village, Che Cu Nha Commune

Based on the general information gained from the experts, two PRA methods [44] were applied at each study site, i.e., seasonal calendars and SWOT analyses. The objective of these PRA sessions was to obtain a better understanding of the people's rationales behind their present-day agricultural practices. For each PRA session, a group of ten farmers from the pool selected for the standardized survey were invited, whereas it was ensured to have equal numbers of male and female participants. The seasonal calendars were used to identify the prevalent agricultural practices in the villages (field preparation, sowing, harvesting, crop residue management). The SWOT analysis was conducted to gain information about the positively and the negatively evaluated factors (strength, weakness) and trends (opportunities, threats) in the villages in this context. In each of these sessions, the farmers used beans or stones to indicate quantities or significance. All answers of the farmers were noted down in Vietnamese by the researchers and their assistants.

2.2.7. Standardized questionnaire and survey

For conducting the survey, the team of researchers received lists of all village households from the respective village leaders. In each village, each household was given a number and each of these numbers was written down on a small card. After all cards were manually shuffled, in each commune a sample of 60 cards representing the households were taken from the set of cards. Taken together a total of 180 interviews were conducted. The farmers were interviewed between September and November 2015. For the survey, a standardized questionnaire was used to collect information on the families' socio-economic status (family structure, income, expenses), farming system (fertilization, irrigation, pesticide use), and crop residue management (burying in field, burning on field, using as fodder, using as fuel for cooking). A pre-test of the questionnaire in the commune visited first helped to delete repetitive and unprecise questions, so that the final version comprised a total of 25 open and closed questions. The questionnaire was developed in English and later translated into Vietnamese. While interviews could be conducted in Vietnamese language in Yen Dong Commune (Nam Dinh Province) and Luong Phong Commune (Bac Giang Province), in Che Cu Nha Commune (Yen Bai Province) questions and answers were translated from Vietnamese into H'Mong by a native speaker and interpreter. Each interview was conducted with the available male or female head of the household and took between one and two hours of length. The results were analyzed by applying descriptive statistics.

2.2.8. Sample taking of crop residues

At the end of the fieldwork, a total number of 33 samples of rice residues were collected at the time of harvesting: nine samples in Yen Dong Commune (Nam Dinh Province), 18 samples in Luong Phong Commune (Bac Giang Province), and six samples in Che Cu Nha Commune (Yen Bai Province). The samples were collected from a 2m x 2m area, separated, and weighed. In Hanoi, subsamples were air-dried, cut into small pieces, dried to constant weight at 60–70°C, and ground fine enough to pass through 4mm nylon sieve for chemical analysis. Crop residue sample analysis was carried out at the lab at the SFRI in Hanoi. The amount of contained nitrogen was determined by using a semi-micro Kjeldahl procedure (steam distilling unit UDK132); phosphorus was determined by applying the vanadomolybdophosphoric acid method (H_2SO_4:HNO_3 with the ratio of 1:1) and a spectrophotometer (Spectro UV-VIS double beam UDV-3500); and potassium, by using a photoelectric flame photometer (Corning 410-UK; H_2SO_4:HNO_3 with the ratio of 1:1). Based on this analysis, the mean share of nutrients in the rice residues accumulated after each harvest was estimated.

2.3 Results

2.3.1 Cropping systems

With the help of the PRA method of seasonal calendars, seven food cropping systems were found in the study sites based on water management (irrigated vs. rain fed) and topography (lowlands, hills, and mountains) (Table 2.4).

Yen Dong Commune (Nam Dinh Province)

In Yen Dong Commune (Nam Dinh Province), farmers practice three cropping systems: (A) spring peanuts – summer rice – potatoes, (B) spring peanuts – summer rice, and (C) spring rice – summer rice (Table 2.4). Spring peanuts are planted in February and harvested in June. Afterwards, the same areas are planted with summer rice in July and harvested in early October. On some smaller fields, a 20 minute walk from the village, the farmers plant potatoes in late October that are harvested in January. Spring rice is cultivated in February and harvested in June. Typically, the spring rice is planted on irrigated fields. As our survey data show, the farmers generate on average 75% of their annual income by agriculture (62% by producing crops, 13% by raising cattle) and 25% by being engaged in off-farm businesses.

Table 2.4 Food cropping systems at the study site (field work 2015, n = 180)

Study site (province)	Yen Dong Commune (Nam Dinh)	Luong Phong Commune (Bac Giang)	Che Cu Nha Commune (Yen Bai)
Water supply	Irrigated	Irrigated	Rain fed
Cultivation technique	Tractor	Tractor	Buffalo
Cropping systems	(A) spring peanuts – summer rice – potatoes (B) spring peanuts – summer rice (C) spring rice – summer rice	(D) spring rice – summer rice – maize (E) spring rice – summer rice – sweet potato (F) spring rice – summer rice	(G) summer rice planted on terraced fields (H) maize grown on slopes

Luong Phong Commune (Bac Giang Province)

In Luong Phong Commune (Bac Giang Province), there are three prevalent cropping systems: (D) spring rice – summer rice – maize, (E) spring rice – summer rice – sweet potato, and (F) spring rice – summer rice (Table 2.4). Spring rice is usually planted in

February and harvested in late May. Summer rice is planted in late June and harvested in late December. In select areas, farmers plant maize and sweet potatoes in October that are harvested in January. Our survey data show that the distribution of household income in Luong Phong Commune contrasts with that reported in Yen Dong Commune, in that only 33% of the total income is derived from agriculture, while the major share of 67% stems from working in local factories. As such off-farm business is the main source of income.

Che Cu Nha Commune (Yen Bai Province)

Finally, in Che Cu Nha Commune (Yen Bai Province), two cropping systems were identified: (G) summer rice planted on terraced fields, and (H) maize grown on slopes (Table 2.4). Summer rice is planted in May and harvested in September, while maize is also planted in May, but harvested in October. Our survey data show that the production of food crops accounts on average for 43% of the villager’s total income, while the majority of 57% of revenues stem from forestry. Cultivated cardamom provides the main income source.

2.3.2 Cultivated rice varieties

Apart from that, the PRA sessions showed that in Yen Dong Commune (Nam Dinh Province) and Luong Phong Commune (Bac Giang Province), the fields are irrigated and traditional rice varieties are grown, such as, Khang Dan 18, Q5, or Bac Thom 7. Almost all farmers use tractors for plowing. In contrast, in Che Cu Nha Commune (Yen Bai Province), fields are rain fed and hybrid rice varieties are grown, such as Viet Lai 20, and buffalos are used to plow the fields.

2.3.3 Crop residue management

By means of the PRA method of seasonal calendars, four different patterns of rice straw and stalk management were found in the three study sites: (1) use as cooking fuel, (2) burying in the field, (3), burning on the field, and (4) use as fodder for cattle. Frequencies could be determined with the help of the standardized survey. Accordingly, in Yen Dong

Commune (Nam Dinh Province), 53% of rice residues are buried in the field, 27% are burned, 11% are fed to animals and 9% are used as fuel for cooking. In Luong Phong Commune (Bac Giang Province), 51% of rice residues are buried, 38% are burned, 10% are fed to animals, and 1% are used as fuel for cooking. In Che Cu Nha Commune (Yen Bai Province), eventually, 100% of rice residues are fed to animals (Figure 2.2).

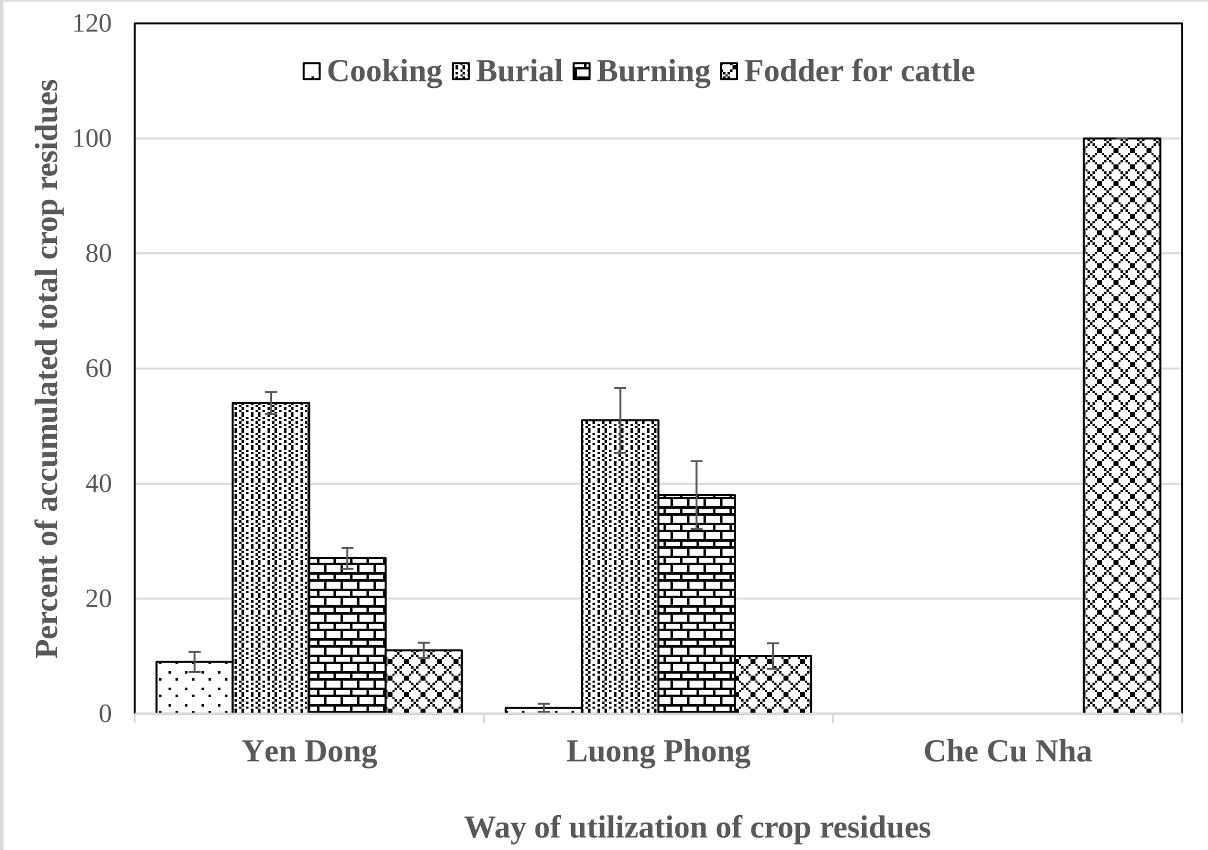


Fig. 2.2 Rice residue management in the study sites.

The aforementioned practices of rice residue management dictate specific nutrient cycles that were in focus of the crop residue analysis. The data presented below are the results of this analysis. They are averaged across farms and the nutrient cycles are expressed in relation to the particular pattern of crop residue management, thus allowing the different systems to be compared (Figures 2.3–2.8).

Yen Dong Commune (Nam Dinh Province)

According to the survey data, the average quantity of rice residues in Yen Dong Commune (Nam Dinh Province) accounts for 7.0 tons per ha. The analysis of the collected rice residue samples revealed an N, P, and K content of 0.72%, 0.15%, and 0.82%. On average, 27% of these residues are burned in the field. Several sources [14, 45, 46] estimate that the burning of rice residues leads to an average loss of almost 100% of N, 25% of P, and 20% of K. Provided these figures, the current practice leads to an annual loss of 13.6 kg of N, 0.7 kg of P, and 3.1 kg of K per ha per season. An additional 53% of the rice residues are incorporated into the soils, which deliver 26.7 kg of N, 5.6 kg of P, and 30.4 kg of K per ha and season to the soils (Figures 2.3–2.5).

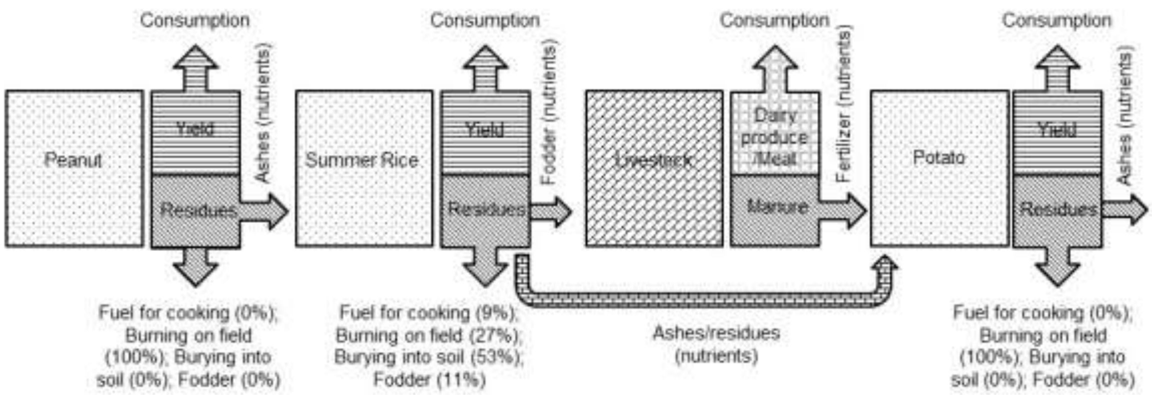


Fig. 2.3 Residue management and nutrient cycle of cropping system (A) in Yen Dong Commune, Nam Dinh Province (field work 2015; n = 60). Note: (1) The figure shows the cropping system over time and is to be read from left to right. (2) The sizes of the depicted boxes have no numeric meaning. (3) while the boxes show the physical substance of the cropping system (field, yield, residues), the arrows show the involved processes (consumption, residues management, nutrient flows)

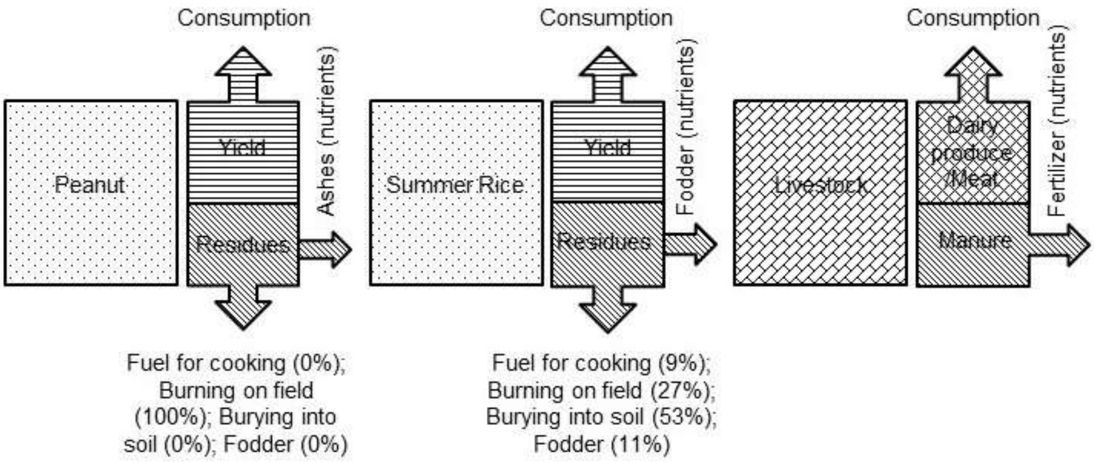


Fig. 2.4 Residue management and nutrient cycle of cropping system (B) in Yen Dong Commune, Nam Dinh Province (field work 2015; n = 60). Note: (1) The figure shows the cropping system over time and is to be read from left to right. (2) The sizes of the depicted boxes have no numeric meaning. (3) while the boxes show the physical substance of the cropping system (field, yield, residues), the arrows show the involved processes (consumption, residues management, nutrient flows)

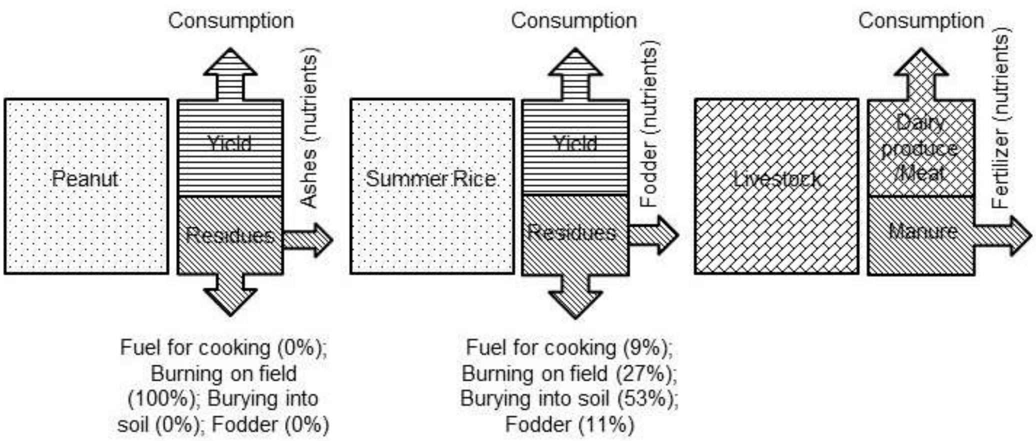


Fig. 2.5 Residue management and nutrient cycle of cropping system (C) in Yen Dong Commune, Nam Dinh Province (field work 2015; n = 60). Note: (1) The figure shows the cropping system over time and is to be read from left to right. (2) The sizes of the depicted boxes have no numeric meaning. (3) while the boxes show the physical substance of the

cropping system (field, yield, residues), the arrows show the involved processes (consumption, residues management, nutrient flows)

Luong Phong Commune (Bac Giang Province)

By means of the standardized survey, in Luong Phong Commune (Bac Giang Province), the average amount of rice residues was found to be 5.8 tons per ha, out of which 38% are burned. Considering the average nutrient composition contained in rice residue being 0.72% N, 0.16% P, and 0.74% K, as own analysis showed, the burning results in the loss of 15.9 kg of N, 0.9 kg of P, and 3.3 kg of K per ha. By incorporating 51% of the rice residues, a total amount of 21.3 kg of N, 4.7 kg of P, and 21.9 kg of K is returned to the soil per season (Figures 2.6–2.7).

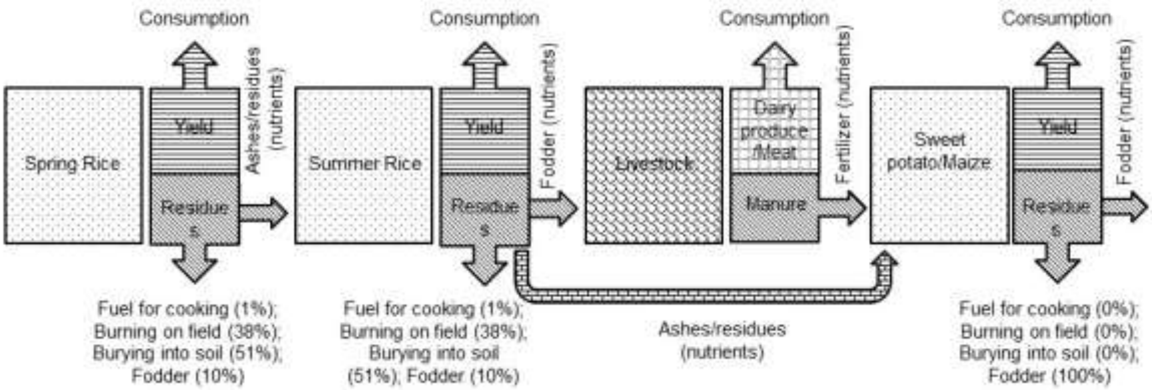


Fig. 2.6 Residue management and nutrient cycle of cropping system (D/E) in Luong Phong Commune, Bac Giang Province (field work 2015; n = 60). Note: (1) The figure shows the cropping system over time and is to be read from left to right. (2) The sizes of the depicted boxes have no numeric meaning. (3) while the boxes show the physical substance of the cropping system (field, yield, residues), the arrows show the involved processes (consumption, residues management, nutrient flows)

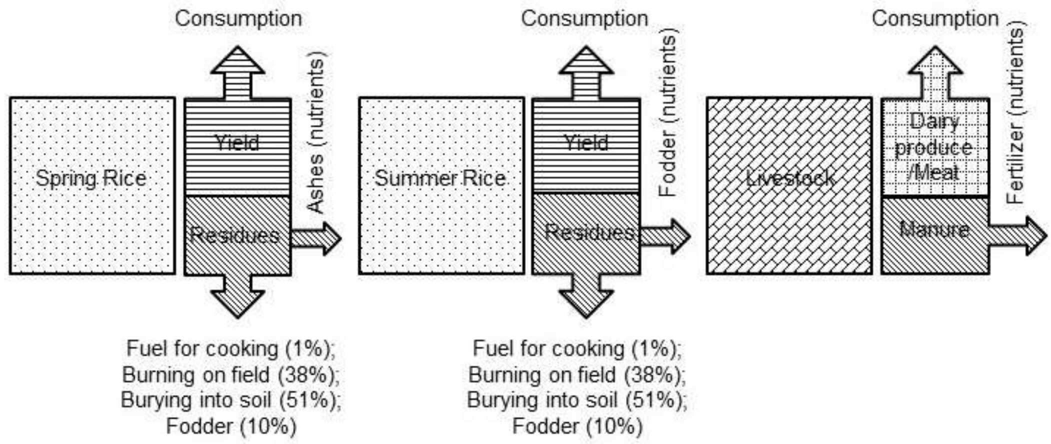


Fig. 2.7 Residue management and nutrient cycle of cropping system (F) in Luong Phong Commune, Bac Giang Province (field work 2015; n = 60). Note: (1) The figure shows the cropping system over time and is to be read from left to right. (2) The sizes of the depicted boxes have no numeric meaning. (3) while the boxes show the physical substance of the cropping system (field, yield, residues), the arrows show the involved processes (consumption, residues management, nutrient flows)

Che Cu Nha Commune (Yen Bai Province)

According to the survey data, the farmers in Che Cu Nha Commune (Yen Bai Province) use all their rice residues (100%) as fodder to their cattle. In lieu of this finding, no similar calculations could be conducted in this case. The manure of the cattle is applied as organic fertilizer to the maize fields (Figure 2.8).

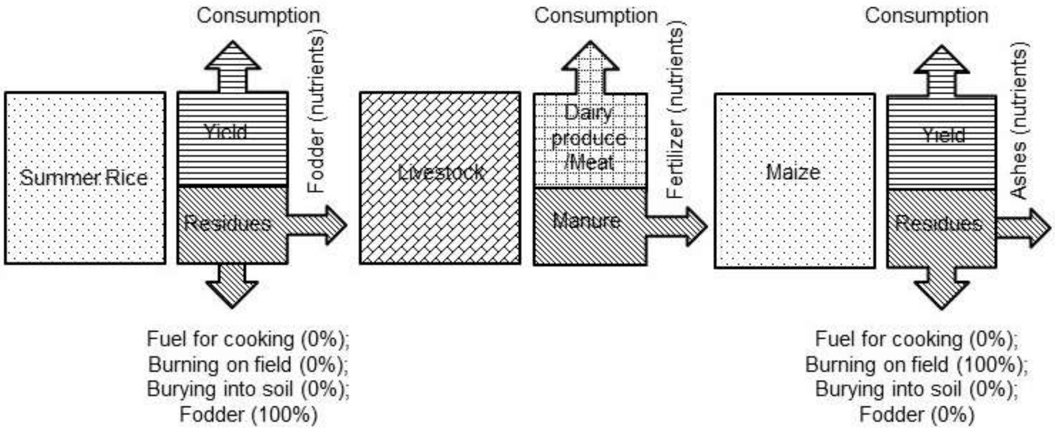


Fig. 2.8 Residue management and nutrient cycle of cropping system (G/H) in Che Cu Nha Commune, Yen Bai Province (field work 2015; n = 59). Note: (1) The figure shows the cropping system over time and is to be read from left to right. (2) The sizes of the depicted boxes have no numeric meaning. (3) while the boxes show the physical substance of the cropping system (field, yield, residues), the arrows show the involved processes (consumption, residues management, nutrient flows)

2.3.4 Evaluation of crop residue management

Asked why they are pursuing the practice of burning crop residues within the frame of the SWOT analysis, farmers in Yen Dong Commune (Nam Dinh Province) and Luong Phong Commune (Bac Giang Province) stated that it would destroy pests, clear weeds, and release nutrients needed for the next crop cycle. Furthermore, they mentioned that it was a convenient way to clear the field in preparation for the next crop. Apart from this positive assessment of the burning practice, the farmers were also aware that the burying of residues would improve the physical properties and the fertility of the soils. In addition, they agreed on the opinion that the burning of crop residues would negatively affect the environment and human health.

2.4 Discussion

2.4.1 Transformative potential in different ecological zones

The results show that due to their location in three different ecological zones, the communes studied feature unequal potentials for transforming available rice residue management patterns. Because of the extent that agriculture contributes to the villagers' livelihoods, Yen Dong Commune (Nam Dinh Province) in the lowlands is seen as most promising for a change from burning to burying rice residues. In Luong Phong Commune (Bac Giang Province) in the northern hill areas, in contrast, the potential of transforming the practice of burning rice residues is more restricted and has to be discussed considering the limited time available to villagers for farming, as their main income stems from off-farm business. Finally, in Che Cu Nha Commune (Yen Bai Province) in the mountainous region, no potentials for transformation are existing, since the full amount of rice residues is used in an environment-friendly way as fodder for cattle.

2.4.2 Environmental costs of crop residue burning

The environmental costs of the present practice of burning rice residues in the lowlands and the hill areas of northern Vietnam becomes visible when the findings from the commune level are up-scaled to the province level. There are 154,400 ha under rice cultivation in Nam Dinh Province and 111,500 ha in Bac Giang Province [3]. Given the average seasonal quantity of rice residues in our study sites of 7.0 tons per ha in Yen Dong Commune (Nam Dinh Province) and 5.8 tons per ha in Luong Phong Commune (Bac Giang Province), the total amount sums up to 1,080,800 tons in Nam Dinh Province and 646,700 tons in Bac Giang Province. If incorporated into the soils, the seasonal amount of rice residues produced in the two provinces researched would deliver 12,438 tons of N, 2,656 tons of P, and 13,648 tons of K to the soils. By burning the produced rice residues, however, farmers in Nam Dinh Province lose 7,782 tons of N (100%), 405 tons of P (25%), and 1,773 tons of K (20%), while in Bac Giang Province they lose 4,656 tons of N (100%), 259 tons of P (25%), and 957 tons of K (20%).

2.4.3 Cost-benefit analysis

The negative environmental impact of the prevalent burning of rice residues can be mitigated if the farmers change this practice. This adjustment can be encouraged by means of building awareness. Yet, the results of the SWOT analysis made clear that awareness is sufficiently present in the communes studied. Thus, in viewing both practices as reasonable, the farmers eventually opt for the alternative that is perceived as more cost-effective. Based on these findings, a cost-benefit analysis is to be conducted in order to figure out, whether the farmers are correct in their decision or not. For this purpose, the financial savings are to be calculated that accrue to farmers when burying their rice residues instead of burning them. If these savings are higher than the costs involved, the farmers' choice is found to be false and an incentive is found for changing from the practice of burning. If the savings are lower than the involved costs, the farmers' choice is found to be correct and the amount of expenses is identified that needs to be refunded to farmers in order to make them change their residue management practice towards a more sustainable manner.

2.4.4 Rice residues and fertilizer

Each season, smallholders accrue expenses for purchasing and applying chemical fertilizers. The amount of chemical fertilizer applied in Yen Dong Commune (Nam Dinh Province) was found to be 189 kg per ha for cultivating rice, 166 kg per ha for cultivating peanuts, and 195 kg per ha for cultivating potatoes. The corresponding amounts of chemical fertilizer applied in Luong Phong Commune (Bac Giang Province) were found to be 218 kg per ha for rice, 371 kg per ha for maize, and 153 kg per ha for sweet potatoes (Table 2.5).

Table 2.5 Amount of chemical fertilizers applied at study sites (n = 178) (1) Figure are presented the amount (mean) that are currently applied. (2) Figure in parenthesis show amount (mean) that need to be applied if full rice residue are incorporated. (3) Saving (in parenthesis) show amounts (mean) that need not be applied if full amounts rice residues are incorporated.

	N (kg/ha)	P (kg/ha)	K (kg/ha)	Sum (kg/ha)	Saving (kg/ha)
Yen Dong Commune (Nam Dinh Province)					
Rice	111(61)	28(18)	50(0)	189(78)	111
Peanut	92(42)	28(18)	46(0)	166(60)	106
Potatoes	115(65)	31(24)	49(0)	195(89)	106
Luong Phong Commune (Bac Giang Province)					
Rice	92(50)	22(13)	104(61)	218(124)	94
Maize	212(170)	43(34)	116(73)	371(277)	94
Sweet potatoes	83(41)	10(1)	60(17)	153(59)	94

If the total 7.0 ton rice residue amount per ha in Yen Dong Commune (Nam Dinh Province) were buried, a quantity of 50.4 kg of N, 10.5 kg of P, and 57.4 kg of K could be returned to the soils following each individual rice season. This would lead to a possible reduction of applied chemical fertilizer: for cultivating rice 60.6 kg of N, 17.5 kg of P and zero kg of K would be sufficient. Similarly, fertilizer application could be reduced to 41.6 kg of N, 17.5 kg of P, and zero kg of K for cultivating peanuts, and to 64.6 kg of N, 20.5 kg of P, and zero kg of K for cultivating potatoes. Likewise, by burying the full amount of 5.8 tons of rice residues per ha in Luong Phong Commune (Bac Giang Province), nutrient quantities of 41.8 kg of N, 9.3 kg of P, and 42.9 kg of K could be returned to the soils, which again would decrease the amounts of chemical fertilizer needed. For cultivating the next rice season, 50.2 kg of N, 12.7 kg of P, and 61.1 kg of K were sufficient. For cultivating maize and sweet potato, fertilizer application could be reduced to 170.2 kg of N, 33.7 kg of

P, and 73.1 kg of K, and to 41.2 kg of N, 0.7 kg of P, and 17.1 kg of K, respectively. Altogether, in Yen Dong Commune (Nam Dinh Province), the demand of fertilizer for rice could be reduced to 78.1 kg, for peanuts to 59.1 kg, and for potatoes to 85.1 kg per ha and season. In Luong Phong Commune (Bac Giang Province), the demand for fertilizer for rice could be reduced to 124.0 kg, for maize to 277.0 kg, and for sweet potato to 59.0 kg per ha per season (Table 2.5).

Table 2.6 Cost of chemical fertilizers applied at the study site (n = 178). Note: (1) Figure presented are the costs (mean) that farmers currently pay. (2) Figure in parenthesis show costs mean that need to paid, if full amount of rice residues are incorporated. (3) Saving (in parenthesis) show costs (mean) that need not be paid, if full amount of rice residues are incorporated.

	N(VND/ha)	P(VND/ha)	K(VND/ha)	Sum(VND/ha)	Saving(VND/ha)
Yen Dong Commune (Nam Dinh Province)					
Rice	2,171,739 (1,185,652)	178,723 (111,702)	5,125 (0)	2,355,588 (1,297,354)	(1,058,233)
Peanut	1,800,000 (813,913)	178,723 (111,702)	4,725 (0)	1,983,448 (925,615)	(1,057,833
Potatoes	2,250,000 (1,263,913)	197,872 (130,851)	5,025 (0)	2,452,897 (1,394,764)	(1,058,133)
Luong Phong Commune (Bac Giang Province)					
Rice	1,800,000 (982,174)	140,426 (81,064)	10,525 (6235)	1,950,951 (1,069,473)	(881,478)
Maize	4,147,826 (3,330,000)	274,468 (215,106)	11,725 (7435)	4,434,019 (3,552,541)	(881,478)
Sweet potatoes	1,623,913 (806,087)	63,830 (4468)	6,125 (1835)	1,693,868 (812,390)	(881,478)

These presented figures can be translated into economic values, if established conversion factors (1 kg urea equals 0.46 kg N; 1 kg super phosphate equals 0.07 kg of P; 1 kg of potassium chloride equals 0.50 kg K) and the local prices for fertilizer are taken into account. In the local retail markets, the current price of urea is 9,000 Vietnamese Dong (VND), super phosphate is 3,000 VND, and potassium chloride is 9,000 VND per kg, as experts mentioned. Provided these conversions, the average savings from incorporating rice residues in Yen Dong Commune (Nam Dinh Province) can be estimated to be 1,058,233 VND (US$ 46.4) in the case of rice, 1,057,833 VND (US$ 46.3) in the case of peanuts, and 1,058,133 (US$ 46.4) in the case of potatoes. In Luong Phong Commune (Bac Giang Province), the savings are 881,478 VND (US$ 38.6) in the case of rice, maize and sweet potatoes individually (Table 2.6).[1]

2.4.5 Mechanization and labor costs

These potential savings seem appealing, however, they will only work as an incentive if there are no indirect costs, which might outweigh the previously calculated financial benefits. So, a closer look is necessary at the different management practices conducted by the farmers. In the burning scenario, the farmers remove the crop residues, stack them up in one corner of the field, and burn them. Afterwards, they distribute the ashes across the field and wait for one to two weeks, then, plow the field, apply fertilizer, and plant new seedlings. In contrast, in the burying scenario, the farmers shred the residues and incorporate them into the soils by plowing, and proceed afterwards with similar steps as described in the first scenario. This means that the burying scenario requires the smallholders to plow an extra time, which incurs costs.

[1] The currency rate was stable throughout the entire field work with 100,000 VND correlating to US$ 4.38 (https://www.oanda.com/lang/de/currency/converter/).

In the two study sites, the costs for removing and burning the crop residues for a one ha field were identified to be 2,770,000 VND (US$ 121.3) in Yen Dong Commune (Nam Dinh Province) and 2,216,000 VND (US$ 97.1) in Luong Phong Commune (Bac Giang Province). Since in the study sites only 4.4% (Yen Dong Commune) and 6.5% (Luong Phong Commune) of the households interviewed own a tractor, most farmers rent a machine to prepare their fields. The costs for smallholders to plow their fields by operating a tractor (including involved costs for fuel, labor, maintenance, etc.) were found to be on average 4,986,000 VND (US$ 218.4) in Yen Dong Commune (Nam Dinh Province) and 3,600,000 VND (US$ 157.7) in Luong Phong Commune (Bac Giang Province) per ha cultivated. In turn, in both study sites, the practice of burying involves higher costs as compared to the practice of burning, with the added expenses per ha equating to 1,157,767–1,158,167 VND (US$ 50.8) in Yen Dong Commune (Nam Dinh Province) and to 502,283 VND (US$ 22.0) in Luong Phong Commune (Bac Giang Province). Therefore, the farmers' decision to burn crop residues is only rational (Table 2.7).

Table 2.7 Savings and extra costs of burying rice residues at the study site (n = 178)

Study site (province)	Potential saving from burning rice residue (per ha)	Costs for burning rice residue (per ha)	Costs for burying rice residue (per ha)	Balance (per ha)
Yen Dong Commune (Nam Dinh Province)	1,057,833—1,058,233 VND (US$ 46.4)	2,770,000 VND (US$ 121.3)	4,986,000 VND (US$ 218.4)	− 1,158,167 — − 1,157,767 VND (US$ 50.8)
Luong Phong Commune (Bac Giang Province)	881,478 VND (US$ 38.6)	2,216,000 VND (US$ 97.1)	3,600,000 VND (US$ 157.7)	− 502,283 VND (US$ 22.0)

2.5 Conclusions

Our study showed that there is great potential for using the remains of planted crops as a substitute of cost-intensive chemical fertilizer and thus for making rice farming in Vietnam more sustainable. By generalizing our findings from the three examined study sites in Yen Dong Commune (Nam Dinh Province), Luong Phong Commune (Bac Giang Province), and Che Cu Nha Commune (Yen Bai Province) in northern Vietnam, we see the greatest potential in Vietnam's lowlands, where rice cropping contributes the major share to farmers' livelihoods. In hill areas we also see potential for a transition. Although rice farming does not provide for the major share of income there, involved labor costs are lower in agriculture, which makes the burying of rice residues less unattractive. In mountainous regions, in contrast, we see no potentials for transformation, since the full amount of rice residues is used already in an environment-friendly way as fodder for cattle.

In Vietnam's lowlands and hill areas, rice farming can be made more sustainable if farmers are convinced to shift from burning crop residues to burying them. Our study showed that those communities that practice the burning of rice residues, namely Yen Dong Commune (Nam Dinh Province) and Luong Phong Commune (Bac Giang Province), are very much aware of the nutrients available in crop residues, and of their potentials for improving the physical properties of the soils. They are also aware of the negative impacts of burning crop residues on human health and the environment. Nevertheless, given extra expenses involved in the burying of crop residues, the farmers ultimately decide in favor of the more cost-effective practice of burning them. As our cost-benefit analysis showed, the burying of rice residues involves indeed extra costs of 1,157,767–1,158,167 VND (US$ 50.8) per ha in Yen Dong Commune (Nam Dinh Province) and to 502,283 VND (US$ 22.0) per ha in Luong Phong Commune (Bac Giang Province). Given these figures we conclude that burning rice residues might be an erroneous trend from an ecological perspective, but it is rational from an economic point of view.

Having said this, it needs to be mentioned that the findings of our study have their limitations. In sum, we see four options to produce a more fine-grained picture of the examined matters of this study: (1) Different varieties of rice plants should be taken into account individually, since varieties with weaker or stronger growth and root systems will make a noticeable difference in the results of the cost-benefit analysis. (2) Nutrient release rates should be considered, which would improve the comparison of nutrients from crop residues with those of chemical fertilizer over time. (3) Reduced health costs should be acknowledged that can be expected, as the abstinence of burning crop residues should lead to less respiratory diseases in rural areas. (4) It should be tested whether farmers apply more pesticides when not burning crop residues. If so, also these extra expenses should be included in the calculations.

Against the background of our findings, we see four options for the government of Vietnam to make the transition from burning to burying crop residues happen: (1) The state can legislate a law that prohibits the burning of rice residues. However, due to high monitoring costs, this option is less attractive. (2) The state can invest in the mechanization of the agricultural sector so that tractors become available to farmers at lower prices. This would make the burying of rice residues more attractive, since involved costs would be decreased. However, due to the large number of smallholders in Vietnam, this option is not attractive neither. (3) The state could award a premium to all farmers, who forgo burning rice residues. This premium would be directly experienced by the farmers, which makes it a very attractive approach. Yet, also in this case, the monitoring costs seem very high. (4) Eventually, the state could lower its subsidies on imported chemical fertilizer, which would make substitutes in the form of crop residues more attractive. While option number 4 is most realistic from the perspective of the state, option number 3 would be best suited to farmers’ livelihoods.

Reference

1. GRiSP (*Global Science Partnership*) *Rice Almanac 4th*. International Rice Research Institute, Metro Manila, Philippines, 2013.
2. (FAO) Food and Agriculture Organization. Smallholders data portrait. Online available: http://www.fao.org/family-farming/data-sources/dataportrait/farm-size/en/ (Accessed on 19 May 2017).
3. (GSO) General Statistics Office of Vietnam. *Statistical year book*. Statistical Publishing House, Hanoi, Vietnam, 2016.
4. Hoang, A.L.; Nguyen, T.T.H.; Le, T.L. Estimated gas emissions from burning rice straw in open fields in Thai Binh Province. *J of Sci*. **2013**, 29, 26–33.
5. Tran, S.N.; Nguyen, T.; Nguyen, H.C.; Nguyen, V.; Le, H.V.; Ingvorsen, K. To quantify the seasonal rice straw and its use in different provinces in the Vietnamese Mekong Delta. *J. Sci*. **2014**, *32*, 87–93.
6. Gadde, B.; Bonnet, S.; Menke, C.; Garivait, S. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. *Environ. Pollution 157*.**2009**, *5*, 1554–1558. DOI:org/10.1016/j.envpol.2009.01.004\.
7. Gupta, P.K.; Sahai, S.; Singh, N.; Dixit, C.K.; Singh, D.P.; Sharma, C.; Tiwari, M.K.; Gupta, R.K.; Garg, S.C. Residue burning in rice-wheat cropping system: Causes and implications. *Curr. Sci*. **2004**, *87*, 1713–1716.
8. Nguyen, M.D. An estimation of air pollutant emissions from open rice straw burning in the Red River Delta. *J of Sci. Develop*. **2012**, *1* (10), 190–198.
9. Niveta, J.; Arti, B.; Himanshu, P. Emission of air pollutants from crop residue burning in India. *Aero. Air Qual. Research.* **2014**, *14*, 422–430. DOI: 10.4209/aaqr.2013.01.0031.
10. Ryu, S.Y.; Kwon, B.G.; Kim, Y.J.; Kim, H.H.; Chun, K.J. Characteristics of biomass burning aerosol and its impact on regional air quality in the summer of 2003 at Gwangju, Korea. *Atmosph. Research.* **2007**, *84* (4), 362–373. DOI:org/10.1016/j.atmosres.2006.09.007.
11. Streets, D.G.; Yarber, K.F.; Woo, J.H.; Carmichael, G.R. (2003) Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions. *Global Biogeochem. Cycles.* **2003**, *17* (4), 1099. DOI:10.1029/2003GB002040.

12. Kumar, K.; Goh, K.M.; Scott, W.R.; Frampton, C.M. Effects of 15N-labelled crop residues and management practices on subsequent winter wheat yields, nitrogen benefits and recovery under field conditions. *J. Agric. Sci. Camb.* **2001**, *136*, 35–53.
13. Prabhat, K.G.; Shivraj, S.; Nahar, S.; Dixit, C.K.; Singh, D.P.; Sharma, C.; Tiwari, M.K.; Raj, K.G.; Garg, S.C. Residue burning in rice-wheat cropping system: causes and implications. *Curr. Sci.* **2004**, *87* (12), 1713–1717.
14. Fairhurst, T.; Witt, C.; Buresh, R.; Dobermann, A. *Rice: A practical guide to nutrient management.* International Rice Research Institute, International Plant Nutrition, International Potash Institute, Metro Manila, Philippines.2007.
15. Krishna, G.M.; Arun, K.M.; Kuntal, M.H.; Kali, K.B.; Prabir, K.; Bandyopadhyay, P.K.G.; Manoranjan, M. Rice residue-management options and effects on soil properties and crop productivity. *Food, Agric. & Environ*. **2004**, *2*, 224–231.
16. Hobbs, P.; Morris, M. *Meeting South Asia's future food requirements from rice-wheat cropping systems: Priority issues facing researchers in the post-green revolution era*. NRG Paper 96-01. Mexico, D.F.: CIMMYT.2002
17. Cancado, J.E.D.; Saldiva, P.H.N.; Pereira, L.A.A.; Lara, L.B.L.S.; Artaxo, P.; Martinelli, L.A.; Arbex, M.A.; Zanobetti, A.; Braga, A.L.F. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. *Environ. Health Perspect*. **2006**, *114* (5), 725–729.
18. Awasthi, A.; Singh, N.; Mittal, S.; Gupta, P.; Agarwal, R. Effect of agriculture crop residue burning on children and young on PETs in North West India. *Sci. Total Environ.* **2010**, *408*, 4440–4445. DOI.org/10.1016/j.scitotenv.2010.06.040
19. Chan, K.Y.; Heanan, D.P. Surface hydraulic properties of a red earth under continuous cropping with different management practices. *Australian J. Soil Research.* **1993**, *31* (1), 13–24.
20. Valzano, F.P.; Greene, R.S.B.; Murphy, B.W. Direct effects of stubble burning on soil hydraulic and physical properties in a direct drill tillage system. *Soil Till. Res.* **1997**, *42*, 209–219.
21. Bhagat, R.M.; Bhardwaj, A.K.; Sharma, P.K. Long-term effect of residue management on soil physical properties, water use and yield of rice in North-Western India. *J. Indian Soc. Soil Sci*. **2003**, *51*, 111–117.

22. Pathak, H.; Singh, R.; Bhatia, A.; Jain, N. Recycling of rice straw to improve wheat yield and soil fertility and reduce atmospheric pollution. *Paddy Water Environ.* **2006**, *4*, 111–117. DOI: 10.1007/s10333-006-0038-6.
23. Hoang, N.T.; Tran, T.T.; Dao, T.H.; Nguyen, N.M.; Pham, T.N.; Nguyen, T.N.; Nguyen, H.T.; Vu, D.Q.; Ho, C.T. *Effect of agricultural residues incorporation into soils on increasing crop yields, reducing mineral fertilizer application and improving soil properties.* Soils and Fertilizers Research Institute, Research Number 6. Agricultural Publishing. Hanoi, Vietnam, 2014.
24. Perman, R.; Ma, Y.; Common, M.; Maddison, D.; McGilvray, J. *Natural resource and environmental economics.* Pearson Education Ltd, Edinburgh. 2014.
25. Harris, J.M.; Roach, B. *Environmental and natural resource economics. A contemporary approach.* Routledge, New York. 2017.
26. Hussen, A. *Principles of environmental economics and sustainability: An integrated economic and ecological approach*. Routledge, New York. 2013.
27. Nguyen, V.B.; Bui, D.D.; Ho, Q.D.; Bui, H.H.; Dang, T.L.; Thai, P.; Nguyen, V.T. *Basic information of main soil types of Vietnam*. The Gioi Publishing, Hanoi, Vietnam. 2002.
28. Nguyen, Q.H.; Hoang, T.Q.; Truong, X.C. *Evaluation of arable land for the transfer of suitable crop systems in Hiep Hoa District, Bac Giang Province*. Soils and Fertilizers Research Institute. Hanoi, Vietnam. 2011.
29. Nguyen, T.L.; Truong, X.C.; Nguyen, V.H.; Dinh, V.S. *Survey and evaluation of fertility: Soils map for intensive crop restructuring and sustainable agricultural land resources management in Viet Yen District, Yen Dung District, Luc Nam District, Yen District, Son Dong District and Bac Giang City, Bac Giang Province*. Soils and Fertilizers Research Institute, Hanoi, Vietnam. 2015.
30. (BSO) Bac Giang Statistics Office. *Statistical year book*. Statistical Publishing House, Hanoi, Vietnam. 2015.
31. (GSO) General Statistics Office of Vietnam. *Statistical year book*. Statistical Publishing House, Hanoi, Vietnam. 2015.
32. (NSO) Nam Dinh Statistics Office. *Statistical year book*. Statistical Publishing House. Hanoi, Vietnam. 2015.
33. (YSO) Yen Bai Statistics Office. *Statistical year book*. Statistical Publishing House. Hanoi, Vietnam. 2015.

34. (GSO) General Statistics Office of Vietnam. *Result of the 2016 rural, agricultural and fisher census.* Statistical Publishing House, Hanoi, Vietnam. 2016.
35. (NIAPP) National Institute of Agricultural Planning and Projection. *The information of Nam Dinh soil types.* National Institute of Agricultural Planning and Projection. Hanoi, Vietnam. 2003.
36. Tran, Q.V.; Ho, Q.D.; Bui, H.D.; Tran, M.T. Assessment of the qualities, quantities, and properties of grey degraded soil in Northern Vietnam. *Sci. Techno. J. Agri. Rural Dev.* **2012**, *207*, 19–25.
37. Tran, Q.V.; Ho, Q.D.; Le, T.M.H.; Bui, T.Y. The situation of phosphorus in grey degraded soils in Northern Vietnam. *Sci. Techno. J. Agric. Rural Dev.* **2013**, *210+211*, 24–30.
38. Truong, X.C.; Hoang, T.Q. *Research on terrace field land use and proposed integrated technical solutions to improve efficiency in Yen Bai Province.* Soils and Fertilizers Research Institute, Hanoi, Vietnam. 2013.
39. Tran, M.T.; Tran, M.T.; Tran, A.T.; Vu, H.H. *Survey and evaluation of land use in Nam Dinh Province.* Soils and Fertilizers Research Institute. Hanoi, Vietnam. 2015.
40. Le, T.C. *Swidden agriculture in Vietnam. Reskasem, B. Montane Mainland Southeast Asia in Transition.* Reskasem, Chiang Mai University, B. Chiang Mai, Thailand. 1996.
41. Hoa, D.V. *Ten years after implementing "fixed field, fixed residence": Migration and the Establishment of new economic zones in the mountains*. Department of Sedentarisation, Ministry of Agriculture and Rural Development. Hanoi, Vietnam. 2002.
42. Flick, U. *An introduction to qualitative research*. Sage Publishing, London. 2014.
43. Mayring, P. Qualitative content analysis. Forum: Qualitative Social Research. Online available: http://www.qualitative-research.net/index.php/fqs/article/viewArticle/1089/2385 (Accessed February 2018).
44. Chambers, R. Participatory Rural Appraisal (PRA): Analysis of Experience. *World Dev.* **1994**. *22* (9), 1253–1268.
45. Ponnamperuma, F.N. *Straw as a source of nutrients for wet-land rice. In: Banta S, Mendoza CV (eds) Organic matter and rice*. International Rice Research Institute (IRRI), Manila, Philippines, 117–136. 1984.

46. Dobermann, A.; Fairhurst, T.H. *Rice: Nutrient disorders & nutrient management.* Handbook series. Potash & Phosphate Institute (PPI), Potash & Phosphate Institute of Canada (PPIC), International Rice Research Institute (IRRI). 2000.

Chapter 3

This chapter is based on the published paper: Hung, D.; Hughes, H.; Keck, M.; Sauer, D. **Rice-Residue Management Practices of Smallholder Farms in Vietnam and their Effects on Nutrient Fluxes in the Soil-Plant System**. *Sustainability*. **2019**, *11*(6), 1641

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) 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 amounts of chemical fertilizers can be considerably reduced. If not, there is a risk of eutrophication in 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

3.1 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 accruement 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, 5, 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, 8, 9, 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 of chemical fertilizers. As such, crop residues may serve as a potential partial substitute for chemical fertilizers in agriculture [12–14, 15].

Vietnam relies heavily on the import of chemical fertilizers. In the case of K fertilizers, even 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 million US dollars annually for the national economy, and causing eutrophication and greenhouse gas emissions [16, 17, 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, 25, 26, 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, 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.

3.2 Materials and Methods

3.2.1 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 (Fig. 1, bottom).

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 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, 29, 30]. The texture of the soils is predominantly sandy loam. Their fertility is generally low [31].

The other study area is located in Che Cu Nha Commune (Mu Cang Chai District, Yen Bai Province; 104°10’ E, 21°51’ N), 320 km Northwest of Hanoi (Fig. 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. 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.

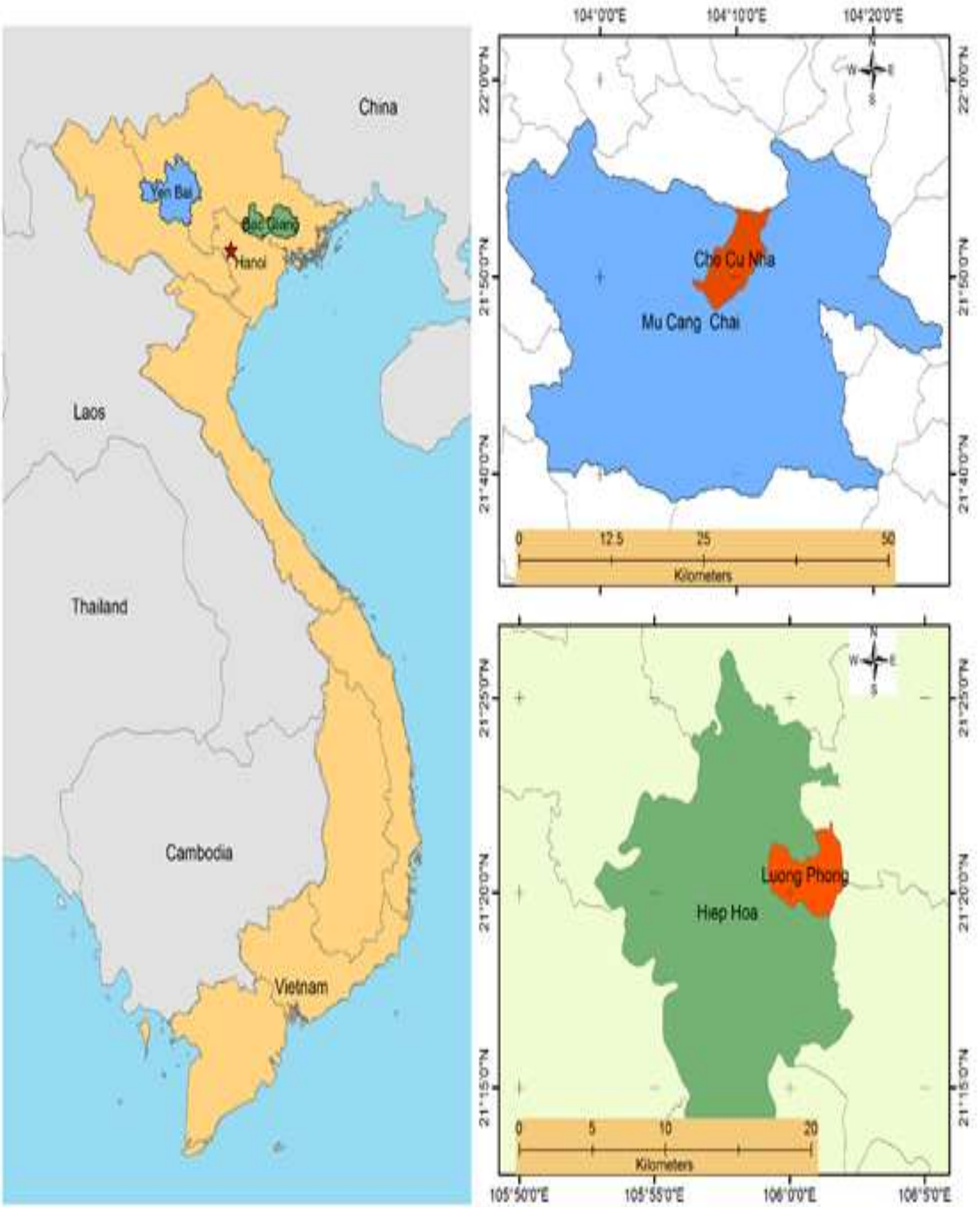


Figure 3.1 Study sites in northern Vietnam

3.2.2 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 3.1).

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 September. 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 sweat potatoes in the two study areas amount 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].

Table 3.1 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)	1,620	1,337
Water source	Irrigation	Rainfall
Cropping systems	Spring rice - summer rice; spring rice - summer rice - maize (sweat potatoes)	Summer rice; summer maize grown on sloping land

3.2.3 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 3.2).

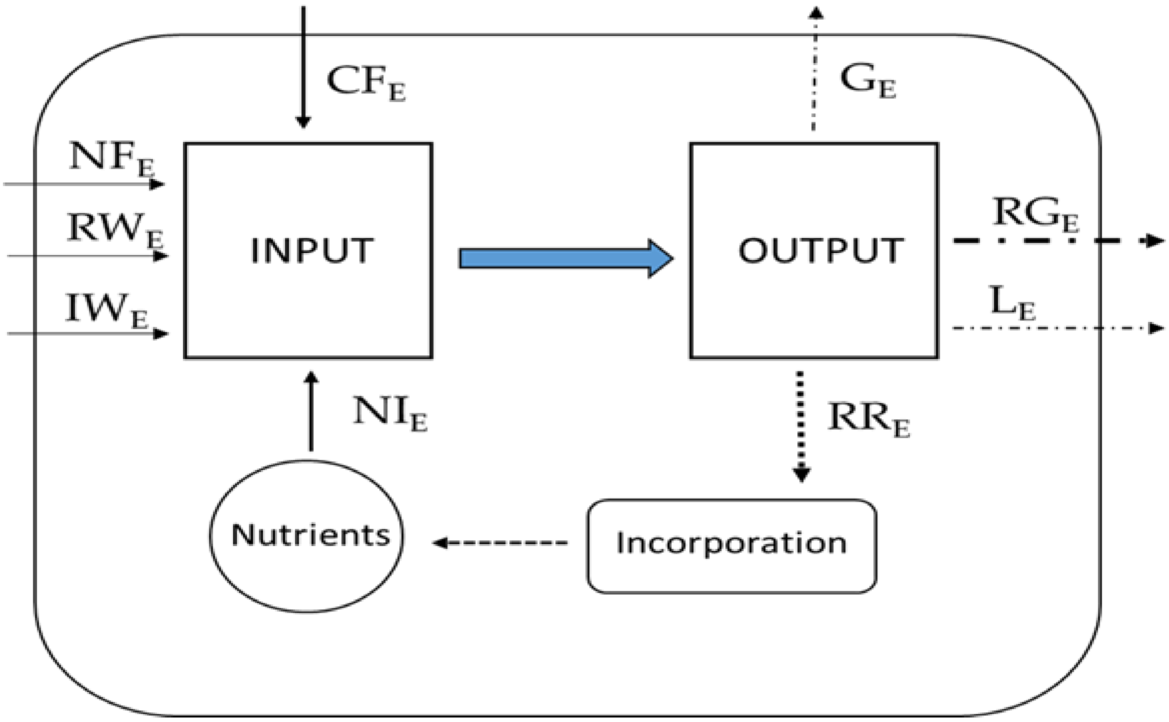
We collected data on rice-residue management practices from September 2015 to September 2017. For this purpose, we established nine plots in Luong Phong Commune (Bac Giang Province), including the following practices: 1) incorporation of crop residues into the soil, 2) application of composted rice residues, 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 data of [7, 34, 35].

Table 3.2 Rice-residue management in the study areas

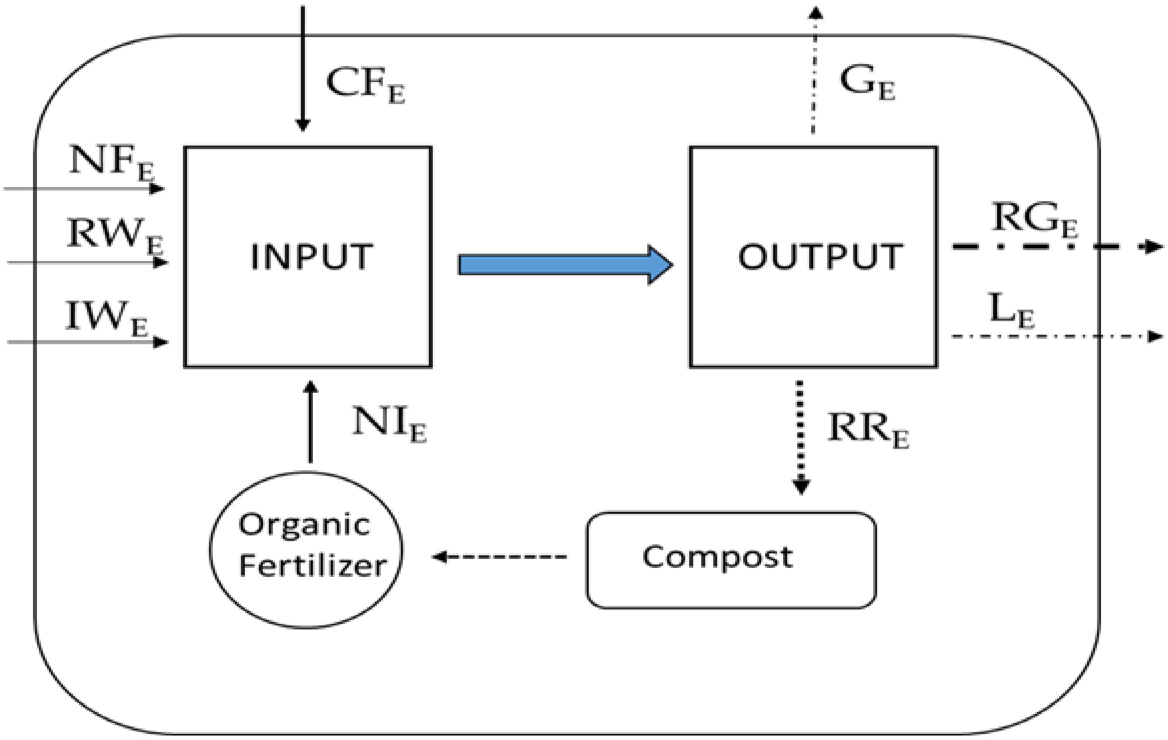
Study area	Rice-residue management
Luong Phong Commune (Bac Giang Province)	Complete rice-residue incorporation before transplanting of spring rice (incorporation 1) and summer rice (incorporation 2)
Luong Phong Commune (Bac Giang Province)	Application of composted rice residues before transplanting 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

3.2.4 Sampling and analysis

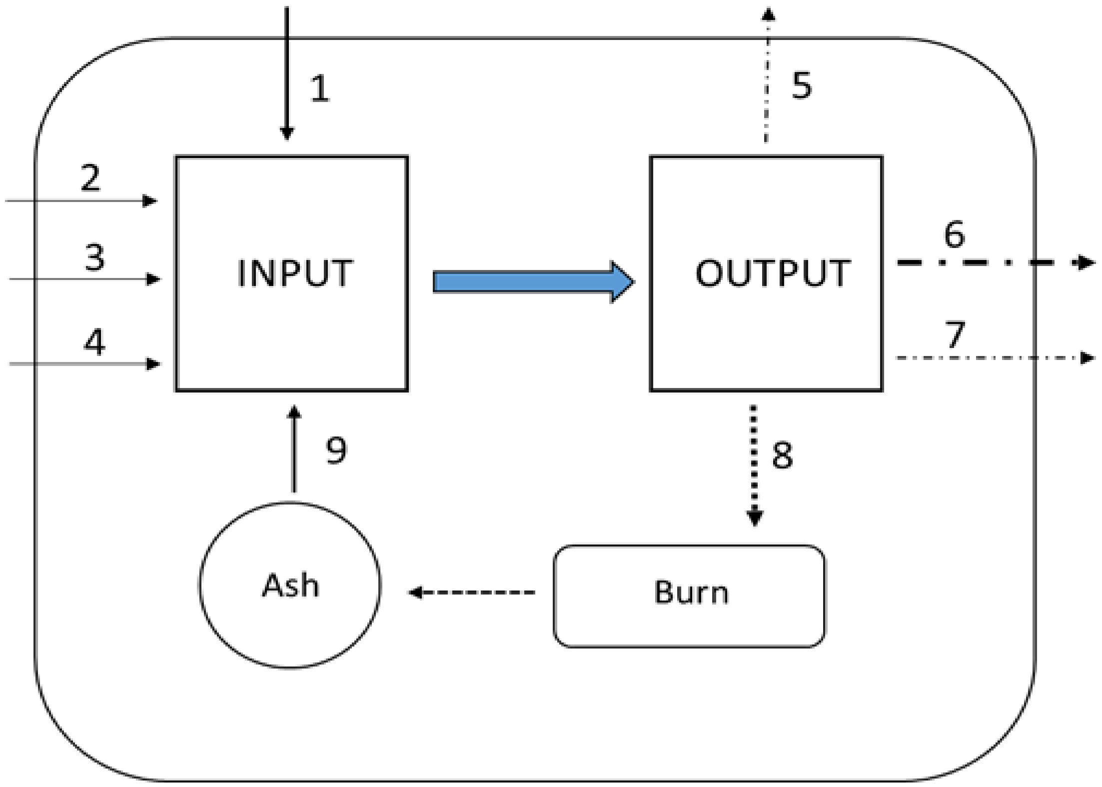
Samples of topsoil, crop residues, rice grains, chemical fertilizers and manure were collected at all plots, to monitor element fluxes of the four types of rice residue management, with three replicates per management practice (Fig. 3.2).



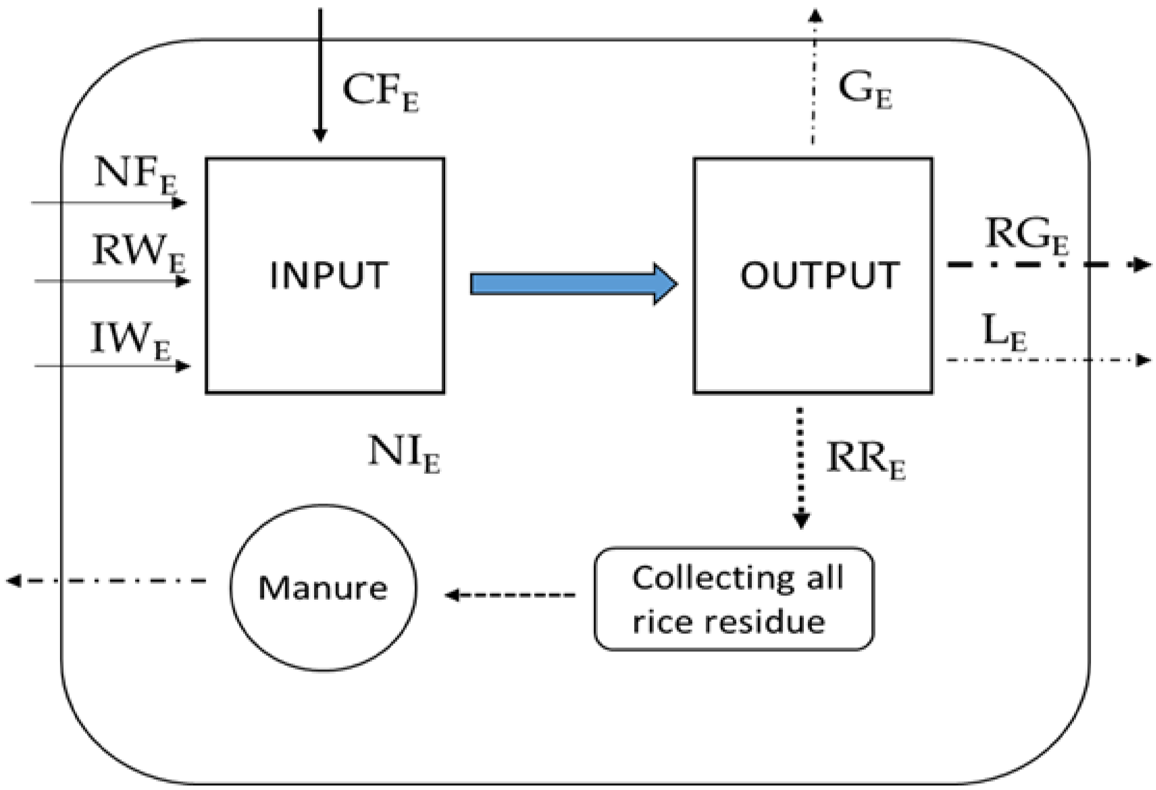
(a)



(b)


1
5
2
3
4
INPUT
OUTPUT
6
7
9
8
Ash
Burn

(c)


CF_E
G_E
NF_E
RW_E
IW_E
INPUT
OUTPUT
RG_E
L_E
NI_E
RR_E
Manure
Collecting all
rice residue

(d)

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

Figure 3.2 Schematic representation of nutrient fluxes in the four types of rice-residue management practices

The topsoils were sampled at 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 H_2O) 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 Walkey-Black method (ISO-22003 : 2008) , and concentrations of total N were analyzed by semi-micro-Kjeldahl (ISO 11261 : 1995). Available P was extracted by the Bray 2 method and analyzed colorimetrically (by use of the vanadomolybdophosphoric acid colorimetric method). Total contents of P and K were analyzed after digestion with H_2SO_4 + HNO_3 (1:1, v:v). Total contents of P were determined colorimetrically, and those of K were determined by using a photoelectric flame photometer (Corning 410-UK). 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.

3.2.5. Calculation of nutrient balances

Nutrient balances of N, P, and K were calculated as 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 N_2 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:

$$\Delta Soil_E = (IW_E + RW_E + CF_E + NI_E + RR_E + N_E) – (GC_E + CR_E + G_E + L_E) \quad \textbf{(}2)$$

3.2.6 Statistical analysis.

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.

3.3 Results

The soils of the investigated farms in Luong Phong Commune (Bac Giang Province) were characterized by low fertility (Table 3.3).

Table 3.3 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_2O)	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).

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 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.

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 3.4).

Table 3.4 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 (Fig. 3.3).

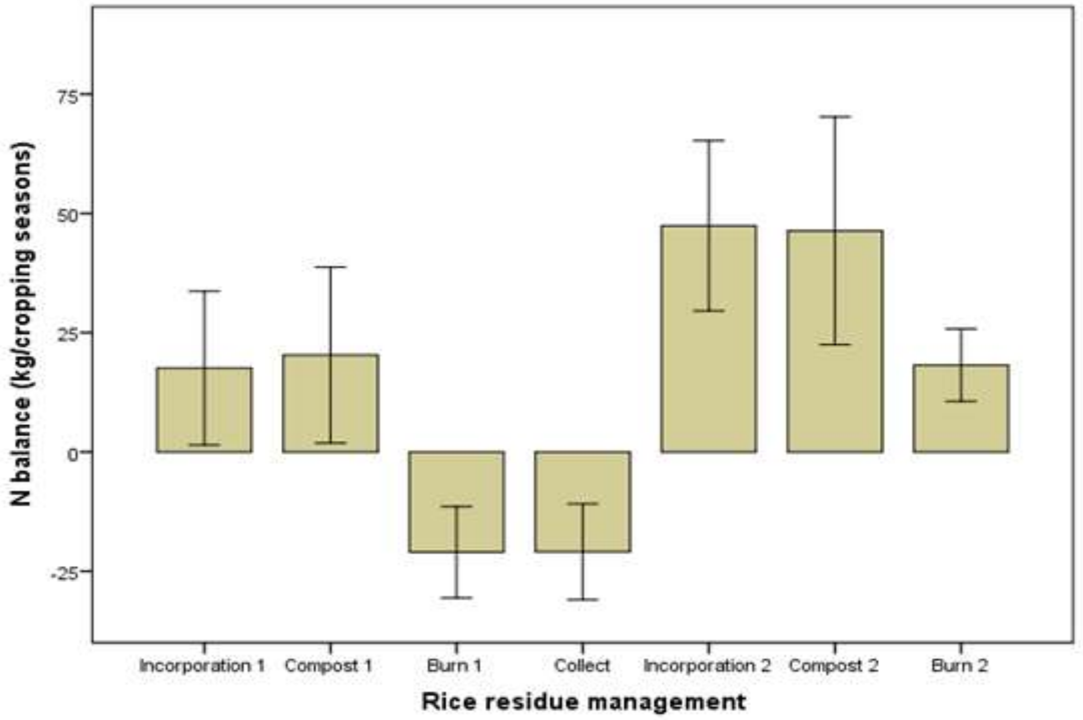


Fig. 3.3 Mean balance of N per cropping season under the selected rice-residue management practices. The columns show arithmetic means (n = 6) and the bars represent standard deviations.

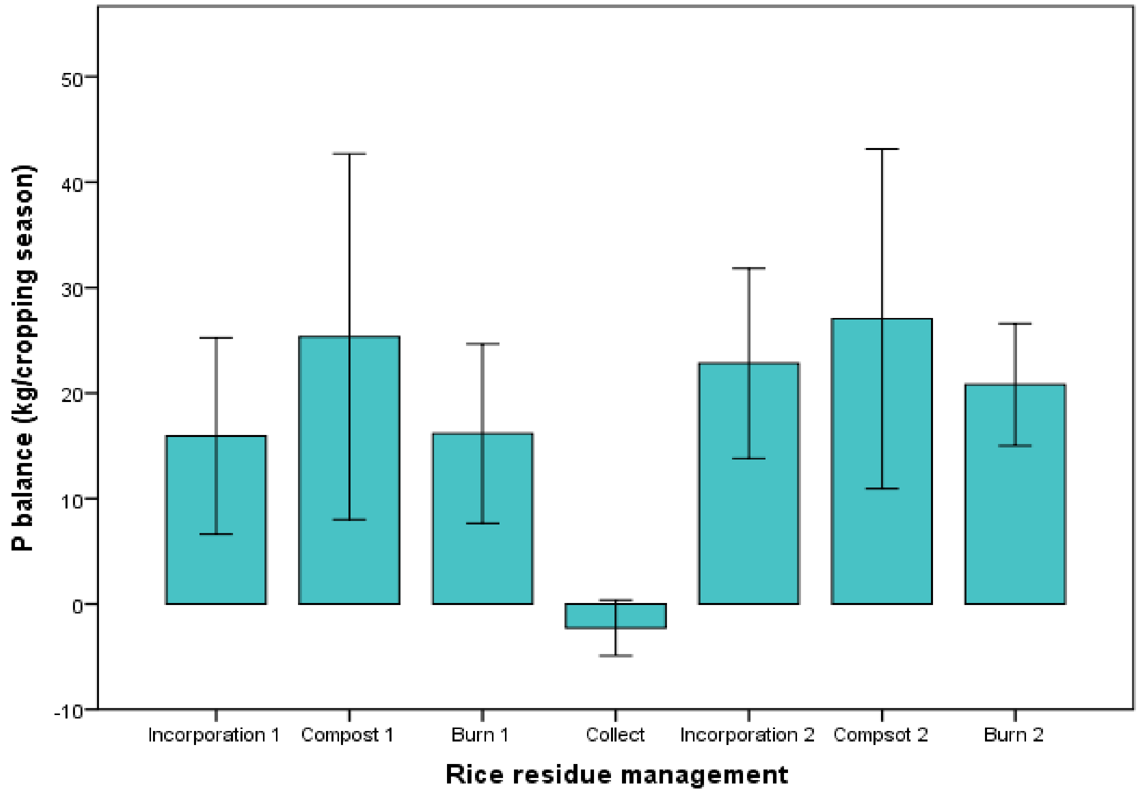


Fig. 3.4 Mean balance of P per cropping season under the selected rice-residue managementpractices. The columns show arithmetic means (n = 6) and the bars represent standard deviations.

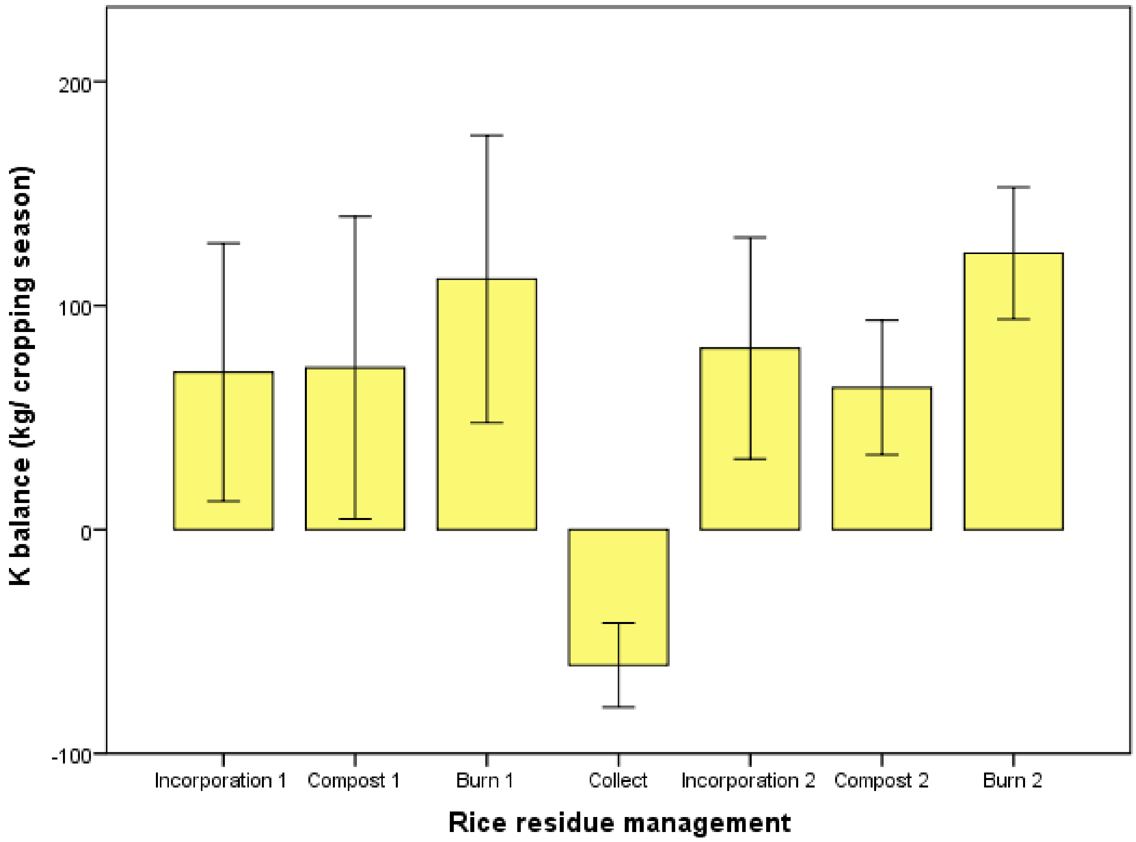


Fig. 3.5 Mean balance of K per cropping season under the selected rice-residue management practices. The columns show arithmetic means (n = 6) and the bars represent standard deviations.

The burning plots received the highest total K (125/133 kg ha^{-1}) and P inputs (27/32 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 (Figs. 3.4, 3.5).

In contrast, nutrient inputs through chemical fertilizers were lowest in collection plots in 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 rice, which resulted in negative N, P and K balances for these plots (Figs. 3.3-3.5).

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 3.5).

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.

Table 3.5 Mean N, P and K inputs from 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]	8a	34[a]	2246[d]	42[c]	8[a]	61[b]
Compost	788[b]	46[c]	19b	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 ($p < 0.05$).

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

For the collection plots in Che Cu Nha Commune, all nutrient balances were negative, amounting to -21 kg ha^{-1} a^{-1} for N, -3 kg ha^{-1} a^{-1} for P, and -60 kg ha^{-1} 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 18-47 kg ha^{-1} a^{-1}, that of P was 16-27 kg ha^{-1} a^{-1}, and that of K was 63-123 kg ha^{-1} a^{-1}. The only exception was spring rice with burning of crop residues (Burn 1 in Fig. 3.3), which resulted in a negative N balance.

3.4 Discussion

3.4.1 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 31-42 kg N ha^{-1}, 8 kg P ha^{-1}, and 34-61 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 44-46 kg N ha^{-1}, 19-24 kg P ha^{-1}, and 35-48 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, also high amounts of C were added to the soils through incorporation of rice residues (2.1-2.2 t C ha^{-1} per cropping season) and rice-residue compost (788-831 kg C ha^{-1} per cropping season). Thus, compared to burning (adding 53-56 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, 42, 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 of it. The compost is however not returned to the rice fields but is applied to maize fields. This practice leads to 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 Figs. 3.4 and 3.5. This outcome of our study is in agreement with data reported by [34].

The K balance was positive for all rice-residue management practices except for the collection of rice residues to feed cattle (Fig. 3.5). 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.

Also, the P balance was positive for all rice-residue management practices except for the collection of rice residues to feed cattle (Fig. 3.4). 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 [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 was less known [13].

The outcomes of our study support 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 by 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].

3.4.2 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 3.4, 3.5), leading to a considerable surplus of these nutrients in the soils (Figs. 3.3-3.5). 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 3.3). Such 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 to 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 CO_2, 2 kg of SO_2, 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 CO_2. This CO_2 release also clearly exceeds the CO_2 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 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}).

3.5 Conclusions

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

I) We advise against burning of rice residues. Given the limited availability of manure and labor force in the study regions, we recommend to incorporate 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 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.

References

1. GRiSP, 2013. GRiSP *(Global Science Partnership). Rice Almanac 4th*. Philippines: International Rice Research Institute. 2013.
2. FAO. Smallholders data portrait. Available online: http://www.fao.org/family-farming/data-sources/dataportrait/farm-size/en/ (05/19/2017). 2017. Available online: http://www.fao.org/family-farming/data-sources/dataportrait/farm-size/en/.
3. (GSO) General Statistics Office of Vietnam. *Statistical Summary Book of Vietnam*; Statistical Publishing House: Hanoi, Vietnam, 2017.
4. Gadde, B.; Bonnet, S.; Menke, C.; Garivait, S. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. *Environmental Pollution*. **2009**, *157*, 1554–1558, DOI: 10.1016/j.envpol.2009.01.004.
5. Tran, S.N.; Nguyen, T. H. N.; Nguyen, H.C.; Nguyen, V. C. N.; Le, H.V.; Kield, I. To quantify the seasonal rice straw and its use in different provinces in the Vietnamese Mekong Delta. *J. of scie Can Tho University*. **2014**, *32*, 87–93.
6. Truc, N.; Sumalde, Z.M.; Espaldon, M.; Pacardo, E.P.; Rapera, C.L.; Palis, F.G. Farmer's awareness and factors affecting adotion of rapid composting in Mekong delta, Vietnam and Central Luzon, Philippines. *Journal of Environmental Science and Management*. **2012**, *15*, 59–73.
7. Fairhurst, T.H.; Witt, C.; Buresh, R.J.; Dobermann, A. *Rice: A practical guide to nutrient management*, 2nd ed, 2007.
8. Niveta, J.; Arti, B.; Himanshu, P. Emission of air pollutants from crop residue burning in India. *Aerosol and Air Quality Research*. **2014**, 422–430, DOI: 10.4209/aaqr.2013.01.0031.
9. Gupta, P.K.; Singh, S.; Dixit, C.K. Singh, D.P. Sharma.; C. Tiwari, M.K.; Gupta, R.K.; Garg S.C. Residue burning in rice-wheat cropping system: causes and implications. *Current Science*. **2004**, *12*, 1713–1717.
10. Ponnamperuma, F.N. *Straw as a Source of Nutrients for Wet-Land Rice*: Organic matter and rice, 1984.
11. Bijay-Singh; Shan, Y.H.; Johnson-Beebout, S.E.; Yadvinder-Singh; Buresh, R.J. *Crop Residue Management for Lowland Rice-Base Cropping Systems in Asia: Advances in Agronomy*; Elsevier Inc.: Amsterdam, the Netherlands, 2008.

12. Hoang, N.T.; Tran T.T.; Dao T.H.; Nguyen, N.M.; Pham, T.N.; Nguyen, T.N.; Nguyen, H.T.; Vu, D.Q.; Ho, C.T. *Effect of agricultural residues incorporation into soils on increasing crops yield, reducing mineral fertilizers applied and improving soil properties.*: The results of Soils and Fertilizers Research; Agricultural Publishing: Hanoi, Vietnam, 2014.
13. Keck, M. Hung, D.T. Burn or bury? A comparative cost–benefit analysis of crop residue management practices among smallholder rice farmers in northern Vietnam. *Sustainability Science.* **2019**, 1–15, DOI: 10.1007/s11625-018-0592-z.
14. Tran, T.T.; Hung, T.D. Effect of crop by-product on yield and possibility of reducing potassium application rate for crops under rice-based cropping systems on marine sandy soils and grey-degraded soils. *Vietnam soil science J*. **2010**, *33*, 89–95.
15. Zhao, Y.; Wang, P.; Li, J.; Chen, Y.; Ying, X.; Liu, S. The effects of two organic manures on soil properties and crop yields on a temperate calcareous soil under a wheat–maize cropping system. *European Journal of Agronomy*. **2009**, *31*, 36–42, DOI: 10.1016/j.eja.2009.03.001.
16. (MARD) Ministry of Agriculture & Rural Development. *Annual report 2017 of fertilizers sector:* Hanoi, Vietnam, 2018.
17. FAO. FAOSTAT database. Available online: http://www.fao.org/faostat/en/#data/EF (accessed on 24 April 2018).
18. Pham, Q.H.; Nguyen. V. B. *Fertilizer and mitigation of greenhouse gas emission: National workshop on measures for improving fertilizer use efficiency in Vietnam (March 28, 2014).* Agricultural Publishing: Hanoi, Vietnam, 2014.
19. Bui, H.H. Assessing the present use of chemical fertilizers and promoting methods to improve the use of fertilizers for crop production in Vietnam. *Soils and Fertilizers Research Institute.* Hanoi, Vietnam, 2008.
20. Nguyen, V.B.; Tran, M.T.; Nguyen, V.C.; Le, T.; Bui, H.A.; Nguyen, T.T.; Chu, V.H.; Nguyen, H.; Bui, H.D.; Nguyen, D.; et al. Study on determination of limited factors of soils in red river delta, Mekong river delta and recommended solutions. *Soils and Fertilizers Research Institute.* Hanoi, Vietnam, 2014.
21. Baumann, L. *Insights into vulnerability of smallholder farming systems in the upland region of North Vietnam. Swiss Federal Institute of Technology*: Zurich, Switzerland, 2014.

22. Cobo, J.G.; Dercon, G.; Cadisch, G. Nutrient balances in African land use systems across different spatial scales: a review of approaches, challenges and progress. *Agric Ecosyst Environ*. **2010**, *136*, 1–15.
23. Stoorvogel, J.J.; Smaling E.M.A. *Assessment of soil nutrient depletion in Sub-Saharan Africa.*ISRIC: Wageningen, The Netherlands, 1990.
24. Abdalla, S.B.; Predotova, M.; Gebauer, J.; Buerkert, A. Horizontal nutrient flows and balances in irrigated urban gardens of Khartoum, Sudan. *Nutrient Cycling in Agroecosystems.* **2012**, *92*, 119–132, DOI: 10.1007/s10705-011-9476-7.
25. Huang, B.; Shi, X.; Yu, D.; Öborn, I.; Blombäck, K.; Pagella, T.F.; Wang, H.; Sun, W.; Sinclair, F.L. Environmental assessment of small-scale vegetable farming systems in peri-urban areas of the Yangtze River Delta Region, China. *Agriculture, Ecosystems & Environment.* **2006**, *112*, 391–402, DOI: 10.1016/j.agee.2005.08.037.
26. Khai, N.M. Ha, P.Q. Öborn, I. Nutrient flows in small-scale peri-urban vegetable farming systems in Southeast Asia—A case study in Hanoi. *Agriculture, Ecosystems & Environment*. **2007**, *122*, 192–202, DOI: 10.1016/j.agee.2007.01.003.
27. Phong, L.T.; Stoorvogel, J.J.; Van Mensvoort, M. E. F.; Udo, H. M. J. Modeling the soil nutrient balance of integrated agricultural aquaculture systems in the Mekong Delta, Vietnam. *Nutrient Cycling in Agroecosystems*. **2011**, *90*, 33–49.
28. (GSO) General Statistics Office of Vietnam. *Statistical Year Book of Vietnam*; Statistical Publishing House: Hanoi, Vietnam, 2018.
29. Nguyen, V.B.; Bui, D.D.; Ho, Q.D.; Bui, H.H.; Dang, T.L.; Thai, P.; Nguyen, V.T. *The basic information of main soil units of Vietnam.* The gioi: Hanoi, Vietnam, 2002.
30. Tran, Q.V.; Ho, Q.D.; Le. T. M. H.; Bui, T.Y. The situation of phosphorus in grey degraded soil in North Vietnam. *Science and Technol J. of Agric. & Rural development.* **2013**, *210+211*, 24–30.
31. Nguyen, T.L.; Truong, X.C.; Nguyen, V.H.; Dinh, V.S. *Survey and evaluate fertility soils map for intensive crop restructuring and sustainable agricultural land resources management in Viet Yen District, Yen Dung District, Luc Nam District, Yen District, Son Dong District and Bac Giang city, Bac Giang province*. Soils and Fertilizers Research Institute. Hanoi, Vietnam, 2015.
32. Truong, X.C.; Hoang, T.Q. *Research on terrace field land use and proposed integrated technical solutions to improve efficiency land use in Yen Bai.* Soils and Fertilizers Research Institute. Hanoi, Vietnam, 2013.

33. Hoang, A.L.; Nguyen, T.; Le, T.L. Estimated Gas Emission from Burning Rice Straw in Open Fields in Thai Binh Province. *J. of Sciences VNU*. **2013**, *2*, 26–33.
34. Doberman, A.; Fairhurst, T.H. *Rice Nutrient Disorders & Nutrient Management*, 2000.
35. Pham, Q.H.; Pham, T.H.; Nguyen, T.H.; Vu, D.T. Study on nutrient balance based intensive cropping system. *Soils and Fertilizers Research Institute.* Hanoi, Vietnam, 2005.
36. Tran, Q.V.; Ho, Q.D.; Bui, H.D.; Tran, M.T. Assessment of the qualities, quantities, and properties of grey degraded soil in North Vietnam. Ministry of Agriculture and Rural development. *Sci. and Technol. J. of Agric & Rural development*. **2012**, *207*, 19–25.
37. (MARD) Ministry of Agriculture & Rural Development. *Apply balance and efficiency fertilizer to crops*. Agricultural Publishing House. Hanoi, Vietnam, 1999.
38. Chien, N.V. *Balance fertilization – the solution to improving the efficiency of fertilizer use in Vietnam. National workshop on measures for improving fertilizer use efficiency in Vietnam (March 28, 2014)*. Agricultural Publishing. Hanoi, Vietnam, 2014.
39. Liu, X.; Herbert, S.J.; Hashemi, A.M.; Zhang, X.; Ding, G. Effects of agricultural management on soil organic matter and carbon transformation – a review. *Plant Soil Environ.* **2006**, *52*, 531–543.
40. Turmel, M.-S.; Speratti, A.; Baudron, F.; Verhulst, N.; Govaerts, B. Crop residue management and soil health: A systems analysis. *Agricultural Systems*. *2015*, *134*, 6–16, DOI: 10.1016/j.agsy.2014.05.009.
41. Lal, R. Managing Soils and Ecosystems for Mitigating Anthropogenic Carbon Emissions and Advancing Global Food Security. *BioScience.* **2010**, *60*, 708–721, DOI: 10.1525/bio.2010.60.9.8.
42. Hoang, N.; Tran, T.T.; Dao, T.H.; Vu, D.Q. Effect of crop by-product on yield of rice and maize under Spring rice – Summer rice – Winter maize cropping system on Red river alluvial soils, grey degraded soils and marine soils. *Vietnam soil science J.* **2010**, *33*, 95–106.
43. Ussiri, D.A.; Lal, R. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. *Soil and Tillage Research*. **2009**, *104*, 39–47, DOI: 10.1016/j.still.2008.11.008.
44. Bui, D. An overview on fertilizer use in Vietnam. *Vietnam Soil Science Journal*. **1996**, *6*, 21–25.

45. Vu, T.; Tran, M.T.; Dang, T. A survey of manure management on pig farms in Northern Vietnam. *Livestock Science*. **2007**, *112,* 288–297, DOI: 10.1016/j.livsci.2007.09.008.
46. (SFRI) Soils and Fertilizers Research Institute. *Fertilizers Handbook*; Agriculture Publishing House: Hanoi, Vietnam, 2005.
47. Pillot, D.; Le Coq, J. F.; Hoa, N.T.; Porphure, V. *Stakeholders' perception of pig effluent management in Thai Binh province.: Pig Production Development, Animal Waste Management and Environment Protection: A case Study In Thai Binh Province, North Vietnam.*; CIRAD-PRISE Publication: France,, 2006.
48. Phuong, N.D.; Tuan, V.D.; Toan, T.D. *Farmers practices in organic and inogarnic fertilization on crops, trees and vegetables.: Pig Production Development, Animal Waste Management and Environment Protection: A case Study In Thai Binh Province, North Vietnam.*; CIRAD-PRISE Publication: France, 2006.
49. Öborn, I.; Edwards, A.; Witter, E.; Oenema, O.; Ivarsson, K.; Withers, P.; Nilsson, S.; Richert Stinzing, A. Element balances as a tool for sustainable nutrient management: a critical appraisal of their merits and limitations within an agronomic and environmental context. *European Journal of Agronomy*. **2003**, *20*, 211–225, DOI: 10.1016/S1161-0301(03)00080-7.
50. Muoi, N. *Some character of gray degraded soil (Plinthic Acrisols) and relationship between those and spring rice yield. Agriculture Science and Technology*. Agricultural Publishing. Hanoi, Vietnam. 1983.
51. Mi, L. *The results of improving the gray degraded soil (Plinthic Acrisols) in North Vietnam. Soils and Fertilizers Research Institute*; Agricultural Publishing House: Hanoi, Vietnam. 1979.
52. Cancado, J.; Saldiva, P.; Pereira, L.; Lara, L.; Artaxo, P.; Martinelli, L.A.; Arbex, M.A.; Zanobetti, A.; Braga, A. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. *Environ Health Perspect*. **2006**, *114*, 725–729.
53. Awasthi, A.; Singh, N.; Mittal, S.; Gupta, P.K.; Agarwal, R. Effects of agriculture crop residue burning on children and young on PFTs in North West India. *Science of the Total Environment*. **2010**, *408*, 4440–4445, DOI: 10.1016/j.scitotenv.2010.06.040.
54. Hung, D.T; Callum, C.B.; Maxim, D.; Sauer, D. Effect of crop residues and water management to N_2O and CH_4 emissions from paddies rice in Vietnam (unpublished). 2019.

Chapter 4

This chapter is based on: Hughes, H.; Hung, D.; Sauer, D**. Silicon recycling through rice-residue management does not prevent silicon depletion in paddy rice cultivation** *(Submitted to Nutrient Cycling in Agroecosystems)*

Abstract

Silicon (Si) is known to have beneficial effects on plants, in particular on rice, which is a strong Si accumulator. Si helps mitigate environmental stresses and nutrient deficits of plants. In some regions, the limited plant-available Si in soils might have detrimental effects on rice cultivation. Crop residue management practices can affect the amount of plant-available Si in soils. However, the effect of crop residue management practices on the soil-plant Si cycle and on Si availability to plants remains, so far, largely understudied. Here, we attempt to fill this knowledge gap by reporting a study on the effects of three different rice-residue management practices on Si-depleted paddy rice systems from northern Vietnam. The management practices included (1) direct incorporation of rice residues into the soils, (2) burning of rice residues in the field, and (3) use of rice straw as fodder for animals, composting of the obtained manure, and subsequent application of the composted manure to the field. We analyzed different Si reservoirs in soils and plant Si contents under these different practices. Our results show a strong correlation between the different soil Si reservoirs and plant Si contents. We found no significant difference with respect to plant-available Si in soils and plant Si contents between the different management practices. These new data also suggest that Si-depleted rice-cultivation systems may proportionally lose Si through grain harvest faster than less Si-depleted systems. Such information is important for maintaining the level of plant-available Si and an appropriate Si levels in paddy rice.

Keywords: Rice straw, Phytoliths, Si-depleted soil, Si extraction, Soil Si pools, Biogenic Si

4.1 Introduction

Silicon (Si) is generally not considered an essential element for plant growth [1]. Yet many studies highlight its strong beneficial effects for a variety of plants, particularly under stress [2]. Thus, Si is now broadly recognized as a beneficial element for plants and a quasi-essential nutrient [3, 4]. Si can enhance plant resistance in a large variety of circumstances, which includes for example nutrient depletion, drought stress, pathogens and pest attacks. There is evidence for multiple combined effects of Si rather than one single effect [5]. The functioning of these beneficial effects is, however, far from being fully understood and is still subject to debate [3]. The beneficial effects of Si have been particularly studied for rice due to both its importance as a food source and its strong tendency to accumulate Si. The quantity of Si taken up and accumulated by plants varies according to the species [6]. The average Si content in rice plants is usually higher than 4% of the dry plant mass [6, 7] and can reach up to 10% [1]. Due to these high Si contents, rice is classified as a Si accumulator. Si uptake by plants is achieved both by passive uptake (Si absorption along with water) and, for Si accumulators, by an active transport process using specific transporters. These transporters (termed Lsi1 and Lsi2) respectively support the absorption of Si into the roots and its loading into the xylem [8]. Si is then transferred with the xylem to aerial parts via the transpiration stream [9] and is concentrated in parts of the plants where transpiration takes place. This concentration causes the Si to polymerize and precipitate into biogenic amorphous silica grains known as phytoliths [4]. A small but potentially highly reactive fraction of the Si remains present in the plant in other forms, e.g. as monomeric silicic acid H_4SiO_4 and small silica polymers dispersed in the organic matrix [10, 11]. Some plants also form a thin silica layer at the surface of the leaves named the double silica layer [10], but phytoliths generally account for most of the plant Si content. Si that has precipitated as opal inside the plants cannot be re-mobilized by the plants and remains insoluble until it is returned to soil with the plant litter.

In soils, Si is a ubiquitous element and soils commonly contain as much as 30% Si. Yet, almost all of this Si is usually present in minerals and is only slowly released through chemical weathering. The Si cycle thus begins with the initial release of Si into solution by chemical weathering of rocks. The dissolved Si (Si_{Diss}) is then available for further geochemical reactions and for plant uptake, mainly in the form of monomeric silicic acid [12, 13]. In natural ecosystems, plant Si returns to soil when organic matter is decomposed, thereby rapidly releasing the Si present in the organic matrices (Si_{Org}). Si release from phytoliths, which usually constitute the major part of biogenic silica in soils [14], is comparatively slower. Phytoliths may dissolve, persist, or structurally or chemically alter [15–17]. In most soils, biogenic Si (Si_B) contents range from 0.1 to 3 wt. % of the fine earth fraction (<2 mm), with concentrations generally decreasing with depth [13, 16, 18]. As biogenic silica is amorphous, and as amorphous silica (Si_{Am}) tends to be much more soluble than silicate minerals, most of the Si_B pool is assumed to be rapidly recycled and thus to represent an important source of Si in soil solution [11, 16]. As amorphous silica (Si_{Am}) tends to be much more soluble than silicate minerals, most of the Si_B pool is assumed to be rapidly recycled and thus to represent an important source of Si in soil solution [16, 12]. The balance between the different sources of Si (mineral dissolution vs biogenic silica recycling) absorbed by plants is not yet well established, but there is evidence that in many ecosystems soil–plant Si fluxes, involving intense Si_B recycling, are several times larger than fluxes of Si released from primary minerals via weathering. As a consequence, Si cycles on average several times through the biogenic silica pool before eventually being exported to the hydrological network [19–23]. In agricultural environments, regular Si_B

export through crop harvest interrupts this soil-plant recycling loop and can thus lead to a depletion of the Si_B pool in soils over time [21, 23, 24]. Several studies already proved an anthropogenic influence on Si_B storage and on continental Si fluxes [24, 22, 26–31]. This issue is critical as a decrease of bio-available Si may impact cereal yields; in particular for highly weathered soils as these tend to have a lower plant available Si content.

Rice is the world's most important food crop. More than 750 million tonnes of rice are annually harvested from about 165 million hectares around the world [32]. With an annual production of *ca.* 43 million tonnes, 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 [33]. From 1992 to 2015, the average amount of total N, P, and K fertilizers applied in agricultural production in Vietnam doubled. However, the efficiency of the fertilizer use remains low, resulting in considerable losses for the national economy, and causing eutrophication and greenhouse gas emissions [32, 34, 35]. Rice agriculture produces large amounts of straw and stalk. On average, one hectare of paddy rice generates about five tons of residues annually [36]. These residues can be used as a readily available, cost-efficient, and domestically produced organic fertilizer. A more efficient use of crop residues would reduce the need for Vietnam to import chemical fertilizers [34]. It would also increase farmers' net income by reducing their expenses for chemical fertilizers [37, 38]. Rice-residue management practices may also have an influence on the bio-availability of Si in rice fields [7, 39]. By returning biogenic silica to the fields, fertilization with crop residues also reduces the net export of Si. As such, crop residues may serve as a potential partial substitute for chemical fertilizers in agriculture [40–43]. As the export of Si is usually not compensated by Si-containing fertilizers, such Si fertilization by plant residues thus eventually helps to maintain Si availability for crops. Common crop residue management techniques found in Vietnam are:

- *Burning*: In Vietnam, like in many countries, the major portion of rice residues is burned on the field [44, 45]. The burning of crop residues results in a loss of nutrients, including macronutrients like nitrogen (N), phosphorus (P), and potassium (K) [46, 47]. However, burning of plant material was also shown to enhance the solubility of phytoliths in comparison to unburned plant material [48–50]. Nguyen et al. [51]. specifically studied the effect of burning rice straw and concluded that burning can be an efficient measure to improve Si availability in the short term.

- *Incorporation*: Crop residue incorporation into the soil can increase soil organic carbon stocks, improve soil structure, and substantially contribute to maintaining appropriate levels of nutrients such as N, P, and K in the soil [52, 40, 46]. The crop is harvested mechanically and plant residues are spread on the land. They are then incorporated into the soil, thus burying nearly all Si contained in straw. Studies have shown that the incorporation of plant residues into the soil can markedly increase the Si concentration in soil solution [53–55].

- *Manure production*: Rice residues can be used as fodder for cattle. The obtained manure is then composted. The final product can either be dispersed back on the fields of origin (as in the present study) or on other fields. In the latter case, the result is a net export of plant residues. The reactivity and the solubility of plant Si were shown to increase after passing an animal digestion tract, mainly due to degradation of organic matrices, resulting in increased exposure of phytolith surfaces and thus higher dissolution rates [56].

Each of these three rice-residue management techniques may thus affect the recycling rate of biogenic Si in soils and thereby Si availability to plants. Si cycling and Si availability in rice cultivation have already been the subject of several studies, including some in regions near our research site [53, 57, 58]. These studies showed strong Si limitation in local rice cultivation, with a possible effect on yields. They also emphasized the importance of recycling crop residues for maintaining a sufficient Si supply to paddy rice in the area, and in regions with low Si availability in general. In addition, they pointed to a lack of knowledge on the effects of different agricultural practices, in particular straw management, on Si availability and called for more studies. However, most studies focused on comparing the effect of straw export with straw residues recycling. To the best of our knowledge, no study focused yet on comparing the effects of different crop-residue management practices on Si cycling.

In the present study we aimed at assessing not only the amounts of Si that are immediately available to plants, but also the potential of the soil to provide plant-available Si at the time scale of a growing season. Therefore, we considered a broader set of soil Si reservoirs, including dissolved and readily mobilizable Si (Si_{M}), Si adsorbed to mineral surfaces (Si_{Ads}), Si in organic matter (Si_{Org}), Si occluded in pedogenic oxides and hydroxides (Si_{Occ}), and Si in amorphous silica (Si_{Am}). Si_{M} and Si_{Ads} are both readily available to plants [59, 60]. The plant-availability of Si_{Occ} is likely coupled to the dissolution and re-precipitation of iron hydroxides during the redox cycles in paddy rice cultivation. Dissolution and re-precipitation of these oxides and hydroxides with changes of redox conditions can scavenge or release Si [61, 62, 17]. Si_{Org} turns into Si_{M} and thus becomes plant-available when plant materials or soil organic matter are decomposed. Finally, Si_{Am} comprises both Si from biogenic (mainly phytoliths) and pedogenic origin. This reservoir is thought to be an important source of plant-available Si as well. However, literature data about the recycling rates of phytoliths are still scarce [11, 21, 23], but a recent litterbag experiment suggested that the Si recycling speed from paddy rice straw might be especially high, with more than half of the plant Si being recycled within one month [53].

Owing to the various beneficial effects of Si for plants mentioned above, the current lack of knowledge about the effect of agricultural practices on the Si cycle is unfortunate. According to the knowledge gaps pointed out above, the objectives of our study were to assess the effects of different rice-residue management practices on (i) various soil Si pools in a silicon-depleted system, (ii) Si uptake by rice plants and (iii) rice yields, through the management effects on Si plant-availability. The overall goal of this assessment was to identify management practices that may contribute to a more sustainable rice cultivation in Vietnam.

4.2 Material and methods

4.2.1 Study area

The study area is located in the Luong Phong Commune, in the alluvial plain of the Red River, *ca.* 55 km north-east of Hanoi, northern Vietnam (Hiep Hoa District, Bac Giang Province; 106°01′ E, 21°20′ N). The climate is humid subtropical with a monsoon season. The mean annual temperature is 23.5°C and the mean annual rainfall is 1620 mm, of which more than 80% occurs between May and October. The soils are Plinthic Acrisols according to the World Reference Base for Soil Resources[63].The texture of the soils is predominantly sandy loam. Acrisols are among the main soils used for agriculture in Vietnam, occupying 1.4 million hectares (12% of the agricultural land of Vietnam). In northern Vietnam, these soils are concentrated in regions that are known for their intensive agricultural production [64]. The fertility of these soils is however generally low [65]. The predominant cropping system is a lowland paddy rice (*Oryza sativa* L.) system, with two harvests per year. Agriculture is mostly rainfed with complementary irrigation from a nearby reservoir. Spring rice is usually planted in February and harvested in late May. Summer rice is planted in late June and harvested in late September. Although some farmers combine rice cultivation with other crops, we focused on plots where only rice is cultivated.

With a median landholding size of 0.63 ha, smallholders are the backbone of the Vietnamese agriculture [33]. Due to this relatively small size of the fields, various management practices can be found within a short distance. This allows for an easy comparison of the effects of management practices, whereby other influencing environmental parameters can be kept similar. The different plots used for this study have identical climate and similar soils. This study is complementary to a previous study by Hung et al. [66] in which we analyzed the effects of crop-residue management practices on N, P and K budgets of the same paddy rice fields.

4.2.2 Sampling

We selected three plots for each of the following rice-residue management practices: (1) Incorporation of crop residues into the soil, (2) application of composted rice-residue manure, and (3) burning of the rice residues in the fields. Data on rice-residue management practices were collected from September 2015 to September 2017. Samples of topsoil, crop residues, rice grains, and composted rice-residue manure were collected for all plots, to monitor Si fluxes under the three rice-residue management practices, with three replicates per management practice. The topsoil was sampled with a shovel over a depth of 0-20 cm. At each plot, five topsoil samples were taken within an area of 5 m × 5 m and were merged in the field. The samples were air-dried and sieved (< 2 mm). Aliquots of these samples were analyzed by Hung et al. [66] for pH, granulometry, CEC, total N, P and K, available P and K. Plant samples were collected at the time of harvesting of summer rice (September

2015 and 2017) from an area of 2 m × 2 m within the area from which topsoil samples had been taken. Plant samples were separated into crop residues (stems and leaves) and rice grains (including the husk). They were weighed, 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 composted manure were collected either from the fields or obtained from the farm households. Samples of irrigation water were collected in September 2017, filtered and analyzed for their Si_{Diss} content using the molybdate-blue colorimetric method. The Si_{Diss} content of rainwater was not analyzed, as it is known to be usually negligible [67].

4.2.3 Plant analyses

The total Si contents of the plant samples were extracted by the 1% Na_2CO_3 method [68, 69] initially developed for amorphous silica extraction from soil samples. *Ca.* 20 mg of plant material is weighed into a 50 mL centrifuge tube using a high-precision scale. 40 mL of a 1% Na_2CO_3 solution (0.094 M) is added and the tube is then put in a shaking hot water bath at 85°C for minimum 3h. The tubes are manually shaken hourly to fully mix the samples. After centrifugation (5 min at 3000 rpm), an aliquot of the solution is neutralized with HCl and filtered through a paper filter (1-2 µm). The sample is then diluted and analyzed with the molybdate-blue colorimetric method. We ensured that no sample contained more than 2.1 mg Si, as recommended by Meunier et al. [68] as amorphous silica dissolution might be incomplete for samples with higher Si contents. All plant analyses were made in at least two replicates.

4.2.4 Analyses of soils and Si pools in soils

In order to quantify the effects of the different rice-residue management practices on the various Si reservoirs of the paddy soils, we applied a sequential Si extraction to the soil samples. The extraction followed the procedure developed by Georgiadis et al [70, 71].

Throughout the successive steps, Si is extracted from the following reservoirs: mobile Si, adsorbed Si, Si in soil organic matter, Si occluded in pedogenic oxides and hydroxides, and Si in amorphous silica (both biogenic and minerogenic). The extraction steps are shortly described below, the detailed procedure of each extraction step is given in Georgiadis et al. [70, 71]. For each sample, 1 g of soil material is processed through the whole extraction procedure. The extracts are centrifuged and filtered through paper filters (1-2 µm). The Si concentration of the extracts is then measured colorimetrically or by use of an atomic emission spectrometer (ICP-AES), depending on the steps (see below). The remaining soil is rinsed several times with deionized water between steps.

Dissolved and readily mobilized Si (Si_M): The quantification of the dissolved and easily mobilized Si fraction is the first step of the sequential extraction. The soil samples are mixed with 5 ml of calcium chloride solution (0.01 M). The samples are shaken once per hour for one minute over 24h. The filtered extracts are analyzed for Si colorimetrically.

Adsorbed Si (Si_{Ads}): Si adsorbed on mineral surfaces is desorbed by adding 10 ml of acetic acid (0.01 M) to the cleaned soil material from step 1. The mixture is left on the overhead shaker for 24h. The samples are shaken once per hour for one minute over 24h. After filtration, the extracts are analyzed for Si colorimetrically.

Si in organic matter (Si_{Org}): H_2O_2 is used to decompose the soil organic matter in order to release the Si present in the organic matrix. The sample is first treated with 20 ml H_2O_2 (17.5%) at room temperature. Once the reaction has calmed down, 10 ml of concentrated H_2O_2 (35%) is added and the samples are put in a shaking hot water bath at 85°C until no further reaction is visible. After filtration (PES filters, 0.2 µm), the extracts are analyzed for Si by use of an ICP-AES. Aluminum contents are also measured to check for possible contamination from mineral dissolution.

Si occluded in pedogenic oxides and hydroxides (Si_{occ}): Pedogenic oxides and hydroxides are dissolved by adding 50 ml of an ammonium oxalate (0.2 M) and oxalic acid (0.14 M) solution to the samples. After an initial reaction time of 8h, the samples are exposed to UV light overnight. The centrifuged and filtered extracts are analyzed for Si by use of an ICP-AES.

Amorphous Si (Si_{Am}): The remaining soil samples are then transferred into 400 ml of a 0.2 M NaOH solution to extract Si from amorphous silica following the protocol of Georgiadis et al. (2015). The samples are kept for 7 days and are shaken hourly for one minute. After centrifugation and filtration, Si concentrations in the extracts are measured colorimetrically.

4.3 Results

4.3.1 Soils

Si concentrations in the various soil Si reservoirs of the different experimental plots were highly variable. However, our results do not show significant differences between sites with different management practices. The results are summarized in Table 4.1. Amorphous silica is always by far the largest of the different Si pools considered in our study (2.3 mg/g on average). All considered soil Si reservoirs tended to be correlated with each other to variable degree. These correlations contrast with results from Klotzbücher et al.[39] who observed clear anti-correlations between Si reservoirs similar to Si_{Am} and plant available Si (Si_{Ava}, see below) or between Si_{Am} and Si_{Occ} in paddy soils of the Philippines (Hydragric and Irragric Anthrosols).

4.3.2 Irrigation water

Si_{Diss} content in irrigation water was similar in the different fields at the time of the harvest in 2017, ranging from 0.75 mg/L to 1.04 mg/L (average = 0.9 mg/L ±0.2; ±2SD). In comparison, water from the reservoir used in complement to rainwater for irrigating the fields had a Si_{Diss} content of 3.50 mg/L. The low Si_{Diss} content in irrigation water confirms the predominance of rainwater for irrigation at the time of sampling.

4.3.3 Plants

The average Si content in the above-ground plant biomass was 1.5% of the dry plant biomass (±0.4%, ±2SD), with generally slightly higher concentrations in straw than in the grains (1.7% and 1.2% respectively). This is very low compared to data from the literature, which usually exceed 4% [6, 7, 72]. The plant Si contents measured in our study are also low in comparison to those of other paddy rice plots in the lowlands of Northern Vietnam, where Klotzbücher et al.[58]; average Si content of 4.1%. This is also below the 5% threshold proposed by Dobermann and Fairhurst [73] below which Si deficiency affects rice plants and yields. At harvest time, the different plots showed similar biomass (average of 10.0 Mg/ha ±0.8, ±2SD). On average, the grain accounted for 49% of the total aerial plant biomass (±1%, ±2SD) and for 41% (±8%, ±2SD) of the Si present in the above-ground plant biomass (Fig. 4.1). This is relatively high compared to data from other studies. Klotzbücher et al. [57] reported grain masses of about 20% of the total above-ground plant biomass (23% for Vietnamese rice and 17% for Philippine rice). Si uptake within one season ranged from 80 kg/ha to 230 kg/ha. We found no differences between the Si contents of the above-ground plant biomass (Si_{Plant}) under the different rice-residue management practices (Fig. 4.2)

Si contents in straw (Si_{Straw}) correlate closely with Si contents of most of the soil Si reservoirs (Fig. 4.3), in particular with Si_{Ads} (R^2=0.64; p=7×10^{-5}) and Si_{Org} (R^2=0.65; p=5×10^{-5}). Only between Si_{Straw} and Si_{M} no correlation was found. However, we observed a correlation between Si_{Straw} and the sum of Si_{M} and Si_{Ads}, which we interpreted as the plant-available Si fraction (Si_{Ava}=Si_{M}+Si_{Ads}; R^2=0.59; p=2×10^{-4}). Si_{Straw} also tends to correlate with Si_{Occ} and Si_{Am} (R^2=0.47 and R^2=0.46, respectively). In contrast, Si contents of the grains show only weak trends with Si contents in the various soil Si reservoirs. The only noticeable relationship was observed between Si_{Straw} and Si_{Org} (R^2=0.33).

Table 4.1 Measured Si content of the plants and of the different soil Si reservoirs at the studied sites.

			Plants			Si in biomass			Soil					
Treatment	**Site**	**Year**	Si_{Straw} mg/g	Si_{Grain} mg/g	Si_{Plant} %	Straw kg/ha	Grain kg/ha	Plant kg/ha	Si.M µg/g	Si.Ads µg/g	$Si._{M+Ads}$ µg/g	Si.Org mg/g	Si.Occ mg/g	Si.Am mg/g
Manure	1	2015	19.8	23.4	2.2%	98	119	217	15.5	21.7	37.3	0.34	0.34	3.65
	2	2015	15.4	11.9	1.4%	86	65	151	17.2	11.8	29.0	0.22	0.33	2.08
	3	2015	20.3	12.3	1.6%	109	66	175	14.0	15.2	29.2	0.27	0.45	3.25
	1	2017	10.5	10.6	1.1%	53	51	104	3.3	4.0	7.3	0.13	0.12	1.47
	2	2017	18.0	10.6	1.4%	81	48	129	7.6	9.8	17.4	0.18	0.16	2.29
	3	2017	11.6	8.5	1.0%	52	38	89	6.1	5.2	11.3	0.14	0.14	1.22
Burning	1	2015	22.1	11.8	1.7%	116	63	179	14.1	19.5	33.7	0.27	0.33	2.10
	2	2015	21.0	20.6	2.1%	117	113	230	8.4	15.6	23.9	0.27	0.35	2.43
	3	2015	20.7	20.6	2.1%	114	109	223	10.2	11.3	21.5	0.28	0.32	2.44
	1	2017	14.8	7.2	1.1%	68	33	102	4.2	11.9	16.1	0.25	0.43	2.99
	2	2017	26.8	8.2	1.8%	132	37	169	8.6	36.9	45.5	0.33	0.42	3.48
	3	2017	9.9	6.0	0.8%	49	27	76	11.9	11.3	23.3	0.13	0.12	1.19
Incorporation	1	2015	15.7	15.0	1.5%	87	84	171	7.9	12.8	20.7	0.26	0.29	2.58
	2	2015	14.5	14.8	1.5%	78	78	156	8.3	11.9	20.2	0.24	0.24	2.17
	3	2015	18.7	13.2	1.6%	104	73	177	10.0	12.1	22.1	0.23	0.30	1.74
	1	2017	15.2	8.5	1.2%	71	38	109	6.3	9.8	16.1	0.23	0.31	2.40
	2	2017	17.2	8.4	1.3%	81	38	120	8.2	9.0	17.3	0.22	0.39	2.72
	3	2017	15.0	9.7	1.2%	71	43	114	4.0	5.9	9.9	0.14	0.16	1.28
Average			17.1	12.3	1.5%	87	62	149	9.2	13.1	22.3	0.23	0.29	2.30
Average manure			15.9	12.9	1.4%	80	65	144	10.6	11.3	21.9	0.21	0.26	2.33
Average burning			19.2	12.4	1.6%	99	64	163	9.6	17.7	27.3	0.25	0.33	2.44
Average incorporation			16.1	11.6	1.4%	82	59	141	7.5	10.3	17.7	0.22	0.28	2.15

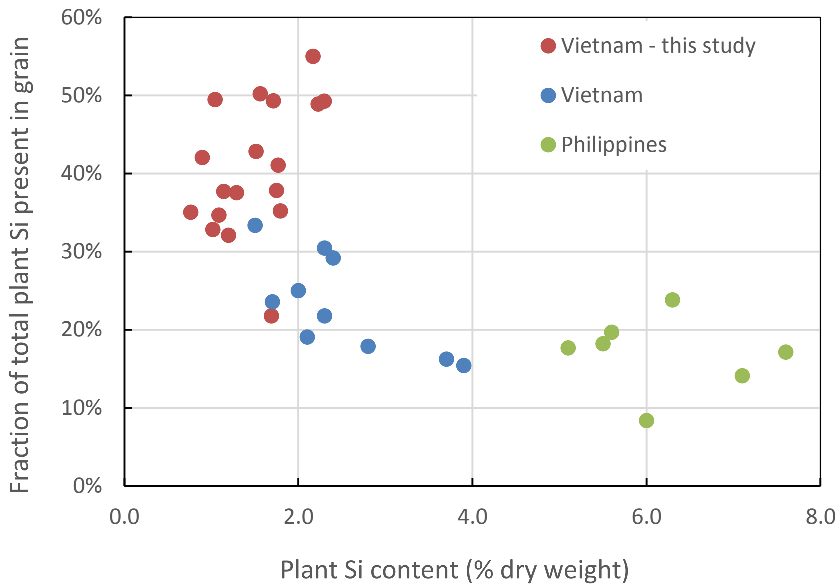


Figure 4.1 Evolution of the proportion of Si present in the grain and in the straw depending on the total plant Si content. Additional data are from Klotzbücher et al. [57].

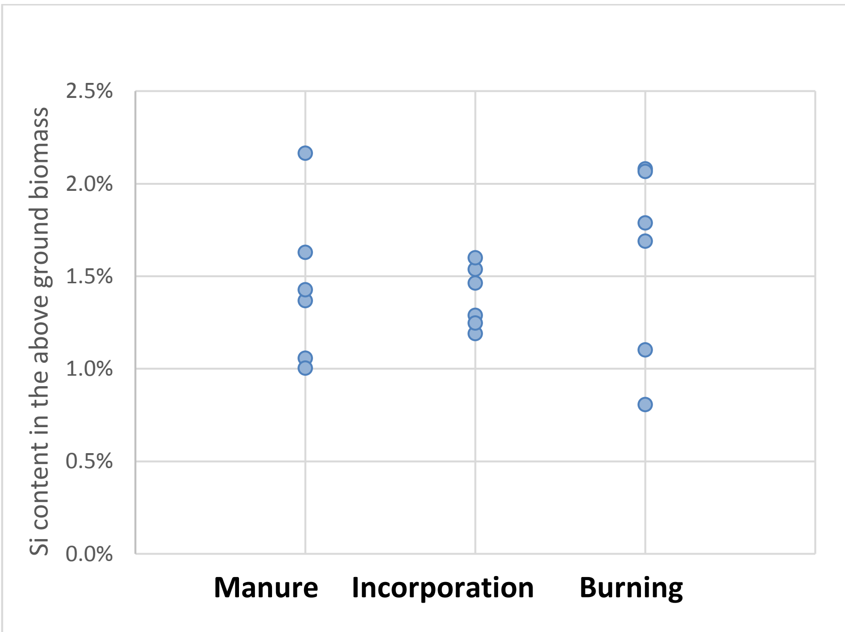


Figure 4.2 Comparison of the plant Si content measured for the different rice residue management practices. Manure = application of composted manure obtained from feeding animals with rice residues, Incorporation = incorporation of rice residues into the soil, Burning = burning rice residues directly in the field.

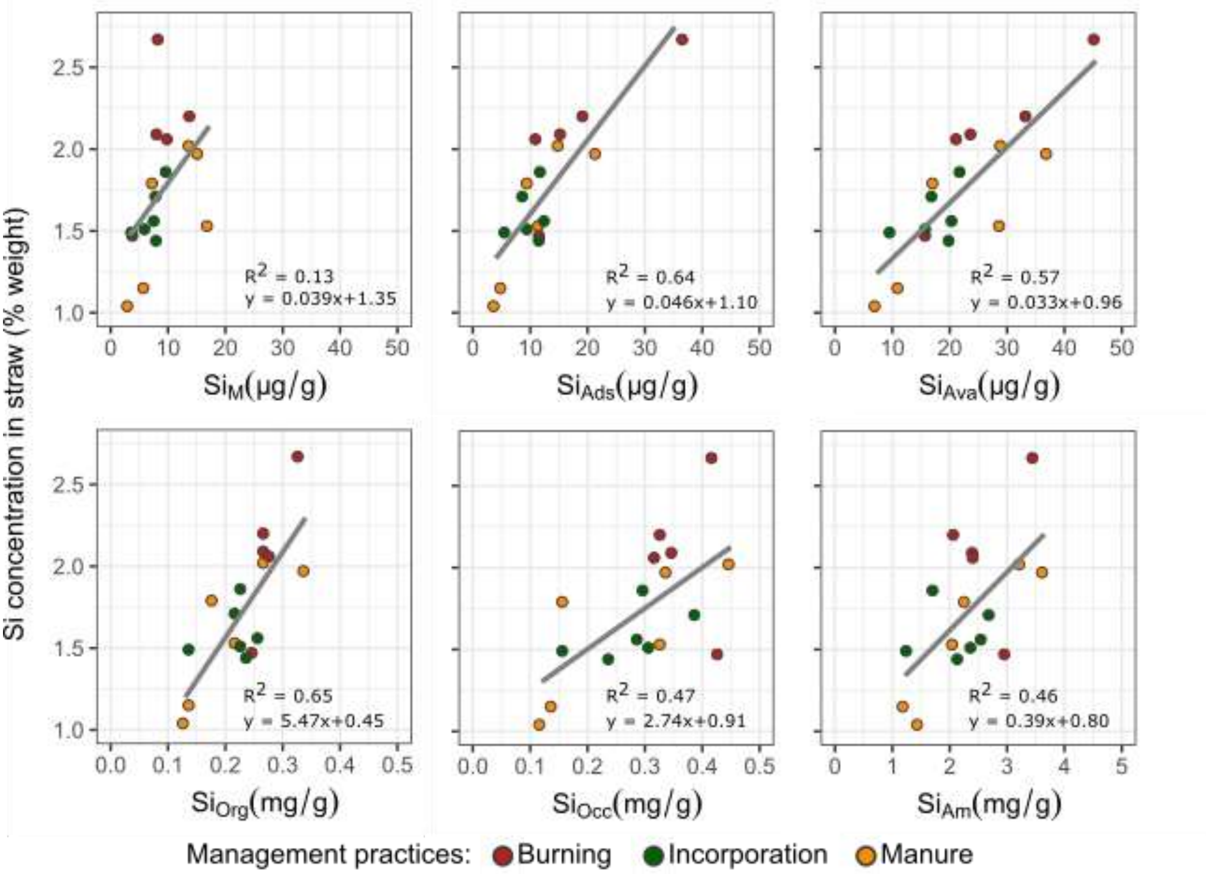
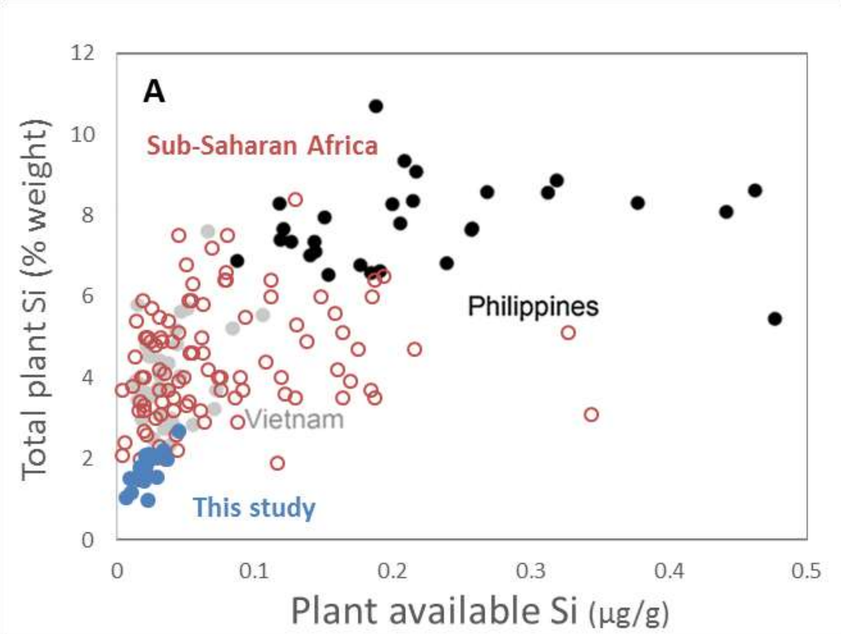


Figure 4.3 Relationships between Si concentrations in rice straw and the different soil Si reservoirs (management practices: red = application of composted manure obtained from feeding animals with rice residues, blue = incorporation of rice residues into the soil, green = burning rice residues directly in the field). Si_M = mobile Si, Si_{Ads} = adsorbed Si, Si_{Ava} = plant available Si, Si_{Org} = Si in soil organic matter, Si_{Occ} = Si occluded in pedogenic oxides, Si_{Am} = Si in amorphous silica



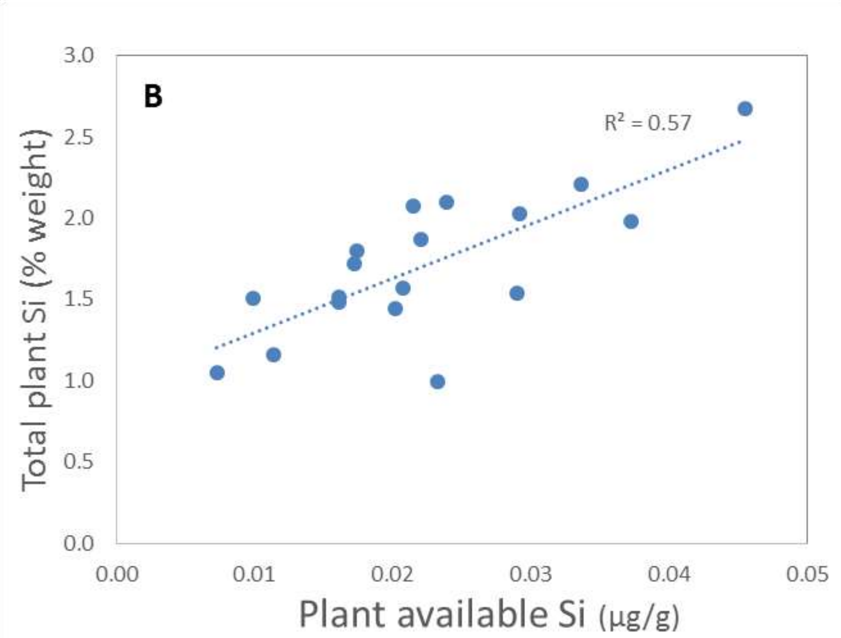


Figure 4.4 – A) Comparison of the Si content in rice straw and the plant available Si measured by acetate extraction or as the sum of Si_M and Si_{Ads}. Data from our study clearly lie at the lower end of the dataset for both parameters. Sub-Saharan data are from Tsujimoto et al. [72], Philippines data and additional Vietnamese data are from Klotzbücher et al. [57]. B) Magnified view of the data from this study showing the strong relationship between the two parameters.

4.4 Discussion

In our study, paddy soils and rice plants are both strongly Si-depleted, compared to previously published data for paddy rice systems. Even compared to data from previous studies in Vietnam, the Si contents of our soil and plant samples fall on the lower end of the existing literature datasets (Fig. 4.4). This finding classifies our paddy rice fields as strongly Si-depleted systems. They are thus ideal for observing the effects of different management practices on Si plant-availability as any minor change in Si input to these Si-depleted systems should proportionally have a larger effect on the soil Si_{Ava} contents than in systems where plant-available Si is abundant. Since Si can be actively taken up by rice plants [3, 74], Si_{Straw} and Si_{Ava} are not necessarily systematically correlated. However, in a previous study on soil-plant Si cycling in rice fields, Klotzbücher et al. [57] found a positive relationship between Si_{Straw} and Si_{Ava} (measured by acetate extraction). This correlation was limited to Si_{Straw} contents below *ca.* 8-10%. Above this threshold, rice plants probably reached a maximum uptake capacity and additional Si_{Ava} did not lead to further increase of plant Si contents. As the Si contents of our plant samples are all below 3%, they fall well within the range for which Klotzbücher et al. [57] found the correlation between plant Si contents and plant-available Si in soils. In agreement with Klotzbücher et al. [57] our data show a clear correlation between Si_{Straw} and Si_{Ava} (R^2=0.57, p=5×10^{-5}), suggesting a direct link between these two parameters. We thus conclude that Si availability in soils limited plant Si uptake at our study sites. However, Si_{Ava} amounted on average only to less than 1/3 of the Si content of the plant biomass at harvest time (table 4.1). Thus, the pool of plant-available Si in soils must be replenished by other, larger, Si sources. Possible Si sources include irrigation water, mineral weathering, Si_{Org}, Si_{Occ} and Si_{Am}. Si inputs from irrigation water over a growing season are difficult to quantify, but Si concentrations of irrigation water samples were generally low (< 1 mg/L on average in September 2017). Data on the amounts of reservoir water used for irrigation are lacking, but as the growing season preceding the September harvest corresponds to the rainy season in northern Vietnam it is reasonable to assume that most of the water input is rain water (containing only negligible Si_{Diss}) and that Si input with irrigation water is limited. Similarly, it is difficult to quantify the Si input from mineral weathering. However, given the high degree of weathering of the soils in the region, input from mineral weathering is expected to be limited, compared to other soil types. Thus, with the setting of our study sites, other potential Si sources become all the more important. Among the other mentioned Si reservoirs, Si_{Org} is likely released at a short time scale. In a litter-bag experiment with Si-poor straw by Marxen et al.[53], 2/3 of the Si in the straw was released within one month. Si in straw is thus potentially an important source of plant-available Si, as also reflected in the strong correlations between Si_{Org} and both Si_{Straw} and Si_{Ava} observed in our study.

Given the low Si plant-availability in our study area, we had expected that small differences in Si input would lead to more easily measurable effects on plant Si contents than in systems with higher Si plant-availability. However, our data do not show any significant differences in plant Si contents between the management practices (Fig. 4.2 and table 4.1). However, caution must be exercised though in the interpretation of these results due to the limited size of the dataset. A possible explanation for the absence of clear differences between the three management practices is the high Si export through harvest. At our study sites, the rice grains contained on average about 40% of the total plant Si at harvest time. As the Si contained in the rice grains (Si_{Grain}) is exported from the system and is thus not recycled on the field, this regular export twice a year leads to a considerable systematic loss of Si from the system. Possible effects of different Si recycling rates by the three management techniques might thus be obscured by this large systematic Si export. This Si loss through harvest is, moreover, enhanced at our study sites, as Si_{Grain} comprises a particularly large proportion of Si_{Plant} compared to other studies (e.g., 23% in Vietnamese rice plants measured by Fig. 4.1). This finding also raises the question whether the high proportion of Si_{Grain} in Si_{Plant} is a consequence of the low contents of plant-available Si in the soils. If this is the case, it might trigger a snowball effect, in which low contents of plant-available Si in soils leads to a higher proportion of Si in the grains compared to Si in the whole plant biomass, thus eventually resulting in a proportionally greater Si export via the harvest of the rice grains. Such snowball effect would have serious implications, as it would mean that the more Si-depleted a soil already is, the higher is the proportion of plant-available Si lost via grain export from the system. Another explanation for the absence of significant differences in Si contents of rice plants grown under the three different management practices could simply be that the recycling of biogenic Si is particularly efficient under the given humid-subtropical climate. All three management practices involve recycling of the Si in crop residues. Thus, if for all three management practices the biogenic Si is recycled at a similar rate, this might result in a similar plant-availability of Si.

4.5 Conclusions

The rice-residue management practices tested in this study, (1) incorporation of rice residues into the soils, (2) burning of rice residues in the field, and (3) application of composted manure from animals fed with the rice straw, did neither lead to significant differences in plant-available Si in soils and other soil Si reservoirs nor in the plant Si contents. Thus, all three rice-residue management practices had similar effects on Si plant-availability. We found a close correlation between the most readily plant-available Si fractions in soils (sum of mobile Si and adsorbed Si) and Si contents in rice straw. As these two soil Si fractions alone cannot account for the Si contents of the plants, this observation highlights the dependency of the readily plant-available soil Si fractions on other soil Si reservoirs such as Si_{Org}, Si_{Am} and Si_{Occ}. All tested management practices involved plant-to-soil Si recycling. In future studies, an additional comparison with rice plots where rice residues are not returned to the field, and where all plant Si is thus exported, would be interesting in order to also assess the exact benefit of returning the Si contained in rice residues to the fields. In agreement with previous studies, our results suggest that in a Si-depleted environment, proportionally more Si is accumulated in grains than in the rice residues. As the grains are not returned to the system after the harvest, on the long term this could enhance Si depletion in soils that already have low contents of plant-available Si.

References

1. Epstein, E. The anomaly of silicon in plant biology. *Proc. Natl. Acad. Sci.* **1994**, *91*, 11–17.
2. Guntzer, F.; Keller, C.; Meunier, J.-D. Benefits of plant silicon for crops: a review. *Agron. Sustain. Dev.* **2012**, *32*, 201–213.
3. Coskun, D.; Deshmukh, R.; Sonah, H.; Menzies, J.G.; Reynolds, O.; Ma, J.F.; Kronzucker, H.J.; Bélanger, R.R. The controversies of silicons role in plant biology. *New Phytol* **2018**, *221*,67–85.
4. Epstein, E. SILICON. Annu. Rev. Plant Physiol. *Plant Mol. Biol.* **1999**, *50*, 641–664.
5. Guntzer, F.; Keller, C.; Meunier, J.-D. Benefits of plant silicon for crops: a review. *Agron. Sustain. Dev.* **2012**, 201–213.
6. Hodson, M.J.; White, P.J.; Mead, A.; Broadley, M.R. Phylogenetic Variation in the Silicon Composition of Plants. *Ann. Bot.* **2005**, 1027–1046.
7. Savant, N.K.; Datnoff, L.E.; Snyder, G.H. Depletion of plant-available silicon in soils: A possible cause of declining rice yields. Commun. *Soil Sci. Plant Anal.* **1997**, 1245–1252.
8. Ma, J.F.;Yamaji, N. A cooperative system of silicon transport in plants. *Trends Plant Sci.* **2015**, *20*, 435–442.
9. Mitani, N.; Ma, J.F. Uptake system of silicon in different plant species. *J. Exp. Bot.* **2005**, 1255–1261, doi:10.1093/jxb/eri121.
10. Currie, H.A.; Perry, C.C. Silica in plants: Biological, biochemical and chemical studies. *Ann. Bot.* **2007**, *100*, 1383–1389, doi:10.1093/aob/mcm247.
11. Fraysse, F.; Pokrovsky, O.S.; Meunier, J.-D. Experimental study of terrestrial plant litter interaction with aqueous solutions. *Geochim. Cosmochim. Acta* **2010**, 70–84.
12. Iler, R.K. The chemistry of silica: solubility, polymerization, colloid and surface properties, and biochemistry. . *Wiley & Sons* **1979**.
13. Drees, L.R.; Wilding, L.P.; Smeck, N.E.; Senkayi, A.L. Minerals in soil environments . **1989**.
14. Clarke, J. The occurrence and significance of biogenic opal in the regolith. *Earth-Science Rev*. **2003**, *60*, 175–194.
15. Alexandre, A.; Meunier, J.-D.; Colin, F.; Koud, J.-M. Plant impact on the biogeochmical cycle of silicon and related weathering processes. *Geochim. Cosmochim. Acta* **1997**, 677–682.

16. Bartoli, F. Le cycle biogeochimique du silicium sur roche acide: application à deux écosystèmes forestiers tempérésrés (Vosges). *Université de Nancy.* **1981**.
17. Sommer, M.; Kaczorek, D.; Kuzyakov, Y.; Breuer, J. Silicon pools and fluxes in soils and landscapes - a review. *J. Plant Nutr. Soil Sci* **2006**, 310–329.
18. Georgiadis, A.; Sauer, D.; Herrmann, L.; Breuer, J.; Zarei, M.; Stahr, K. Testing a new method for sequential silicon extraction on soils of a temperate--humid climate. *Soil Res.* **2014**, 645–657.
19. Bartoli, F. The biogeochemical cycle of silicon in two temperate forest ecosystems. *Ecol. Bull.* **1983**, *35*, 469–476.
20. Blecker, S.W.; McCulley, R.L.; Chadwick, O.A.; Kelly, E.F. Biologic cycling of silica across a grassland bioclimosequence. *Glob. Biogeochem. Cycles* **2006**, 3023.
21. Clymans, W.; Struyf, E.; Govers, G.; Vandevenne, F.; Conley, D.J. Anthropogenic impact on amorphous silica pools in temperate soils. *Biogeosciences* **2011**, 2281–2293.
22. Derry, L.A.; Kurtz, A.C.; Ziegler, K.; Chadwick, O.A. Biological control of terrestrial silica cycling and export fluxes to watersheds. *Nature* **2005**, *433*, 728–731.
23. Struyf, E.; Smis, A.; Van Damme, S.; Garnier, J.; Govers, G.; Van Wesemael, B.; Conley, D.J.; Batelaan, O.; Frot, E.; Clymans, W., others. Historical land use change has lowered terrestrial silica mobilization. *Nat. Commun.* **2010**, 129.
24. Vandevenne, F.; Struyf, E.; Clymans, W.; Meire, P. Agricultural silica harvest: have humans created a new loop in the global silica cycle? *Front. Ecol. Environ.* **2012**, 243–248.
25. Carey, J.C.; Fulweiler, R.W. Human activities directly alter watershed dissolved silica fluxes. *Biogeochemistry* **2012**, 125–138.
26. Carey, J.C.; Fulweiler, R.W. Watershed land use alters riverine silica cycling. *Biogeochemistry* **2013**, 525–544.
27. Fortner, S.K.; Lyons, W.B.; Carey, A.E.; Shipitalo, M.J.; Welch, S.A.; Welch, K.A. Silicate weathering and CO2 consumption within agricultural landscapes, the Ohio-Tennessee River Basin, USA. *Biogeosciences* **2012**, 941–955.
28. Conley, D.J.; Carey, J.C. Biogeochemistry: Silica cycling over geologic time. *Nat. Geosci.* **2015**, 431–432.
29. Vandevenne, F.I.; Barão, L.; Ronchi, B.; Govers, G.; Meire, P.; Kelly, E.F.; Struyf, E. Silicon pools in human impacted soils of temperate zones. *Global Biogeochem. Cycles* **2015**, 1439–1450.

30. Unzué-Belmonte, D.; Ameijeiras-Mariño, Y.; Opfergelt, S.; Cornelis, J.-T.; Barão, L.; Minella, J.Meire, P.; Struyf, E. Land use change affects biogenic silica pool distribution in a subtropical soil toposequence. *Solid Earth* **2017**, 737–750.
31. Ameijeiras-Mariño, Y.; Opfergelt, S.; Derry, L.A.; Robinet, J.; Govers, G.; Minella, J.P.G.; Delmelle, P. Ge/Si ratios point to increased contribution from deeper mineral weathering to streams after forest conversion to cropland. *Appl. Geochemistry* **2018**, 24–34.
32. FAO. FAOSTAT Database. Available online: http://www.fao.org/faostat/en/#data/EF (accessed on 24 April 2018). **2018**.
33. FAO. Smallholders Data Portrait. Available online: http://www.fao.org/family-farming/data-sources/ dataportrait/farm-size/en/ (accessed on 19 May 2017). **2017**.
34. MARD. Ministry of Agriculture & Rural Development. Annual Report 2017 of Fertilizers Sector. *Hanoi, Vietnam.* **2018**.
35. Pham, Q.H., Nguyen, V.B.,;*Fertilizer and Mitigation of Greenhouse Gas Emission*. *National Workshop on Measures for Improving Fertilizer Use Efficiency in Vietnam (March 28, 2014);* Agricultural Publishing: Hanoi, Vietnam. 2014.
36. GSO. *Statistical Summary Book of Vietnam. General Statistics Office of Vietnam;* Statistical Publishing House: Hanoi, Vietnam. 2017.
37. Baumann, L. Insights into Vulnerability of Smallholder Farming Systems in the Upland Region of North Vietnam. 2014.
38. Bui, H.H. *Assessing the Present Use of Chemical Fertilizers and Promoting Methods to Improve the Use of Fertilizers for Crop Production in Vietnam,* Agricultural Publishing: Hanoi, Vietnam. 2008.
39. Klotzbücher, T, Leuther, F., Marxen, A., Vetterlein, D., Horgan, F.G., Jahn, R. Forms and fluxes of potential plant-available silicon in irrigated lowland rice production (Laguna, the Philippines). *Plant Soil* **2015**, 177–191.
40. Hoang, N.T.; Tran, T.T.; Dao, T.H.; Nguyen, N.M.; Pham, T.N.; Nguyen, T.N.;Nguyen, H.T.; Vu, D.Q.; Ho, C.T. *Effect of Agricultural Residues Incorporation into Soils on Increasing Crops Yield, Reducing Mineral Fertilizers Applied and Improving Soil Properties. The Results of Soils and Fertilizers Research;* Agricultural Publishing: Hanoi, Vietnam. 2014.

41. Keck, M.; Hung, D.T. Burn or bury? A comparative cost–benefit analysis of crop residue management practices among smallholder rice farmers in northern Vietnam. *Sustain. Sci.* **2019**, 375–389.
42. Tran, T.T.; Hung, T.D. Effect of crop by-product on yield and possibility of reducing potassium application rate for crops under rice-based cropping systems on marine sandy soils and grey-degraded soils. *Vietnam Soil Sci. J.* **2010**, *33*, 89–95.
43. Zhao, Y.; Wang, P.; Li, J.; Chen, Y.; Ying, X.; Liu, S. The effects of two organic manures on soil properties and crop yields on a temperate calcareous soil under a wheat–maize cropping system. *Eur. J. Agron.* **2009**, 36–42.
44. Tran, S.N.; Nguyen, T.H.N.; Nguyen, H.C.; Nguyen, V.C.N.; Le, H. V; Kield, I. To quantify the seasonal rice straw and its use in different provinces in the Vietnamese Mekong Delta. *J. Scie Can Tho Univ* **2014**, 87–93.
45. Truc, N.T.T.; Sumalde, Z.M.; Espaldon, M.V.O.; Pacardo, E.P.; Rapera, C.L.; Palis, F.G. Farmers' awareness and factors affecting adoption of rapid composting in Mekong Delta, Vietnam and Central Luzon, Philippines. *J. Environ. Sci. Manag.* **2012**, 59–73.
46. Fairhurst, T.; Witt, C.; Buresh, R.; Dobermann, A.; Fairhurst, T. *Rice: A practical guide to nutrient management, 2nd ed.;* International Rice Research Institute: Los Baños, Philippines. 2007.
47. Gupta, P.K.; Sahai, S.; Singh, N.; Dixit, C.K.; Singh, D.P.; Sharma, C.; Tiwari, M.K.; Gupta, R.K.; Garg, S.C. Residue burning in rice–wheat cropping system: Causes and implications. *Curr. Sci.* **2004**, *87*, 1713–1717.
48. Cabanes, D., Weiner, S., Shahack-Gross, R. Stability of phytoliths in the archaeological record: a dissolution study of modern and fossil phytoliths. J. *Archaeol. Sci*. **2011**, *38*, 2480–2490.
49. Unzué-Belmonte, D., Struyf, E., Clymans, W., Tischer, A., Potthast, K., Bremer, M., Meire, P., Schaller, J. Fire enhances solubility of biogenic silica. *Sci. Total Environ*. **2016**, *572*, 1289–1296.
50. Xiao, X., Chen, B., Zhu, L. Transformation, morphology, and dissolution of silicon and carbon in rice straw-derived biochars under different pyrolytic temperatures. *Environ. Sci. Technol*. **2014**, *48*, 3411–3419.
51. Nguyen, M.N., Dultz, S., Guggenberger, G. Effects of pretreatment and solution chemistry on solubility of rice-straw phytoliths. *J. Plant Nutr. Soil Sci.* **2013**, *177*, 349–359.

52. Bijay-Singh, Shan, Y.H.; Johnson-Beebout, S.E.; Yadvinder-Singh, Buresh, R.J. *Chapter 3 Crop Residue Management for Lowland Rice-Based Cropping Systems in Asia*. *Advances in Agronomy;* Elsevier, 2008.
53. Marxen, A.; Klotzbücher, T.; Jahn, R.; Kaiser, K.; Nguyen, V.S.; Schmidt, A.; Schädler, M.;Vetterlein, D. Interaction between silicon cycling and straw decomposition in a silicon deficient rice production system. *Plant Soil* **2016**, 153–163.
54. Savant, N.K., Snyder, G.H., Datnoff, L.E. Silicon Management and Sustainable Rice Production, in: Sparks, D.L. (Ed.), Academic Press, pp. 151–199.**1996**
55**.** Seyfferth, A.L., Kocar, B.D., Lee, J.A., Fendorf, S. Seasonal dynamics of dissolved silicon in a rice cropping system after straw incorporation. *Geochim. Cosmochim. Acta* **2013**, *123*, 120–133.
56. Vandevenne, F.I., Barão, A.L., Schoelynck, J., Smis, A., Ryken, N., Damme, S. Van, Meire, P., Struyf, E., 2013. Grazers: biocatalysts of terrestrial silica cycling. Proc. R. Soc. B Biol. Sci. 280, 20132083.53.
57. Klotzbücher, T.; Marxen, A.; Jahn, R.; Vetterlein, D. Silicon cycle in rice paddy fields: insights provided by relations between silicon forms in topsoils and plant silicon uptake. *Nutr. Cycl. Agroecosystems* **2016**, 157–168.
58. Klotzbücher, Thimo, Marxen, A.; Vetterlein, D.; Schneiker, J.; Türke, M.; van Sinh, N.; Manh, N.H.; van Chien, H.; Marquez, L.; Villareal, S.; Bustamante, J.V.; Jahn, R. Plant-available silicon in paddy soils as a key factor for sustainable rice production in Southeast Asia. *Basic Appl. Ecol.* **2015**, 665–673.
59. Haynes, R.J. A contemporary overview of silicon availability in agricultural soils. *J. Plant Nutr. Soil Sci.* **2014**, 831–844.
60. Sauer, D.; Saccone, L.; Conley, D.J.; Herrmann, L.; Sommer, M. Review of methodologies for extracting plant-available and amorphous Si from soils and aquatic sediments. *Biogeochemistry* **2006**, 89–108.
61. Cornelis, J.-T.; Titeux, H.; Ranger, J.; Delvaux, B. Identification and distribution of the readily soluble silicon pool in a temperate forest soil below three distinct tree species. *Plant Soil* **2011**, 369–378.
62. Opfergelt, S.; de Bournonville, G.; Cardinal, D.; André, L.; Delstanche, S.; Delvaux, B. Impact of soil weathering degree on silicon isotopic fractionation during adsorption onto iron oxides in basaltic ash soils, Cameroon. *Geochim. Cosmochim. Acta* **2009**, 7226–7240.

63. IUSS Working Group WRB, 2015. World reference base for soil resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps, IUSS Working Group WRB. 2015. World Soil Resources Reports No. 106. FAO, Rome.
64. Nguyen, V.B.; Bui, D.D.; Ho, Q.D.; Bui, H.H.; Dang, T.L.; Thai, P.; Nguyen, V.T. *The basic information of main soil units of Vietnam.*, 2002.
65. Nguyen, T.L.; Truong, X.C.; Nguyen, V.H.; Dinh, V.S. *Survey and Evaluate Fertility Soils Map for Intensive Crop Restructuring and Sustainable Agricultural Land Resources Management in Viet Yen District, Yen Dung District, Luc Nam District, Yen District, Son Dong District and Bac Giang city, Bac Giang Province.*, 2015.
66. Hung, D.T.; Hughes, H.; Keck, M.; Sauer, D. Rice-Residue Management Practices of Smallholder Farms in Vietnam and Their Effects on Nutrient Fluxes in the Soil-Plant System. *Sustainability* **2019**, 1641.
67. Tegen, I.; Kohfeld, K.E. Atmospheric transport of silicon. silicon cycle Hum. perturbations impacts Aquat. Syst. **2006**.
68 Meunier, J.D.; Keller, C.; Guntzer, F.; Riotte, J.; Braun, J.J.; Anupama, K. Assessment of the 1% Na2CO3 technique to quantify the phytolith pool. *Geoderma* **2014**, *216*, 30–35.
69. Saccone, L.; Conley, D.J.; Koning, E.; Sauer, D.; Sommer, M.; Kaczorek, D.; Blecker, S.W.; Kelly, E.F. Assessing the extraction and quantification of amorphous silica in soils of forest and grassland ecosystems. *Eur. J. Soil Sci* **2007**, *58*, 1446–1459.
70. Georgiadis, A.; Sauer, D.; Herrmann, L.; Breuer, J.; Zarei, M.; Stahr, K. Development of a method for sequential Si extraction from soils. , . *Geoderma* **2013**, *209–210*, 251–261.
71. Georgiadis, A.; Sauer, D.; Breuer, J.; Herrmann, L.; Rennert, T.; Stahr, K. Optimising the extraction of amorphous silica by NaOH from soils of temperate-humid climate. *Soil Res.* **2015**, *53*, 392.
72. Tsujimoto, Y.; Muranaka, S.; Saito, K.; Asai, H. Limited Si-nutrient status of rice plants in relation to plant-available Si of soils, nitrogen fertilizer application, and rice-growing environments across Sub-Saharan Africa. *F. Crop. Res.* **2014**, 1–9.
73. Dobermann, A.; Fairhurst, T. *Rice : nutrient disorders & nutrient Management.*, 2000.
74. Tack, L.; Wingate, M.T.D.; Liegeois, J.P.; Fernandez-Alonso, M.; Deblond, A. Early Neoproterozoic magmatism (1000-910 Ma) of the Zadinian and Mayumbian Groups

(Bas-Congo): onset of Rodinia rifting at the western edge of the Congo craton. *Precambrian Res.* **2001**, *110*, 277–306.

Chapter 5

This chapter base on: Hung, D.; Callum, C.B.; Dorodnikov, M.; Sauer, D. **Improved water and rice-residue management may reduce greenhouse gas emissions from paddy soils and increase rice yields** *(Under Review to Soil & Tillage Research)*

Abstract

In a field experiment in northern Vietnam, we investigated the effects of water and rice-residue management on greenhouse gas emissions and yields of rice (*Oryza sativa L*). We used a 2 x 4 factorial design, comparing alternate wetting and drying (AWD) and conventional continuous flooding (CCF) water management, each with four different rice-residue treatments: control (CT), application of composted rice residues (CR), on-site burning of rice residues (B), and incorporation of rice residues into the soil (I). All plots received equal amounts of mineral nitrogen (N), phosphorous (P), and potassium (K). The results indicate that water management is a major factor in reducing CH_4 emissions. AWD management led to a reduction of CH_4 emissions by 15-42% for the CR treatment, by 27-47% for the B treatment, and by 36-45% for the I treatment. Similarly, AWD management resulted in a reduction of global warming potential (GWP) by 16-36% (CT), 15-39% (CR), 27-40% (B), and 35-40% (I), respectively. The treatment I led to the highest CH_4 emissions, while the control (CT) showed the lowest CH_4 emissions under both water management systems. Rice yields were slightly higher for treatments including organic fertilizers compared to only mineral fertilizer (CT). In conclusion, we recommend a combination of treatment I with AWD water management, as this combination resulted in reduced greenhouse gas emissions while ensuring high rice yields.

Keywords: Mitigation of methane emissions, Nitrous oxide emissions, Rice farming, Rice-residue management, Water management, Vietnam.

.

5.1 Introduction

Rice production in Asia is facing tremendous challenges in the 21st century. A fast-growing population is demanding larger rice supplies under the increasingly difficult production conditions of declining water availability and quality [1–3]. Rice cultivation accounts for nearly 20% of global anthropogenic methane (CH_4) emissions [4], whereby the magnitude of CH_4 emissions depends on organic matter application, soil organic matter (SOM) contents, and anaerobic soil conditions [5–8]. Another relevant greenhouse gas (GHG) in rice cultivation is nitrous oxide (N_2O). Emissions of N_2O from paddy soils depend on soil nitrogen (N) stocks and quality, and on water management [9, 10]. Carbon dioxide (CO_2) fluxes are a source of GHG emissions, too, but at global scale they are estimated to contribute less than 1% to the global warming potential (GWP) of agriculture [11]. Vietnam is one of the largest rice producers and exporters in the world, with more than seven million hectares of paddy rice [12]. Paddy rice production is the largest source of GHG emission in Vietnam's agriculture, contributing about 44.7 Tg CO_2 equivalents, accounting for more than 50% of the total agricultural GHG emissions [13]. Paddy rice fields have a high potential to emit CH_4, because flooding leads to anaerobic CH_4 production [14]. Furthermore, organic fertilizer and rice residue application, N and water management affect paddy soil GHG emissions.

Rice residue management in Vietnam has changed over the last decades [15]. After harvesting, farmers traditionally used rice residues as a fuel for cooking, animal feed, and compost. Currently, rice residues are used as (1) animal feed, (2) cooking fuel, (3) compost that is applied to other fields (e.g., maize), or they are (4) burned [16]. On-site burning is the most typical practice to manage rice residues in Vietnam (and other Asian countries) [15, 17], and it is dramatically increasing in Vietnam [18]. Farmers frequently apply fire in the field for fast clearing of residues and for soil preparation, as burning is a quick and easy way to manage the large quantities of crop residues and prepare the field for next crop [19, 20]. The enhanced burning of rice residues has also resulted in increased contents of extractable phosphorus (P) and potassium (K) in the top soils. Major disadvantages of rice residue burning include not only air pollution and related respiratory diseases [15, 17, 19–22], but also a contribution to global warming, depletion of essential nutrients like nitrogen (N), P, K, and decrease in soil organic carbon (SOC) stocks.

Incorporation of rice residues into paddy soils improves soil structure and fertility and increases soil cation exchange capacity (CEC). Rice residue incorporation also results in higher microbial activity than residue burning [21–24], increases rice productivity, and reduces the need for chemical fertilizers [16, 25, 26]. Furthermore, rice residue incorporation could be an alternative to use of manure, since the application of manure is decreasing. This is due to (1) a decrease in the availability of manure from pig farms, because most of manure in northern Vietnam is nowadays used for biogas production, (2) insufficient knowledge of farmers about the management of manure and (3) the availability of chemical fertilizers that seem to provide an easy substitution for manure [27–29]. However, incorporation of rice residues under anaerobic conditions enhances CH_4 emissions by 50-60% [10, 30].

Recently, "alternate wetting and drying (AWD)" management has been applied in Asia [1, 31]. Several studies suggested that the drainage of rice paddies once or several times during the growing season can reduce CH_4 emissions. For example, Triol-Padre [32] reported that CH_4 emissions from paddy soils in central Vietnam were reduced by 21-38% with this method compared to conventional continuous flooding (CCF), while the rice grain yield even increased by 4%. Lu [33] found that CH_4 emissions were reduced by 60% under AWD management compared to CCF in southeast China. Hence, the practice may not only reduce GHG emissions but also increase rice grain yield [32].

Therefore, in this study, we hypothesized that incorporation of rice residues or manure in combination with AWD can reduce CH_4 emissions without increasing N_2O emissions. An additional benefit of AWD is the reduction in water usage, whereas the advantages of rice residue incorporation compared to burning include the build-up of SOC, soil N, P, and K, increase of soil water-holding capacity and decrease of bulk density. To test our hypothesis, we conducted a field experiment in Bac Giang Province, Vietnam. The objectives were (1) to assess the potential of AWD to reduce GHG (combined CH_4 and N_2O) emissions compared to the usual practice of CCF, (2) to compare the effects of rice residue incorporation, rice residue burning, and application of composted rice residues on GHG emissions, (3) to evaluate the combined impact of water and rice residue management on the GWP and on rice yields.

5.2 Methods

5.2.1 Experiment site

The field experiment was conducted in Luong Phong Commune (Hiep Hoa District, Bac Giang Province; 106°01’ E, 21°20’ N), 50 km East of Hanoi (Fig. 5.1). 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.

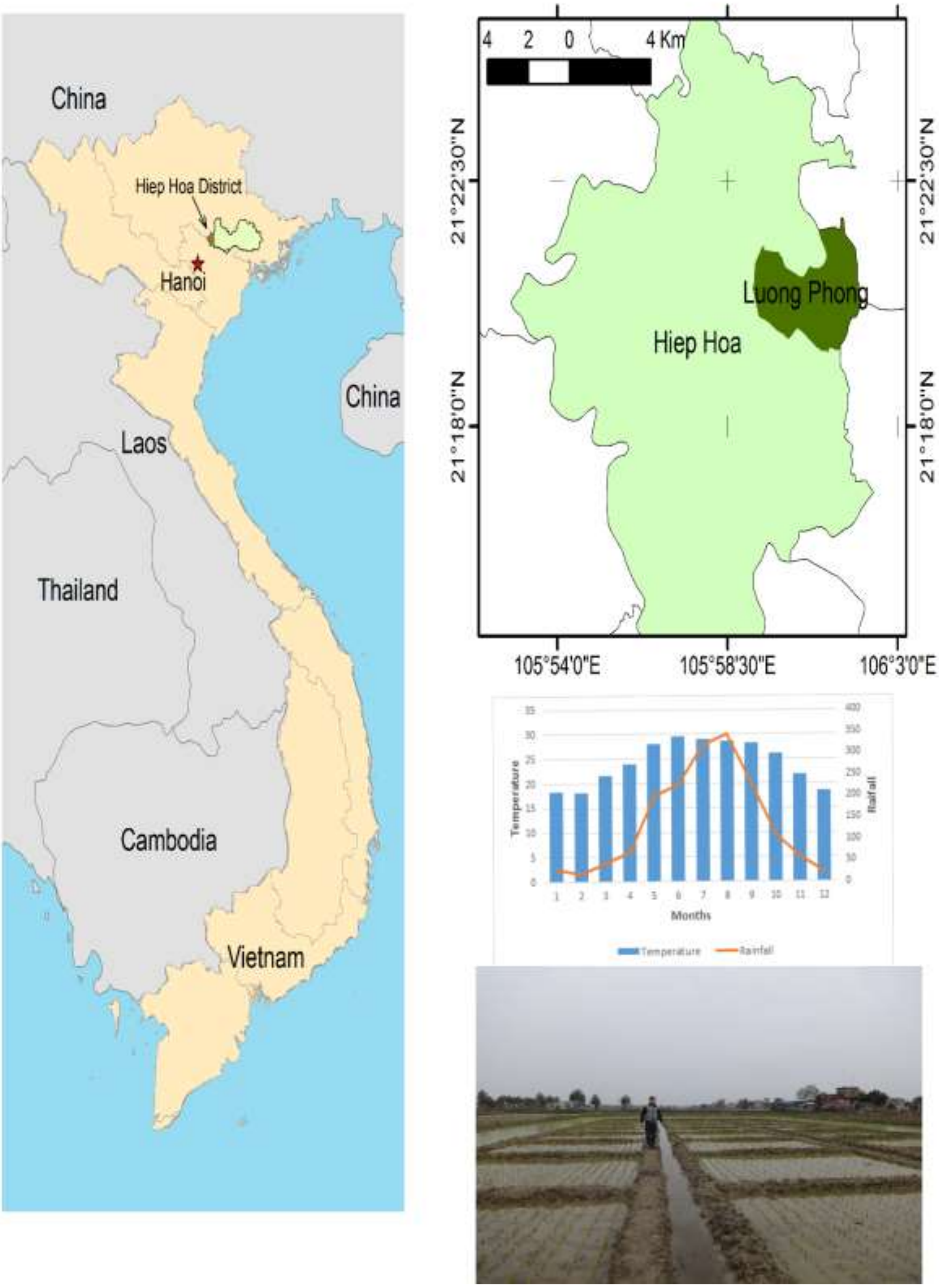


Fig. 5.1 Location and climate of the experimental sites in Vietnam.

The soils are Plinthic Acrisols according to WRB (2014). 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 outskirts of Hanoi City. These regions are known for the most intensive agricultural production [35]. The soils have light textures in all horizons, typically varying from sand to silt. They have low CEC (5.0 cmol kg^{-1}) and low contents of SOC (7.8 g kg^{-1}) and nutrients such as total N (0.7 g kg^{-1}), and total K (0.2 g kg^{-1}), but their contents of available P (30.2 g kg^{-1}) are high. These soils with low fertility are widespread in many agriculturally used floodplain areas of Vietnam [34, 36, 37].

5.2.2 Field experiment

The field experiment was conducted with a 2 x 4 factorial randomized complete block design with three replications on a plot size of 4 x 5 m each. The first factor was water management and the second factor was rice residue management. Two water management techniques were applied. The first was conventional continuous flooding (CCF), whereby the water level was 3-7 cm above the soil surface during flooding. The second water management technique was alternate wetting and drying (AWD). The AWD plots were continuously flooded from the first day of transplanting (DAT) until the 24th DAT, when the irrigation was stopped. As soon as the water level dropped to 15±2 cm below the soil surface, as indicated by the water level of tubes installed in each plot, single irrigation was applied until the water level reached 2 cm above the soil surface. The AWD plots were then left to dry again, and this cycle was continued until 15 days before harvesting. Continuous flooding was only applied again during flowering, i.e., during the period 56-76th DAT. Four rice residue management treatments were established, whereby in all treatments chemical NPK fertilizers were applied. The treatments included: (1) CR = application of composted rice residues, (2) B = on-site burning of rice residues, (3) I = incorporation of rice residues into the soil, and (4) CT = control. The CT plots received only NPK but no rice residues.

All treatments, both in summer and spring rice seasons, received the same amounts of chemical fertilizers of 105-120 kg N; 26 kg P; 50-75 kg K per ha, respectively. The chemical fertilizers were applied three times during crop growth. Basal fertilization (100% P, 30% N and 30% K) was applied before transplanting, and the rest of the N and K was given in two applications, on the 18-22nd DAT (40% N, 30% K) and 40-50th DAT (30% N, 40% K). The full amounts of rice residue compost, rice residues and ash were applied as basal fertilization before transplanting. The C and N contents of these organic materials are shown in Table 5.1.

Table 5.1 Mean C and N contents of organic mat applied to spring and summer rice

	Spring rice			Summer rice		
	CR	B	I	CR	B	I
Total C (g kg $^{-1}$)	332.48	10.00	360.15	342.96	11.02	380.01
Total N (g kg $^{-1}$)	18.70	0.60	7.97	17.80	0.70	9.17
C:N ratio	18	17	45	19	16	41

5.2.3 Gas sampling and analysis

We took GHG samples on 32 dates over two rice-growing seasons, from February 24, 2017 to September 20, 2017. In total, 3072 GHG samples were taken from spring rice and summer rice plots. The fluxes of GHGs were determined using the static flux chamber technique and gas chromatography, following the recommendations of [38] and [39]. Each opaque chamber consisted of a base unit (45 cm length x 40 cm width x 45 cm height, open bottom) and a removable top chamber. The removable top chamber (45 cm length x 40 cm width x 90 cm height) covered six rice mounds, whereby the plant density inside the chamber was the same as outside the chamber, with a spacing of 20 cm x 15 cm and 3-4 seedling per mound (333,333 mounds ha^{-1}). Water was used to seal the Plexiglas™ top to the base unit during gas sampling. The removable top was equipped with two small fans to mix the chamber air, and a thermometer to measure the temperature during gas sampling [40]. Pressure was kept equal inside and outside the chamber through a connecting plastic tube (7.6 m long and 1.5 mm in diameter) [41]. Removable wooden boardwalks were set up at the beginning of the rice-growing season to avoid soil disturbance during gas sampling. The gas sampling syringes (60 ml) were flushed four to six times with chamber air before the gas samples were collected. The gas samples were collected immediately after closing the chamber (T_0), after 20 min (T_1), 40 min (T_2) and 60 min (T_3). The gas samples were immediately injected into evacuated 12 ml vials closed with butyl rubber septa (Exetainer® vials, UK). They were shipped to Georg-August University of Göttingen, Germany, for analysis.

The concentrations of CH_4 and N_2O were measured by a gas chromatograph (GC 14B, Shimadzu, Japan) equipped with an electron capture detector (ECD for N_2O) and a flame ionization detector (FID for CH_4) according to [42]. The gas fluxes were calculated using the following equation by Smith [43] :

$$F = \left(\frac{\Delta C}{\Delta t}\right) * \left(\frac{v}{A}\right)\left(\frac{M}{V}\right) * \left(\frac{P}{Po}\right) * \left(\frac{273}{T}\right) \quad (1)$$

where F = gas flux, ΔC = change in the concentration of the gas of interest over the time interval Δt, v = chamber volume (liters), A = soil surface area (m^2), M = molecular mass (g mol^{-1}) of the gas of interest, V = volume (liters) occupied by 1 mol of the gas at standard temperature and pressure, P = barometric pressure (mbar), Po = standard pressure (mbar), and T = average temperature inside the chamber during the deployment time (K).

The cumulative CH_4 and N_2O emissions were calculated for each season using the linear trapezoid formula [40].

$$A_{t(ab)} = (t_b - t_a) * \frac{(F_{ta} - F_{tb})}{2} \, (2)$$

where $A_{t(ab)}$ = cumulative emission of the gas of interest between two subsequent sampling dates t_a and t_b; t_a, t_b = two subsequent sampling dates; F_{ta}, F_{tb} = fluxes of the gas of interest at the sampling dates t_a,t_b, respectively. Cumulative CH_4 and N_2O emissions were calculated as $\sum A_{t(ab)}$.

The global warming potential (GWP) was calculated over a 100 years timespan, whereby CH_4 and N_2O emissions were converted to CO_2 equivalents by multiplying CH_4 emissions by the factor 34 and N_2O emissions by the factor 310 [44].

GWP and greenhouse gas intensity (GHGI) are important factors to consider when assessing CH_4 and N_2O mitigation options [45]. The following equation was used to calculate the GHGI, i.e., the GWP per unit of rice grain yield, for each of the treatments:

$$\mathrm{GHGI} = \frac{\mathrm{GWP}}{\mathrm{Rice\ grain\ yield}}$$

5.2.4 Determination of rice grain yield and amounts of rice residues

Rice grain yields and amounts of rice residues were determined at the end of each season by harvesting the 24 plots. The grains were threshed from the harvested rice plants, and the fresh weight of the grains and the rice residues was determined. The rice residue samples were dried in the sun. 300 g of fresh grains and straw of each sample were oven-dried at 60 °C to constant weight to transform all results to oven-dry material.

5.2.5 Production and application of rice-residue compost (RC)

According to the usual farmers' practice in the region, the rice residues were chopped into pieces of 4-6 cm length. Solid pig manure (40 Vol. %) and rice residues (60 Vol. %) were mixed. The homogenized mixture was kept in a pit for two months to decompose with no further mixing or aeration. After two months, the RC was collected from the pit, again thoroughly mixed and applied to the rice plots.

RC of the rice residues of the previous harvest were applied to the following crop as basal fertilization before transplanting. Hence, the rice residues were collected before the spring and summer rice-growing seasons. For the on-site burning treatment, the rice residues were burned on the respective plot and then applied. In the I treatment, all plant residues that were left after threshing were incorporated into the soil.

5.2.6 Soil and straw sampling and analysis

Table 5.2. Properties of soils under conventional continuous flooding (CCF) and alternate wetting and drying (AWD) with four treatments: CR = application of composted rice residues, B = on-site burning of rice residues, I = direct incorporation of rice residues into the soil, CT = control (all treatments including equal NPK fertilization). Data represent the mean of three replicates. Superscript letters indicate significant differences ($p < 0.05$) between treatments.

	CCF				AWD			
	CR	B	I	CT	CR	B	I	CT
$pH_{(KCL)}$	5.23	5.14	5.17	5.16	5.30	5.29	5.12	5.29
$pH_{(H2O)}$	4.72	4.63	4.64	4.61	4.76	4.78	4.60	4.77
Bulk density (g cm^{-3})	1.38	1.37	1.36	1.41	1.40	1.37	1.38	1.43
CEC ($cmol_c$ kg^{-1})	4.59	5.12	4.66	4.99	5.17	5.23	4.55	5.65
SOC (g kg^{-1})	0.96^{a}	0.78^{ab}	0.90^{ab}	0.90^{ab}	0.88^{ab}	0.74^{b}	0.87^{ab}	0.79^{ab}
Total N (g kg^{-1})	0.08	0.08	0.08	0.07	0.08	0.08	0.08	0.10
Total P (g kg^{-1})	0.53	0.53	0.50	0.55	0.57	0.55	0.51	0.58
Total K (g kg^{-1})	0.19	0.17	0.17	0.14	0.14	0.17	0.14	0.19
Available P (mg kg^{-1} soil)	25.93	30.78	27.60	31.62	34.72	34.32	31.12	34.48
Available K (mg kg^{-1} soil)	1.54^{ab}	4.07^{a}	2.11^{ab}	1.03^{b}	2.77^{ab}	3.66^{ab}	1.82^{ab}	1.70^{ab}

Three random soil samples were taken from each plot at 0–20 cm depth with a soil corer (100 cm length, 2.5 cm diameter). The three samples were mixed to obtain one composite sample for each plot. Total SOC, total N, total P and total K contents in soil, straw, manure and ash were analyzed. SOC contents were determined by the Walkey-Black method (ISO-22003: 2008), and total N contents were analyzed by semi-micro Kjeldahl analysis (ISO 11261: 1995). Total contents of P and K were analyzed after digestion with H_2SO_4 + HNO_3 (1:1, v:v), whereby P contents were determined colorimetrically, and K contents were determined by use of a photoelectric flame photometer (Corning 410-UK). Furthermore, the soil samples were analyzed for pH (KCl and H_2O), bulk density, and CEC. Soil pH was measured at a soil: solution ratio of 1:5, using a pH electrode (ISO 10390: 2005). Plant-available P was extracted by the Bray 2 method and analyzed colorimetrically by use of the vanadomolybdophosphoric acid colorimetric method. Cation exchange capacity (CEC) was determined using ammonium acetate at pH 7. Soil physical and chemical properties are listed in Table 5.2.

5.2.7 Statistical analysis

Statistical analysis of the data was performed in STATISTICA 13.3 (TIBCO Software Inc., California, and USA). Normality and homogeneity of variance were checked in groups using Shapiro-Wilk's W test and Levene's test, respectively. Following this step, the significance of differences between the four rice residue management treatments (CR, B, I, CT) and two water management techniques (CCF, AWD) was tested by two-way ANOVA, with subsequent multiple comparisons by the Turkey HSD test where p values <0.05 indicated significance.

5.3 Results

5.3.1 Methane emissions

The CH_4 emissions from the rice plots under the different treatments are shown in Fig. 5.2 for spring rice and in Fig. 5.3 for summer rice. In the spring season, CH_4 emissions were low during the first 15 DAT in all treatments and then increased (Fig 5.2). On the 54th DAT, the emissions dropped considerably for all treatments but again increased a week later, peaking on the 72nd DAT (end of the heading stage). Emissions from the AWD plots (dashed curves in Fig. 5.2) tended to be lower than those from the CCF plots (solid curves in Fig. 5.2). In the summer season, emissions generally tended to be higher than in the spring season (note different scales of y-axes). The I and CR treatments under both water management types showed higher initial CH_4 emissions compared to the other treatments. Both I treatments exhibited absolute peak emissions on the 19th DAT, whereby the I treatment under CCF water management showed the highest CH_4 emission of 31.4 mg m^{-2} h^{-1} of the whole study on that day. On the 41st DAT, the fluxes dropped considerably for all treatments, reaching an absolute summer minimum on the 48th DAT, but increasing again thereafter (Fig. 5.3).

Cumulative CH_4 emissions were higher in the summer rice season than in the spring rice season (Table 5.3). They were also significantly higher ($p < 0.05$) for CCF than for AWD water management in both the spring and summer seasons (Table 5.3). Under CCF water management, cumulative CH_4 emissions increased by 33-55%, 8-17%, and 35-160% for CR, B, and I treatments, compared to the control (for both spring and summer seasons). Under AWD water management, the increases in CH_4 emissions with respect to the control were 31-56%, 7%, and 31-65% for CR, B, and I, respectively. Cumulative CH_4 emissions were highest for the I treatment under CCF system, while the B treatment without organic amendments showed the lowest CH_4 emissions under the AWD water management system in both seasons. Significantly higher CH_4 emissions were observed for the I and CR treatments compared to the control (CT) and for the B treatment under the AWD system in both seasons. Comparison of the same treatments for both water management systems and both seasons showed that CH_4 emissions for the plots with organic amendment (I and CR treatments) were lower for AWD than for CCF in both rice seasons. CH_4 emissions of the I treatments were 36-45% lower ($p < 0.05$) and those of the CR treatments were 15-42% lower ($p < 0.05$) for AWD than for CCF, except for the CR treatment in the summer season.

Table 5.3 Cumulative CH_4 and N_2O emissions in spring and summer rice-growing seasons under different rice residue management with NPK fertilization = 120 (105) kg N + 26 kg P + 75 kg (50) K per hectare. CR = application of composted rice residues, B = on-site burning of rice residues, I = direct incorporation of rice residues into the soil. CCF = conventional continuous flooding, AWD = alternating wetting and drying. Data are the means of three replicates (± standard deviation).

Letters reflect significant differences ($p < 0.05$).

		Spring rice-growing season		Summer rice-growing season	
		CH_4 (kg ha^{-1})	N_2O (kg ha^{-1})	CH_4 (kg ha^{-1})	N_2O (kg ha^{-1})
CCF	CR	138.20 (6.47)^{a}	0.61 (0.29)^{a}	170.38 (6.67)^{bc}	0.55 (0.13)^{a}
	B	112.24 (2.28)^{b}	0.46 (0.21)^{a}	128.79 (2.04)^{cde}	0.37 (0.06)^{a}
	I	140.50 (8.03)^{a}	0.56 (0.32)^{a}	286.43 (3.01)^{a}	0.65 (0.23)^{a}
	CT	103.70 (4.50)^{b}	0.37 (0.25)^{a}	110.01 (17.98)^{cd}	0.62 (0.50)^{a}
AWD	CR	79.88 (9.85)^{c}	1.21 (0.56)^{a}	144.67 (12.13)^{cd}	0.47 (0.24)^{a}
	B	59.25 (8.44)^{d}	0.79 (0.09)^{a}	93.79 (14.41)^{e}	0.38 (0.04)^{a}
	I	77.95 (1.16)^{cd}	0.95 (0.25)^{a}	184.11 (33.22)^{b}	0.42 (0.30)^{a}
	CT	61.17 (7.44)^{cd}	0.82 (0.45)^{a}	87.70 (7.61)^{e}	0.36 (0.24)^{a}
Water management effect	AWD	69.56 (11.72)^{b}	0.92 (0.36)^{a}	127.57 (44.41)^{b}	0.54 (0.20)^{a}
	CCF	123.66 (17.41)^{a}	0.50 (0.25)^{b}	173.90 (72.07)^{a}	0.41 (0.16)^{a}
Seasonal effect		96.61 (31.21)^{b}	0.71 (0.37)^{a}	150.73 (63.15)^{a}	0.48 (0.19)^{b}

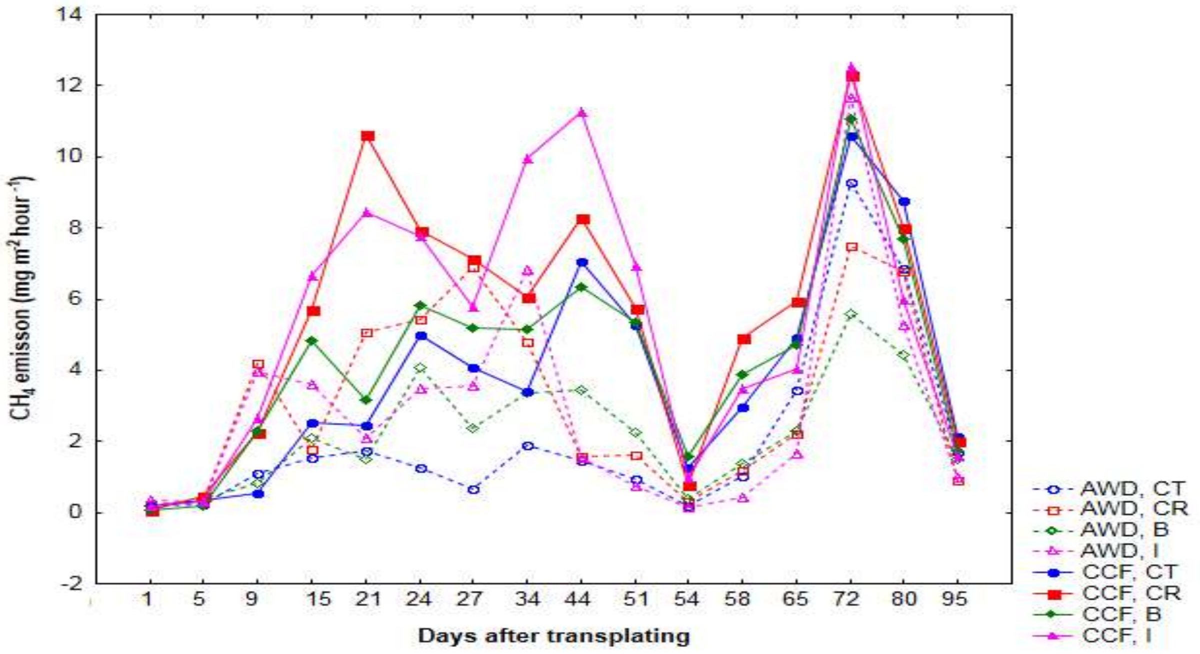


Fig. 5.2 Mean CH_4 emissions in the spring rice season as affected by water and rice residue management. NPK fertilization for all plots = 120 kg N + 26 kg P + 75 kg K per hectare. CR = application of composted rice residues, B = on-site burning of rice residues, I = direct incorporation of rice residues into the soil.

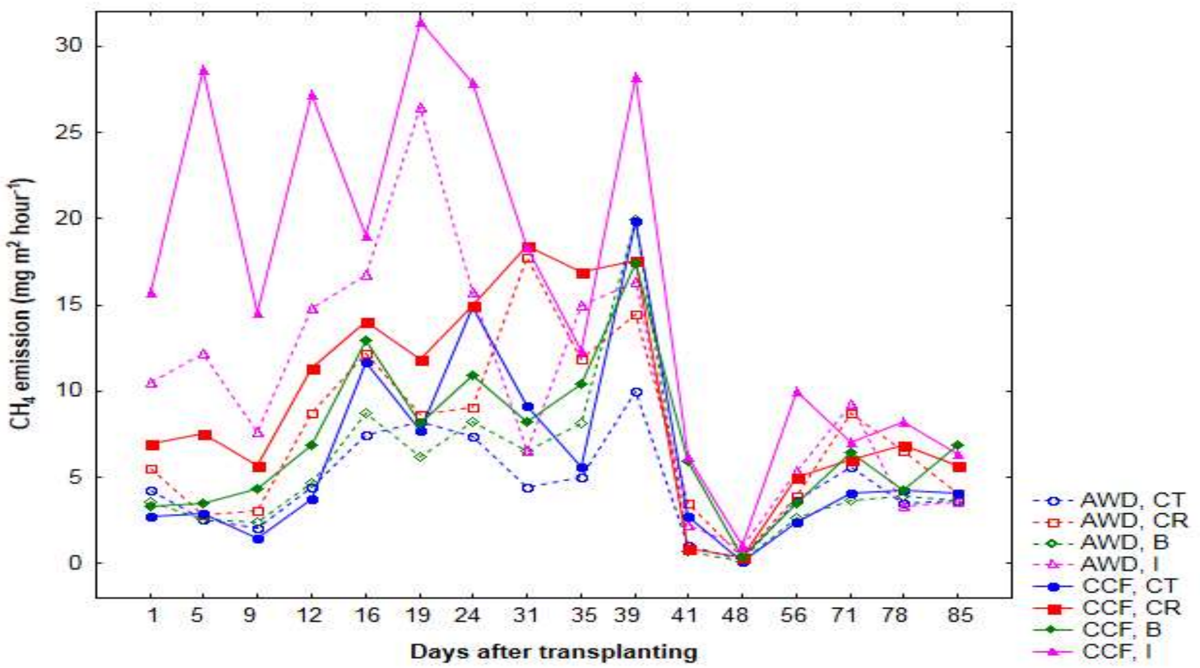


Fig. 5.3 Mean CH_4 emissions in the summer rice season as affected by water and rice residue management. NPK fertilization for all plots = 105 kg N + 26 kg P + 50 kg K per hectare. AWD = alternating wetting and drying, CCF = conventional continuous flooding. CT = control, CR = application of composted rice residues, B = on-site burning of rice residues, I = direct incorporation of rice residues into the soil.

5.3.2 Nitrous oxide emissions

Cumulative N_2O emissions were significantly higher in the spring rice season than in the summer rice season (Table 5.3). N_2O emissions in summer rice were very variable, with two peaks after the two mineral fertilizer applications, on the 19th and 39-48th DAT (data not shown). N_2O emissions in summer rice were less than 2 mg per day most of the time; clear peaks of N_2O emission occurred after mineral fertilizer applications on the 24th and 51st DAT (data not shown). In both seasons, N_2O emissions were not significantly ($p > 0.05$) different for different rice residue management (Table 5.3). Significantly higher N_2O emissions were observed for all treatments under AWD water management compared to the respective treatments under CCF management. Especially in summer rice, the peaks of N_2O emission after application of mineral fertilizers were much higher under AWD management than under CCF management (data not shown).

5.3.3 Rice yield, global warming potential (GWP) and greenhouse gas intensity (GHGI)

The rice grain yield in the spring rice season was higher than in the summer rice season (Table 5.4). It was not significantly different between the two water management techniques. In summer rice, the rice grain yields with the treatments CR, B, and I were significantly higher than those of the control plots (CT), irrespective of the water management system.

GWP in the spring season was significantly lower than in the summer season (Table 5.4). The GWP in spring was higher under CCF than under AWD water management (Table 5.4). Within each water management system, there was no significant difference in GWP ($p > 0.05$) between B treatment and the control CT. GWP was significantly higher ($p < 0.05$) for the I treatments compared to the control CT, for both water management systems and both seasons. Under AWD water management, the GWPs with I treatment were 40% (spring) and 35% (summer) lower than under CCF water management. These results suggest that it should be possible to significantly reduce GWP by using the AWD technique.

Table. 5.4 Grain yield, global warming potential (GWP), and greenhouse gas intensity (GHGI) in spring and summer rice under conventional continuous flooding (CCF) and alternate wetting and drying (AWD) with four rice residue treatments; NPK = 120 (105) kg N + 26 kg P + 75 (50) kg K per hectare, CR = application of composted rice residues, B = on-site burning of rice residues, I = direct incorporation of rice residues into the soil. Values represent the mean of three replicates (± standard deviation). The letters indicate significant differences ($p < 0.05$).

		Spring season			Summer season		
		Rice yield ($kg\ ha^{-1}$)	GWP ($kg\ CO_{2\text{-}eq}\ ha^{-1}$)	GHGI ($kg\ CO_{2\text{-}eq}$ per kg yield)	Rice yield ($kg\ ha^{-1}$)	GWP ($kg\ CO_{2\text{-}eq}\ ha^{-1}$)	GHGI ($kg\ CO_{2\text{-}eq}$ per kg yield)
CCF	CR	5778 (241)^{ab}	4886 (150)^{a}	0.85 (0.01)^{a}	4453 (190)^{a}	5960 (593)^{bc}	1.33 (0.08)^{bc}
	B	5868 (81)^{ab}	3959 (143)^{b}	0.68 (0.03)^{b}	4521 (335)^{a}	4522 (528)^{bc}	1.00 (0.19)^{dc}
	I	5714 (324)^{ab}	4949 (345)^{a}	0.87 (0.10)^{a}	4239 (141)^{a}	10000 (2378)^{a}	2.33 (0.64)^{a}
	CT	5443 (82)^{b}	3641 (75)^{b}	0.67 (0.01)^{b}	3721 (257)^{bc}	3853 (632)^{bc}	1.05 (0.24)^{dc}
AWD	CR	5893 (38)^{ab}	2969 (360)^{c}	0.50 (0.06)^{c}	4578 (111)^{a}	5088 (435)^{bc}	1.11 (0.08)^{bcd}
	B	5944 (120)^{a}	2362 (305)^{c}	0.40 (0.05)^{c}	4483 (239)^{a}	3303 (506)^{c}	0.74 (0.12)^{d}
	I	5687 (158)^{ab}	2946 (117)^{c}	0.52 (0.02)^{c}	4356 (117)^{a}	6460 (1104)^{b}	1.48 (0.22)^{b}
	CT	5450 (156)^{b}	2333 (137)^{c}	0.42 (0.01)^{c}	3614 (303)^{b}	3173 (248)^{c}	0.88 (0.14)^{d}
WME	AWD	5744 (231)^{a}	2650 (383)^{b}	0.46 (0.06)^{b}	4258 (435)^{a}	4506 (1525)^{b}	1.05 (0.32)^{b}
	CCF	5701 (244)^{a}	4359 (621)^{a}	0.76 (0.11)^{a}	4234 (387)^{a}	6084 (2725)^{a}	1.43 (0.57)^{a}
Seasonal effect		5722 (233)^{a}	3505 (1008)^{b}	0.61 (0.18)^{b}	4246 (403)^{b}	5295 (2305)^{a}	1.24 (0.49)^{a}

WME = water management effect

GHGI was lower in spring rice than in summer rice (Table 5.4). In both seasons, GHGIs under CCF management for the different treatments were 1.2-1.7 times higher than for the same treatments under AWD management. Overall, GHGI was significantly lower under AWD compared to CCF water management in both seasons. The I treatment under

CCF water management showed the highest GHGI, whereas the control CT and the B treatment under AWD water management had the lowest GHGIs. Under AWD water management, the GHGI with I treatment was reduced by 40% (spring) and 36% (summer) compared to the I treatment under CCF water management. There was no significant difference in GHGI between the control (CT) and the B treatment under both water management systems and in both seasons. Under both water management systems, the I treatment resulted in the highest GHGI, followed by CR treatment, the control CT and the B treatment.

5.4 Discussion

5.4.1 Effect of rice residue management on CH_4 and N_2O emissions

The effect of organic matter application on CH_4 emissions generally depends on the amount and type of the organic matter applied and on the formation of soil organic matter during flooding [6]. In this study, CH_4 emissions rose with increasing input of organic matter under both water management systems and in both seasons (Tables 5.1 and 5.3). Direct incorporation of rice residues into the soil (I treatment) and application of composted rice residues (CR treatment) both led to higher CH_4 emissions compared to the control plots (CT) (Table 5.3), because the input of organic matter stimulated the activity of methanogenic microbes [52, 53]. CH_4 emissions with burning of rice residues were lower than with incorporation of unburnt rice residues, because the charred rice residues did no longer provide an available carbon source for CH_4 emissions [46]. In the summer season, direct incorporation of rice residues into the soil (I treatment) led to significantly higher cumulative CH_4 emissions than application of composted rice residues (CR treatment) under both water management systems. This effect may be related to the decrease in the C/N ratio of rice residues during the composting process, from 41-45 (I treatment) to 18-19 (CR treatment). This likely resulted in a lower remaining carbon availability, which in turn reduced CH_4 emissions [14, 47].

The higher CH_4 emissions in summer compared to spring were presumably due to the higher summer temperature. Overall, average CH_4 emissions for all treatments were 97 kg ha^{-1} $crop^{-1}$ in spring and 151 kg ha^{-1} $crop^{-1}$ in summer, with corresponding mean temperatures of 27°C and 36°C, respectively (Table 5.3). An influence of soil temperature on CH_4 emissions is to be expected, as most methanogenic bacteria are mesophilic, having a temperature optimum of 30-40 °C [48]. Furthermore, higher temperatures in summer also enhance soil organic matter decomposition and respiration rates, thus oxygen consumption, resulting in a further oxygen depletion, leading in turn to an increase of CH_4 emissions [49, 50].

The effects of the application of rice residues and composted rice residues on N_2O emissions reported in the literature are inconsistent. A number of studies demonstrated that N_2O emissions from soils to which rice residues were applied were not significantly higher than those from control plots [40, 49]. However, Pandey [47] found that application of organic matter increased N_2O emissions under AWD water management. In our study, organic matter application had no significant effect on N_2O emissions (Table 5.3). Increased N_2O emissions are commonly observed after nitrogen mineral fertilizer application due to easily available nitrogen, enhancing microbial turnover [50]. In this study, high N_2O emissions occurred immediately after the application of mineral fertilizer, too (data not shown). The high N_2O emissions lasted only for a short time, probably because after a few days, most of the applied NO_3^- was either taken up by plants or denitrified [40]. Total N_2O emissions in our study were lower than in other studies [51, 54]. However, Abao [55] observed similarly low N_2O emissions after mineral fertilizer application. Also Bronson rarely detected any N_2O emissions during the rice-growing season, except immediately after fertilization [56].

5.4.2 Effect of water management on CH_4 and N_2O emissions

We compared CH_4 emissions under two different water management systems, CCF and AWD. Compared to the CCF management, the AWD management reduced CH_4 emissions by 15-42% with CR treatment, by 27-47% with B treatment, and by 36-45% with I treatment, in both spring and summer seasons (Table 5.3). This reduction in CH_4 emissions can be explained by soil aeration during the dry phases under AWD management. These dry phases allowed for rapid oxidation of rice-straw carbon, which led to the observed reduction in CH_4 emissions, also in the plots with rice residue incorporation and rice-residue compost application. Aeration also increases decomposition of labile organic matter and thus reduces CH_4 emissions. Soil aeration increases soil Eh, which directly affects the activity of methanogenic microbes and facilitates CH_4 oxidation by methanotrophic organisms [40, 51, 52]. The reduction of CH_4 emission by modified water management in rice cultivation observed in our study is in line with previous field studies [40, 47, 49]. We conclude that the AWD management in paddy rice is suitable for mitigation of CH_4 emissions resulting from humus- and nutrient-conserving rice-residue management practices.

In the spring season, AWD water management significantly ($p < 0.05$) increased N_2O emissions to 0.92 kg ha^{-1}, compared to 0.50 kg ha^{-1} under CCF management; in the summer season, this effect was not significant (Table 5.3). CCF management involved lower N_2O emissions, because in wet soil reducing conditions generally lead to enhanced emissions of N_2 instead of N_2O [53], whereas in well-aerated soil N_2O is the most common gas emitted from the soil. The AWD management created partially anaerobic conditions in the soil, favoring the simultaneous occurrence of nitrification and denitrification [51].

Consequently, considerable amounts of N_2O were produced and could escape through the empty soil pores before the next flooding phase shifted the process balance again towards further reduction to N_2 [54].

5.4.3 Effect of rice-residue management on rice-grain yield

The observed higher rice yields under the CR, B, and I treatments, compared to the control plots (CT) (Table 5.4), are most likely due to the input of organic matter and nutrients to the soil that resulted from effective rice-residue management. The nutrients that were returned to the soils through the CR and I treatments amounted to 665 kg C (CR) / 1589 kg C (I), 38 kg N (CR) / 40 kg N (I), 17 kg P (CR) / 8 kg P (I), and 25 kg K (CR) / 42 kg K (I) per hectare, respectively. Hoang [23] and Tran [25] also found significant effects of various rice-residue management practices on rice-grain yields. Burning of rice residues (B) delivered 35 kg of K to the soil. Thus, on K-deficient soils, straw ash is used as a substitute for K fertilizer [57]. Also in our study, the plots with B treatment showed the highest amounts of plant-available K (Table 5.2).

5.4.4 Opportunity to reduce global warming potential (GWP) and greenhouse gas intensity (GHGI)

We estimated GWP of CH_4 and N_2O emissions over a 100-year timescale in order to evaluate the effects of various rice-residue management techniques under different water management. GWP in summer rice was higher than in spring rice in both water management systems (Table 5.4). The contribution of CH_4 to GWP greatly exceeded that of N_2O, with the share of CH_4 being more than 93%. Linquist [58] and Tariq [49] also found only minor contribution of N_2O in their paddy rice experiment. The AWD management resulted in a GWP reduction of 18-36% (CT), 15-39% (CR), 27-40% (B), and 35-40% (I), compared to the same treatments under CCF management. This considerable reduction is due to the significantly lower CH_4 emissions during both seasons under AWD management. A similar finding was reported by Linquist [58]. We conclude that the AWD management has a great potential to reduce GWP from rice production.

Traditionally, Vietnamese farmers have been applying organic fertilizers for a long time, as organic fertilizers ensure long-term benefits by maintaining soil fertility and reducing production costs relative to costly mineral fertilizers [59, 60]. In the present study, application of composted rice residues increased rice yields in both CCF and AWD systems. The CR treatment showed no significant reduction in GWP relative to the I treatment under AWD water management in both seasons (Table 5.4). The application of compost and manure fertilizers is generally decreasing in Vietnam. While farmers would be in favor of applying more organic fertilizers, especially to rice, maize, and peanuts, the amounts of organic fertilizers produced on their own farms are not enough to supply their fields [27, 61]. 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 [29, 60] and (3) the availability of chemical fertilizers that seem to provide an easy substitution of manure [28]. Hence, incorporating rice residues directly into the soil may serve as a potential substitute for organic fertilizer [25, 26].

The I treatments added large amounts of degradable organic matter and significantly increased CH_4 emissions but did not result in the highest rice grain yield (Table 5.4). They showed a higher GWP compared to the B treatments in both water management systems and seasons. However, the practice of burning rice residues does not only remove nutrients but also causes environmental pollution [16, 22, 27, 57]. For instance, burning one ton of rice straw releases 3 kg of particulate matter, 60 kg of CO, 1460 kg of CO_2, 2 kg of SO_2, and 199 kg of ash [17]. In our study, the average amount of rice residues was 4.3-5.7 t ha^{-1} per cropping season. Thus, burning rice residues on the entire study area alone would release 6.3-8.3 tons of CO_2. Therefore, the B treatments not only generated GWP during the cultivation but also when the rice residues were burned on the field. When combining the GWPs of cultivation and burning, the CO_2 released from soil with B treatment would clearly exceed the CO_2 released from the decomposition of incorporated rice residue (I treatment), which is relevant in the context of greenhouse gas balances of the various rice cultivation systems. Hence, a combination of direct incorporation of rice residues into the soil with additional mineral fertilizer application provides a potential win-win situation for both rice growers and the environment.

The higher GHGI in summer rice compared to spring rice was related to very high CH_4 emissions in the summer season. The GHGI was significantly lower for the AWD regime compared to the CCF regime (Table 5.4). The AWD regime has gained increasing attention as a mean of reducing CH_4 emissions from paddy rice [33, 39, 62]. However, continuous flooding throughout the growing season is still a common practice in Vietnam [63]. AWD management decreased GHGI by about 17-41% (for CR), 26-41% (for B), and 36-40% (for I), compared to CCF water management, without significantly affecting rice yields. Tariq [49] also reported a more 40% reduction in GHGI by AWD management, because of lower CH_4 emissions and GWP. Hence, AWD management in paddy rice in Vietnam represents a feasible mitigation option to reduce GHG emissions while maintaining rice yield.

5.5 Conclusions

The potential of various rice-residue management options along with improved water management were tested for their potential to mitigate emissions of GHGs (CH_4 and N_2O). The results showed that the combination of optimized water and rice-residue management may reduce CH_4 emissions and at the same time maintain soil fertility. Compared to conventional continuous flooding (CCF), alternate wetting drying (AWD) water management reduced CH_4 emissions by 36-45% in the case of incorporation of rice residues, and by 15-42% with application of composted rice-residues. The application of rice residues with NPK fertilization yielded the highest CH_4 emissions, while the application of NPK alone (control) yielded the lowest CH_4 emissions in both seasons and both water management systems. Nitrous oxide emissions were generally below the detection limit during the experimental period, except immediately after fertilizer application. Global warming potentials were lower for the AWD than for the CCF water management. The AWD management resulted in a reduction of GWP by 18-36% (for CT), 15-39% (for CR), 27-40% (for B), and 35-40% (for I) compared to the CCF management. Rice yields were slightly higher in the treatments with a combination of organic and mineral NPK fertilizer, compared to mineral fertilizers alone. Direct incorporation of rice residues into the soil may reduce CO_2 emissions by 6.3-8.3 tons ha^{-1} a^{-1}, compared to burning 4.3-5.7 t rice residues per hectare. Thus, in addition to reducing GWP through AWD water management, we recommend that farmers incorporate rice residues into the soil instead of burning them, and also apply mineral fertilizer to compensate for nutrient export through the rice-grain harvest. This combination of management practices offers potential economic and environmental benefits, as it mitigates the overall GWP while increasing rice yields.

References

1. Bouman, B.; Tuong, T. Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management* **2001**, *49*, 11–30, doi:10.1016/S0378-3774(00)00128-1.
2. Tuong, T.; Bouman, B. *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. *Rice production in water scarce environments.*, J.W. Kijne, R. Barker, D. Molden, 2003.
3. (GRiSP) Global Science Partnership. 4th. *Rice Almanac*: Los Bahos, Philippines, 2013.
4. Yan, X.; Akiyama, H.; Yagi, K.; Akimoto, H. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Glob. Biogeochem. Cyscles* **2009**, *23*, 1–15.
5. Sass, R.L.; Fisher, F.M.; Harcombe, P.A.; Turner, F.T. Mitigation of methane emission from rice fields: possible adverse effects of incorporated rice straw. *Glob. Biogeochem. Cycles* **1991**, *5*, 275–287.
6. Yagi, K.; Minami, K. Effect of organic-matter application on methane emission from some Japanese paddy fields. *Soil Sci Plant Nutr* **1990**, *36*, 599–610.
7. Mosier, A.; Wassmann, R.; Verchot, L.; King, J.; Palm, C. Methane and nitrogen oxide fluxes in tropical agricultural soils: sources, sinks and mechanisms. *Enviton Dev Sustain* **2004**, *6*, 11–49.
8. Wassmann, R.; Latin, R.S.; Neue, H.U.; Buendia, L.V.; Corton, T.; Lu, Y. Characterrization of methane emissions from rice fields in Asia: Mitigation options and future research needs. *Nutr Cycl Agroecosyst.* **2000**, *58*, 23–26.
9. Skinner, C.; Gattinger, A.; Muller, A.; Mäder, P.; Flieβbach, A.; Stolze, M.; Ruser, R.; Niggli, U. Greenhouse gas fluxes from agricultural soils under organic and non-organic management—a global meta-analysis. *Sci. Total Environ.* **2014**, *468*, 553–563.
10. Wang, J.; Zhang, X.; Xiong, Z.; Khalil, M.; Zhao, X.; Xie, Y.; Xing, G. Methane emissions from rice agroecosystem in South China: effect of water regime, straw incorporation and nitrogen fertilizer. *Nutr. Cycl. Agroecosyst* **2012**, *93*, 103–112.
11. Smith, P.; Martino, D.; Cai, Z. et al. *Agriculture. In: Climate Change 2007: Mitigation. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change*, Metz, B.; Davidson, O.R.; Bosch, P.R.;

Dave, R.; Meyer, L.A.; Cambridge University Press: Cambridge, UK and New York, NY, USA., 2007.

12. FAO. The database of FAOSTAT. http://www.fao.org/faostat/en/#data/QC. Accessed 13 August 2018. **2016**.
13. (MoNRE) Ministry of Natural Resources and Environment. *The second biennial updated report of Vietnam to the United Nations framework convention on climate change;* Vietnam Publishing House of Natural Resources, Environment and Cartography: Hanoi, 2017.
14. Corton, T.M.; Bajita, J.B.; Grospe, F.S.; Pamplona, R.R.; Asis Jr, C.A.; Wassmann, R.; Lantin, R.S.; Buendia, L.V. Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines). *Nutr. Cycl. Agroecosyst.* **2000**, *58*, 37–53.
15. Tran, S.N.; Nguyen, T. H. N.; Nguyen, H.C.; Nguyen, V. C. N.; Le, H.V.; Kield, I. To quantify the seasonal rice straw and its use in different provinces in the Vietnamese Mekong Delta. *J. of scie* **2014**, *32*, 87–93.
16. Keck, M.; Hung, D.T. Burn or bury? A comparative cost–benefit analysis of crop residue management practices among smallholder rice farmers in northern Vietnam. *Sustain Sci* **2018**, 1–15, doi:10.1007/s11625-018-0592-z.
17. Gadde, B.; Bonnet, S.; Menke, C.; Garivait, S. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. *Environmental Pollution* **2009**, *157*, 1554–1558, doi:10.1016/j.envpol.2009.01.004.
18. Hoang, A.L.; Nguyen, T.T.H.; Le, T.L. Estimated gas emissions from burning rice straw in open fields in Thai Binh Province. J of Sci. 2013, 29, 26–33.
19. Truc, N.; Sumalde, Z.M.; Espaldon, M.; Pacardo, E.P.; Rapera, C.L.; Palis, F.G. Farmer's awareness and factors affecting adotion of rapid composting in Mekong delta, Vietnam and Central Luzon, Philippines. *Journal of Environmental Science and Management* **2012**, *15*, 59–73.
20. Niveta, J.; Arti, B.; Himanshu, P. Emission of air pollutants from crop residue burning in India. *Aerosol and Air Quality Research* **2014**, 422–430, doi:10.4209/aaqr.2013.01.0031.
21. Bijay-Singh; Shan, Y.H.; Johnson-Beebout, S.E.; Yadvinder-Singh; Buresh, R.:. *Crop Residue Management for Lowland Rice-Base Cropping Systems in Asia;* Elsevier Inc, 2008.

22. Fairhurst, T.H.; Witt, C.; Buresh, R.J.; Dobermann. *A. Rice: A practical guide to nutrient management,*, 2nd ed,, 2007.
23. Hoang, N.T.; Tran, T.T.; Dao, T.H.; Nguyen, T.; Pham, T.N.; Nguyen, T.N.; Nguyen, H.T.; Vu, D.Q., Ho, C.T. *Effect of agricultural residue incorporation into soil increasing crop yield, reducing mineral fertilizer applied and improving soil properties. The scientist research results;* Agricultural Publishing: Hanoi, Vietnam, 2014.
24. Gupta, P.K.; Singh, S.; Dixit, C.K.; Singh, D.P. Sharma, C.; Tiwari, M.K.; Gupta, R.K.; Garg S.C. Residue burning in rice-wheat cropping system: causes and implications. *Current Science* **2004**, *87*, 1713–1717.
25. Tran, T.T.; Hung, T.D. Effect of crop by-product on yield and possibility of reducing potassium application rate for crops under rice-based cropping systems on marine sandy soils and grey-degraded soils. *Vietnam soil science J.,* **2010**, 89–95.
26. Zhao, Y.; Wang, P.; Li, J.; Chen, Y.; Ying, X.; Liu, S. The effects of two organic manures on soil properties and crop yields on a temperate calcareous soil under a wheat–maize cropping system. *European Journal of Agronomy* **2009**, *31*, 36–42, doi:10.1016/j.eja.2009.03.001.
27. Trong Hung, D.; Hughes, H.; Keck, M.; Sauer, D. Rice-Residue Management Practices of Smallholder Farms in Vietnam and Their Effects on Nutrient Fluxes in the Soil-Plant System. *Sustainability* **2019**, *11*, 1641, doi:10.3390/su11061641.
28. Phuong, N.D.; Tuan, V.D.; Toan, T.D. *Pig Production Development, Animal Waste Management and Environment Protection:. Farmers Practices in Organic and Inogarnic Fertilization on Crops, Trees and Vegetables: A case Study in Thai Binh Province, North Vietnam;* CIRAD-PRISE Publication: France, 2006.
29. Pillot, D.; Le Coq, J.F.; Hoa, N.T.; Porphure, V. *A case Study In Thai Binh Province, North Vietnam;. Stakeholders' Perception of Pig Effluent Management in Thai Binh Province: Pig Production Development, Animal Waste Management and Environment Protection:;* CIRAD-PRISE Publication: France,, 2006.
30. Watanable, A.; Takeda, T.; Kimura, M. Evaluation of origins of CH4 carbon emitted drom rice paddies. *J. Geophys. Res.* **1999**, *104*, 23623–23629.
31. Lampayan, R.M.; Rejesus, R.M.; Singleton, G.R.; Bouman, B. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Research* **2015**, *170*, 95–108, doi:10.1016/j.fcr.2014.10.013.

32. Triol-Padre, A., Dang, H.T., Nghia, H.T., Hau, D.V., Ngan, T.T., An, L.V., Minh, N.D., Wassmann, R., Sander, B.O. *Measuring GHG emissions from rice production in quang nam province (Central vietnam): emission factors of different landscapes and water management practices. Land Use and Climate Change Interaction in Central Vietnam, Water Resources Development and Management,*, A. Nauditt, L. Ribbe (Eds.),; Springer Science + Business Media: Singapore, 2017.
33. Lu, W.F.; Chen, W.; Duan, B.W.; Guo, W.M.; Lu, Y.; Lantin, R.S.; Wassmann, R.; Neue, H.U. Methane emissions and mitigation options in irrigated rice fields in Southeast China. *Nutr Cycl Agroecosyst* **2000**, *58*, 65–73.
34. (GOS) General Statistics Office of Vietnam. *Statistical Year Book of Vietnam;* Statistical Publishing House.: Hanoi, Vietnam, 2018.
35. Nguyen, V.B.; Bui, D.D.; Ho, Q.D.; Bui, H.H.; Dang, T.L.; Thai, P.; Nguyen, V.T. *The basic information of main soil units of Vietnam.;* The gioi Publishing: Hanoi, Vietnam, 2002.
36. Tran, Q.V.; Ho, Q.D.; Bui, H.D.; Tran, M.T. Assessment of the qualities, quantities, and properties of grey degraded soil in North Vietnam. *Sci. and Technol. J. of Agric & Rural development* **2012**, *207*, 19–25.
37. Nguyen, T.L.; Truong, X.C.; Nguyen, V.H.; Dinh, V.S. *Survey and evaluate fertility soils map for intensive crop restructuring and sustainable agricultural land resources management in Viet Yen District, Yen Dung District, Luc Nam District, Yen District, Son Dong District and Bac Giang city, Bac Giang province.*: Hanoi, Vietnam, 2015.
38. Rochette, P.; Eriksen-Hamel, N.S. Chamber measurements of soil nitrous oxide flux: are absolute values reliable? *Soil Sci Soc Am J* **2008**, *72*, 331–342.
39. Ly, P.; Jensen, L.S.; Bruun, T.B.; Neergaard, A. de. Methane (CH4) and nitrous oxide (N2O) emissions from the system of rice intensification (SRI) under a rain-fed lowland rice ecosystem in Cambodia. *Nutr Cycl Agroecosyst* **2013**, *97*, 13–27.
40. Ly, P.; Vu, D.Q.; Jensen, L.S.; Pandy, A.; Neeraard, A. de. Effects of rice straw, biochar and mineral fertilizer on methane (CH4) and nitrous oxide (N2O) emissions from rice (Oryza sativa L.) grown in a rain-fed lowland rice soil of Cambodia: a pot experiment. *Paddy Water Environ.* **2015**, *13*, 465–475.
41. Lindau, C.W.; Bollich, P.K.; Delaune, R.D.; Patrick, W.H.; Law, V.J. Effect of urea fertilizer and environmental factors on methane emissions from a Louisiana, USA rice field. *Plant Soil* **1991**, *36*, 195–203.

42. Loftfield, N.; Flessa, H.; Augustin, J.; Beese, F. Automated gas chromatographic system for rapid analysis of the atmospheric trace gases methane, carbon dioxide, and nitrous oxide. *Journal of Environmental Quality* **1997**, *26*, 560–564.
43. Smith, K.A.; Conen, F. *Measurement of trace gases: I. gas analysis, chamber methods, and related procedures. Soil and environmental analysis. Modern instrumental techniques, techniques.*, Smith KA, Cresser MS (eds) 3rd; Marcel Dekker: NEW YORK, 2004.
44. (IPCC) Intergovernmental Panel on Climate Change. *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*, Stocker, T.F.; Qin, D.; Plattner, G.-K.; Tignor, M.; Allen, S.K.; Boschung, J. A.; Nauels, Y.; Xia, V., Bex; P.M. Midgley (Eds.); Cambridge University Press,: Cambridge, United Kingdom, 2013.
45. Hinton, N.J.; Cloy, J.M.; Bell, M.J.; Chadwick, D.R.; Topp, C.; Rees, R.M. Managing fertiliser nitrogen to reduce nitrous oxide emissions and emission intensities from a cultivated Cambisol in Scotland. *Geoderma Reg* **2015**, *4*, 55–65.
46. Knoblauch, C.; Maarifat, A.A.; Pfeiffer, E.M.; Haefele, M.S. Degradability of black carbon and its impact on trace gas fluxes and carbon turnover in paddy soils. *Soil Biol Biochem* **2011**, *43*, 1768–1778.
47. Pandey, A.; Mai, V.T.; Vu, D.Q.; Bui, T.; Mai, T.; Jensen, L.S.; A. de Neergaard. Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam.Agric. *Ecosyst. Environ.*, **2014**, *196*, 137–146.
48. Holzapfel-Pschorn, A.; Seiler, W. Methane emission during a cultivation period from an Italian rice paddy. *J. Geophys Res* **1986**, *91*, 11803–11814.
49. Tariq, A.; Vu, Q.D.; Jensen, L.S.; Tourdonnet, S.; Sander, B.O.; Wassmann, R.; Mai, T.; Neergaard, A. Mitigating CH 4 and N 2 O emissions from intensive rice production systems in northern Vietnam: Efficiency of drainage patterns in combination with rice residue incorporation. *Agriculture, Ecosystems & Environment* **2017**, *249*, 101–111, doi:10.1016/j.agee.2017.08.011.
50. Das, S.; Adhya, T.K. Effect of combine application of organic manure and inorganic fertilizer on methane and nitrous oxide emissions from a tropical flooded soil planted to rice. *Geoderma* **2014**, *213*, 185–192.
51. Zou, J.; Huang, Y.; Jiang, J.; Zheng, X.; Sass, R.L. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water

regime, crop residue, and fertilizer application. *Glob. Biogeochem. Cycles,* **2005**, *19*, 1–9.

52. Woese, C.R.; Magrum, L.J.; Fox, G.E. Archaebacteria. *J. Mol. Evol.* **1978**, *11*, 245–252.
53. Davidson, E.A.; Keller, M.; Erickson, H.E.; Verchot, L.V.; Veldkamp, E. Testing a conceptual model of soil emissions of nitrous and nitric Oxides: using two functions based on soil nitrogen availability and soil water content, the hole-in- the-pipe model characterizes a large fraction of the observed variation of nitric oxide and nitrous oxide emissions from soils. 50. *BioScience* **2000**, *50*, 667–680.
54. Cai, Z.; Xing, G.; Yan, X.; Xu, H.; Tsuruta, H.; Yagi, K.; Minami, K.. Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. *Plant and Soil* **1997**, *196* (1), 7–14. 10.1023/A:1004263405020.
55. Abao, E.B.; Bronson, K.F.; Wassmann, R.; Singh, U. Simultaneous records of methane and nitrous oxide emission in rice-based cropping system under rainfed condition. *Nutr Cycl Agroecosyst* **2000**, *58*, 131–139.
56. Bronson, K.F.; Neue, H.U.; Singh, U.; Abao, E.B. Automated chamber measurement of methane and nitrous oxide flux in a flooded rice soil: 1. Residue, nitrogen and water management. *Soil Sci Soc Am J* **1997**, *61*, 981–987.
57. Ponnamperuma, F.N. *Straw as a source of nutrients for wet-land rice. Organic matter and rice*, Banta S, Mendoza CV (eds); International Rice Research Institute (IRRI), 1984.
58. Linquist, B.A.; Anders, M.M.; Adviento-Borbe, M.; Chaney, L.L.; Nalley, E.; Da Rosa, C.; Kessel. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Glob. Change Biol.* **2015**, *21*, 407–417.
59. (SFRI) Soils and Fertilizers Research Institute. *Fertilizers Handbook;* Agriculture Publishing House: Hanoi, Vietnam, 2005.
60. Vu, T.; Tran, M.T.; Dang, T. A survey of manure management on pig farms in Northern Vietnam. *Livest. Sci.* **2007**, *112*, 288–297.
61. Nguyen, V.B.; Tran, M.T.; Nguyen, V.C.; Le, T.; Bui, H.A.; Nguyen, T.T.; Chu, V.H.; Nguyen, H.; Bui, H.D.; Nguyen, D.*; et al. Study on Determination of Limited Factors of Soils in Red River Delta, Mekong River Delta and Recommended Solutions;;* Soils and Fertilizers Research Institute: Hanoi, Vietnam, 2014.

62. Jain, N.; Dubey, R.; D., D.S.; Singh, J.; Khanna, M.; Pathak, H.; Bhatia, A. Mitigation of greenhouse gas emission with system of rice intensification in the Indo-Gangetic Plains. *Paddy Water Environ* **2014**, *12*, 355–363, doi:10.1007/s10333-013-0390-2.
63. van Trinh, M.; Tesfai, M.; Borrell, A.; Nagothu, U.S.; Bui, Thi Phuong Loan; Quynh, V.D.; Le Thanh, Q. Effect of organic, inorganic and slow-release urea fertilisers on CH4 and N2O emissions from rice paddy fields. *Paddy Water Environ* **2017**, *15*, 317–330, doi:10.1007/s10333-016-0551-1.

Chapter 6

6.1 Conclusions

(i) Among various rice residue management options, 27-38 % of the total rice residues on smallholder rice farms in Yen Dong Commune (Nam Dinh Province) and Luong Phong Commune (Bac Giang Province), respectively, are burned on the field. In contrast, 100 % of the rice residues are fed to animals in Che Cu Nha Commune (Yen Bai Province).

(ii) Rice residues represent a valuable source of plant nutrients for crop production; however, at present many farmers are disposing the rice residue as a waste, not utilizing this nutrient resource. Proper use and management requires more knowledge and skills than is currently available to most farmers in Vietnam.

(iii) The communities in Yen Dong Commune (Nam Dinh Province) and Luong Phong Commune (Bac Giang Province) recognized that the burning of rice residues generated available nutrients for the next crop season. They are also aware of the negative impacts of burning rice residues on human health and the environment.

(iv) My cost-benefit analysis showed that the incorporation of rice residues leads to extra costs of 50.8 US$ per ha in Yen Dong Commune (Nam Dinh Province) and 22.0 US$ per ha in Luong Phong Commune (Bac Giang Province). Thus, burning rice residues might be an erroneous trend from an ecological perspective, but it is rational from an economic point of view.

(v) In due consideration of the limited availability of manure and labor force, we recommend to incorporate 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.

(vi) Nutrient inputs need to be better adapted to the crop needs, as demonstrated by the unbalanced nutrient budgets of all investigated crop-residue management systems, whereby burning of rice residues, application of rice residue compost, and incorporation of rice residues into the soil resulted in nutrient accumulation, and collecting all rice residues for feeding cattle resulted in nutrient depletion. Knowledge about (1) soil nutrient contents prior to planting, (2) expected harvest and corresponding nutrient uptake by plants, (3) nutrient concentration 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.

(vii) All three rice-residue management practices (incorporation, burning, and compost) had similar effects on Si plant-availability. This study found a close correlation between the most readily plant-available Si fractions in soils (sum of mobile Si and adsorbed Si) and Si contents in rice straw.

(viii) The combination of optimized water management and rice residue management reduced CH_4 emissions. Combining incorporation of rice residues with alternate wetting and drying water management reduced CH_4 emissions and global warming potentials. Furthermore, incorporation of rice residues into the soil would reduce CO_2 emissions by 6.3-8.3 tons a^{-1} ha^{-1} through not burning 4.3-5.7 tons of rice residues per hectare. Thus, I recommend that farmers should incorporate rice residues into the soil instead of burning rice residues on the field. There are potential economic and environmental benefits of rice residue incorporation in combination with chemical fertilizers and optimized water management. This study suggests that application of chemical fertilizer (N, P, and K) and incorporation of rice residues into the soil under alternative wetting and drying water management is an effective option for mitigating the overall GWP, while obtaining higher yields.

(ix) The proposed combination of incorporation of rice residues and alternate wetting and drying water management improved the incomes of famers by reducing fertilizer costs and in addition reduced water consumption. It is thus an appropriate option for making rice farming in Vietnam more sustainable. I see the greatest potential to shift from burning crop residues to incorporating them into the soil in Vietnam's lowlands, where rice cropping contributes the major share to farmers' livelihoods. In hilly areas, I also see some potential for a transition. In contrast, in mountainous regions, I see no potential for such transformation, since all rice residues are already entirely used in an environment-friendly way as fodder for cattle.

6.2 Outlook for future research

From the results of this study, I conclude that rice residue management on smallholder rice farms in northern Vietnam needs to be improved. For this purpose, it is necessary to establish an effective extension service on rice residue treatment in each village. The service network staff will act as consultants for farmers and be responsible for transferring the knowledge about rice residue management.

For crop residue management, the government must legislate a law that prohibits the burning of rice residues. Crop residues should be incorporated into soil for sustainable crop production. So far, the percentage of farmers who incorporate crop residues into soil is low, mainly because this practice is more time and labor consuming than burning crop residues on the field, and it is costly to afford such extra work on smallholder rice farms. A potential solution to this problem could be that the state may subsidize the mechanization of the agricultural sector and make tractors available to farmers at lower prices. Such support would make the incorporation of rice residues into the soil more attractive, since the involved costs would decrease through the mechanization of this work.

A policy or regulation in this direction needs to be established and strictly monitored by the local community. Efforts to enhance the farmers' awareness of environmental issues related to different agricultural practices should be undertaken, especially addressing the young generation.

In this context, there is also the need for testing whether farmers apply more pesticides when not burning crop residues.

Furthermore, from our field experiment and case field study in Bac Giang Province, we found that phosphorus content in the soil had increased markedly compared to in the past. Therefore, more research on phosphorus (e.g. appropriately to avoid P overload in soil, surface and groundwater bodies, Cadmium contamination…) is needs to be studied to apply in a smallholder rice farm.

CURRICULUM VITAE

DAO TRONG HUNG

Address:	Ilmenauer Weg 8
	37075 Göttingen
Telephone:	+49-15258922355
Email:	tdao1@gwdg.de
Date of Birth:	02.02.1977
Place of Birth:	Hatinh, Vietnam

EDUCATION

4.2015 – ongoing	PhD student at Department Physical Geography, University of Göttingen, Germany Research topic: ***Reducing green-house gas emissions in Vietnam through improved crop residues management in smallholder rice farms*.** Supervisor: Prof. Dr. Daniela Sauer Dr. Markus Keck
8.2006 – 8.2008	Master of Vietnam National University of Agricultural, Hanoi, Vietnam Main study field: Soil Science Research topic: *Study on the change of saline soil properties in Tien Hai district, Thai Binh province, Vietnam through the land use process.*
9.1995 – 10.1999	Engineer of Vietnam National University of Agricultural, Hanoi, Vietnam Main study field: Land Resource Management

AWARDS

5.2019 – 9.2019	Family Oriented Finishing Grant from GAUSS – University of Göttingen, Germany.
4.2015 – 4.2019	Scholarship from the Vietnam government for PhD program at the University of Göttingen, Germany.
10. 2011	Award from Presidency of the Republic of Sudan on complete outstanding Tasks and research technology transfer project Development of rice production and other crops in Sudan.

EMPLOYMENT

1.2000 – now	Soils and Fertilizers Research Institute (SFRI), Hanoi, Vietnam Researcher on climate change; improved crop nutrition; improved soil use and management; land evaluation.

PUBLICATIONS

1. KECK, M., **HUNG, D**. (2019): Burn or bury? A comparative cost-benefit analysis of crop residue management practices among smallholder rice farmers in northern Vietnam. In: Sustainability Science 14 (2): 375-389.doi.org/10.1007/s11625-018-0592-z

2. **HUNG, D.**, HUGHES, J.H., KECK, M., SAUER, D. (2019): Rice-residue management practices of smallholder farms in Vietnam and their effects on nutrient fluxes in the soil-plant system. In: Sustainability 11 (6): 1641. doi.org/10.3390/su11061641

3. **HUNG, D.**, CALLUM, C.B, DORODNIKOV, M., SAUER, D. Improved water and rice-residue management may reduce greenhouse gas emissions from paddy soils and increase rice yields ***(Under Review in Soil & Tillage Research)***

4. HUGHES, J.H., **HUNG, D.,** SAUER, D. Silicon recycling through rice-residue management does not prevent silicon depletion in paddy rice cultivation ***(Under Review in Nutrient Cycling in Agroecosystems)***

REVIEWER ACTIVITIES

Journals:

Agriculture (MDPI publisher)

Agronomy (MDPI publisher)