Soil properties and the response of rice production to water regime and fertilizer source in low fertility soils of the Republic of Panama

Marie-Soleil Turmel

Department of Natural Resource Sciences,
McGill University, Montreal
February, 2011

A thesis submitted to McGill University
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

SUGGESTED SHORT TITLE:

Soil properties and rice production systems in Panama

Abstract

The System of Rice Intensification (SRI) is a resource-conserving rice production system that uses intermittent flooding and organic fertilization. The SRI is emerging as an alternative to conventional rice production systems that use continuous flooding and mineral fertilizer only, however yield improvements with SRI have been highly variable. The objective of this research was to determine if soil properties control the yield improvements with SRI and, if so, the underlying chemical and biological mechanisms. A meta-analysis of 72 SRI vs. conventional system trials from 16 countries found a significant yield response to SRI in low fertility soils (P<0.0001), but no difference between SRI and the conventional system in moderate and high fertility soils. These results were validated in a greenhouse study. Soils with low P availability (≤7.1 mg P kg^{-1}) responded positively to intermittent flooding and organic fertilizer by increasing plant biomass, plant P uptake, available soil P and microbial P concentrations, compared to soils under continuous flooding and amended with mineral NPK fertilizer only. A field study investigating the interactive effects of water regime and fertilizer source found that, under conditions of P limitation, yields were greater with NPK + composted cow manure (compost) than NPK fertilizer alone in the intermittently flooded (6.6 t ha^{-1} vs. 4.9 t ha^{-1}) and continuously flooded (6.8 t ha^{-1} vs. 6.2 t ha^{-1}) soils. The available soil P concentration was significantly increased by compost and was correlated with yield (P=0.007). When N was the most limiting nutrient, according to the Diagnostic and Recommendation Integrated System (DRIS) analysis, yields were greater in the continuously flooded (5.2 t ha^{-1}) than intermittently flooded (2.7 t ha^{-1}) soils receiving NPK fertilizer only, but showed no difference when compost was applied. Compost had a positive effect on the crop nutrient balance according to DRIS analysis (P=0.0007). On-farm trials of SRI at 10 locations in Panama showed an average yield increase of 47% and 86% less water use. SRI is recommended as a rice production system to conserve water and improve rice yields under conditions of P limitation. Organic fertilization is recommended to improve crop nutrient balance and yield under intermittently flooded soil conditions.

Résumé

Le Système de Riziculture Intensive (SRI) est un système de production du riz qui préserve les ressources naturelles en utilisant l'irrigation intermittente et la fertilisation organique. SRI apparait comme une alternative aux systèmes de production de riz conventionnels qui utilisent l'irrigation continue et seulement des engrais minéraux; cependant les améliorations de rendement avec le SRI ont été très variables. L'objectif de cette recherche a été de déterminer si les améliorations de rendement dépendent des propriétés du sol avec SRI et quels sont les mécanismes chimiques et biologiques sous-jacents. Une méta-analyse de 72 tests SRI vs systèmes traditionnels dans 16 pays a révélé une réponse significative du rendement au SRI sur sols à faible fertilité (P<0.0001) mais pas de différence sur des sols à moyenne et forte fertilité. Ces résultats ont été validés par une étude en serre. Des sols bas en P (≤7.1 mg P kg^{-1}) ont réagis positivement à l'irrigation intermittente et aux engrais organiques en augmentant la biomasse de la plante, l'assimilation P, la disponibilité du P du sol, les concentrations microbiennes de P, comparativement aux sols avec irrigation continue et modifiés avec des engrais minéraux NPK seulement. Une étude de terrain investiguant les interactions des types d'alimentation en eau et des types d'engrais a démontré que dans les conditions de limitation de P, les rendements étaient plus importants avec NPK + fumier de vache (compost) qu'avec l'engrais NPK seul sur sols irrigués par intermittence (6.6 t ha^{-1} vs 4.9 t ha^{-1}) et sur sols irrigués en continue (6.8 t ha^{-1} vs 6.2 t ha^{-1}). La concentration P a été augmentée de façon significative par le compost et corrélée au rendement (P=0.007). Selon l'analyse du Système Intégré de Diagnostic et Recommandation (DRIS), lorsque l'N était la substance nutritive la plus limitée, les rendements étaient meilleurs sur des sols à irrigation continue (5.2 t ha^{-1}) que sur sols à irrigation intermittente (2.7 t ha^{-1}) en utilisant l'engrais NPK seulement, mais les rendements n'étaient pas différents quand le compost était utilisé. Le compost avait un effet positif sur l'équilibre des substances nutritives de la récolte selon l'analyse de DRIS (P=0.0007). Des essais du SRI dans les fermes à différents endroits du Panama ont montré une

augmentation moyenne du rendement de 47% et ont utilisé 86% de moins d'eau. SRI est recommandé en tant que système de production du riz pour préserver l'eau et pour augmenter les rendements de production du riz dans les conditions de limitation du P. La fertilisation organique est recommandée pour améliorer l'équilibre des substances nutritives de la récolte et du rendement dans les conditions de sols irrigués par intermittence.

Preface and Contributions of Authors

This thesis is composed of five chapters, preceded by a general introduction. The first chapter is a literature review that summarizes the body of knowledge surrounding this thesis and outlines the objectives of this research project. Chapters two to five are written in manuscript format according to the guidelines of the Graduate and Postdoctoral Studies Office. Connecting paragraphs between these chapters show the progression from one manuscript to the next. Finally, the general conclusions and contributions to knowledge highlight the key findings of this thesis and suggest areas for further research.

All manuscripts are co-authored by the candidate, Joann Whalen and Benjamin Turner. Joann Whalen and Benjamin Turner provided financial support, guidance, and editorial assistance with the manuscripts. Chapter five is modified from the original manuscript that was also co-authored by Juan Espinosa, León Franco, Candelario Pérez, Horacio Hernández, Eric González, Guillermo Fernández, Carlos Rojas, Daniel Sánchez¸ Nicolás Fernández, and Manuel Barrios. The candidate was fully responsible for designing and conducting the experiments, analyzing the data and writing the manuscripts and the co-authors assisted in trial management and data collection. Norman Uphoff provided editorial assistance for chapter five and Ing. Manuel Rojas provided technical support for the field experiment (chapter four).

The manuscripts that compose the body of this thesis are in the following order:

Chapter 2. Turmel, M.-S., Turner, B.L. and Whalen, J.K. 2010. Soil fertility and yield improvements in the System of Rice Intensification (Accepted December 28, 2010 in Renewable Agriculture and Food Systems, DOI: 10.1017/S174217051100007X).

Chapter 3. Turmel, M.-S., Turner, B.L. and Whalen, J.K. 2011. The effect of water regime and fertilizer source on phosphorus availability for rice production in tropical soils of Panama: A greenhouse study.

Chapter 4. Turmel, M.-S., Turner, B.L. and Whalen, J.K. 2011. Composted cattle manure improves the nutrient balance and yield of rice in a tropical soil with low phosphorus availability in Panama.

Chapter 5. Turmel, M.-S., Espinosa, J., Franco, L., Pérez, C., Hernández, H., González, E., Fernández, G., Rojas, C., Sánchez, D., Fernández, N., Barrios, M., Whalen, J.K. and Turner, B.L., 2010. On-farm evaluation of a low-input rice production system in Panama. (In press in Paddy and Water Environment, DOI 10.1007/s10333-010-0227-1).

Acknowledgements

I sincerely thank my supervisors Dr. Joann Whalen and Dr. Ben Turner for their advice and support during the course of this research project. I greatly appreciate all their thoughtful and timely comments on my manuscripts.

I would like to thank the National Science and Engineering Research Council, the International Development Research Centre and the McGill Neotropical Environment Program from providing the funding for this project.

I would like to acknowledge my collaborators from the Instituto de Investigacíon Agropecuaria de Panamá, Ingenieros Benjamin Namé, Manuel Rojas, Estéban Arosemena and Isaac Mejía for providing agronomic advice and field support.

I would also like to thank the agronomists from the Patronato de Nutricíon in Panama, Ingenieros Juan Espinosa, León Franco, Candelario Pérez, Horacio Hernández, Eric González, Guillermo Fernández, Carlos Rojas, Daniel Sánchez¸ Nicolás Fernández, Manuel Barrios and the 46 farmers for collaborating with me to conduct the on-farm trials.

I would also like to thank Dr. Norman Uphoff and Dr. Alan Watson for their comments and advice.

Thank you to my field assistants Annie Smith and Prudencio Martínez for all your hard work.

Thank you to Hélène Lalande and Tania Romero for their guidance and support in the lab.

I would like to thank Dr. Rick Condit, Dr. Kelly Anderson, Dr. Luis Sampedro and Dr. Jose Correa for providing statistical advice.

Special thanks to the soils group at McGill (especially Sandra, Heather, Maria, Simon-Claude and Shamim) and the Smithsonian Tropical Research Institute (Kelly, Sarah, Andy, Laura, Cindy, Tania, Dayana, Dianne, Luis and Didimo) for all the good times talkin' dirt.

Finally, I would like to thank my family, Marnie, Natalie and Ken for all their love and encouragement.

Santiago, I thank you deeply for your endless support and patience, not to mention your soil sampling skills!

It is with great affection and admiration that I dedicate this thesis to my beloved grandmother, Elizabeth Collins (Mame), who has supported and believed in me throughout my studies.

Table of Contents

List of Tables

Chapter 2

Chapter 3

Chapter 4

Chapter 5

List of Figures

Chapter 2

Chapter 3

Chapter 4

Chapter 5

List of Appendices

List of Abbreviations

Abbreviation	Significance
Al	Aluminum
AMF	Arbuscular mycorrhizal fungi
ANOVA	Analysis of Variance
AO	Intermittently flooded system with organic fertilization
C	Carbon
Ca	Calcium
CEC	Cation exchange capacity
$CHCl_3$	Chloroform
cm	Centimeter
Cu	Copper
d	Day
DAT	Days after transplanting
df	Degrees of freedom
DRIS	Diagnosis and Recommendation Integrated System
Eh	Reduction potential
Fe	Iron
Fe-ox	Oxalate extractable amorphous iron
FM	Continuously flooded system with mineral fertilization
g	Gram
H	Hydrogen
h	Hour
H_2O_2	Hydrogen Peroxide
H_2SO_4	Sulfuric acid
ha	Hectare
HCl	Hydrochloric acid
HPO_4^{2-}	Orthosphosphate
K	Potassium
kg	Kilogram
L	Liter
$LiSO_4$	Lithium Sulphate
lnRR	Natural logorithm of the response ratio
LSD	Least Significant Difference
M3P	Mehlich-3 extractable phosphorus
Mg	Magnesium
m	Meter
mg	Milligram

min	Minute
mm	Millimeter
Mn	Manganese
N	Nitrogen
n	Number of observations
Na	Sodium
$NaHCO_3$	Sodium bicarbonate
$NaHCO_3$-P_i	Sodium bicarbonate extractable labile inorganic phosphorus
$NaHCO_3$-P_o	Sodium bicarbonate extractable labile organic phosphorus
NaOH	Sodium hydroxide
NH_4	Ammonium
nmol	Nanomole
NO_3	Nitrate
P	Probability
P	Phosphorus
P_2O_5	Phosphate
P-ox	Oxalate extractable P bound to amorphous metals
Q-Q	Quantile-Quantile
r	Pearson correlation coefficient
S	Sulphur
Se	Selenium
SOM	Soil organic matter
SRI	System of Rice Intensification
t	Ton
Zn	Zinc

General Introduction

Rice (*Oryza sativa*) is the staple food for more than half of the world's population, yet by 2030, global rice production must double to meet demand, placing greater stress on already threatened land and water resources. Rice production in many developing countries is constrained by variable rainfall, low inherent soil fertility and the rising cost of agricultural inputs. Climate change is predicted to increase the variability of rainfall patterns, which will have a major impact on rice production. Among the most vulnerable to climate change are smallholder farmers whose land holdings are concentrated in areas with highly-weathered soils (Oxisols, Ultisols and weathered Inceptisols) having low inherent fertility and high phosphorus (P) fixation capacity associated with Fe and Al oxides, making P one of the main constraints to crop production. To meet future rice needs while preserving environmental resources, farmers need low-input, water conserving systems that can lead to stable, locally produced rice supplies on low-fertility tropical soils.

The System of Rice Intensification (SRI) is emerging as an economically viable alternative to conventional paddy production that both boosts yields and conserves water resources. The System of Rice Intensification was developed in Madagascar in the 1980s, and then adopted in parts of Asia during the early 1990s, and more recently in Africa and Latin America. The adoption of SRI in Latin America has been slower than in Asia, in part due to a lack of local field trials and extension work. More extensive and robust experimentation in Latin

America is required before conclusions can be drawn about SRI's suitability in the region.

Yield differences between SRI and the continuously flooded conventional system are regionally variable and the mechanism for improved crop growth and yield with SRI remains unclear. Many of the studies reporting yield improvements with SRI were conducted in highly weathered soils where P is the limiting nutrient to crop production, suggesting that soil management in SRI may improve soil P availability in highly-weathered soils, thereby improving crop growth.

The main components of SRI are early transplanting with low plant density, intermittent flooding and use of organic fertilizer. The interactive effects of soil water regime and fertilizer source on the P dynamics in highly weathered tropical soils are poorly understood. Soil P availability can be improved by flooding due to an increase in P diffusion and the reductive dissolution of Fe oxides. Yet, flooding can decrease P availability in soils with low P saturation of amorphous Fe-oxides, outweighing the positive effects of flooding on P diffusion to roots.

The effect of flooding on soil P availability may also be influenced by the fertilizer source applied. In highly-weathered soils, organic fertilizer can be more effective than mineral phosphate fertilizer at increasing soil P availability because P is cycled through the microbial biomass, preventing Fe and Al fixation by maintaining nutrients in a biologically available form. Phosphorus availability from organic sources may be greater under intermittently flooded conditions than flooded conditions due to increased microbial activity under aerobic soil conditions. Yet few researchers have evaluated the interactive effects of water regime and fertilizer source on soil P dynamics in tropical soils.

Panama is a country that is dependent on locally produced rice as a staple food. Rice production in Panama is challenged by poor soil fertility, variable rainfall patterns, access to fertilizers and pest control. The SRI has not previously been tested in Panama but may be an appropriate system for the region given its potential to boost rice yields in low fertility soils with locally available organic fertilizer and reduced water inputs.

The objective of this research was to determine (i) if the regional variability in SRI yield is due to soil fertility and (ii) how intermittent flooding and organic fertilization, important components of SRI, affect the soil P dynamics of tropical soils. This project also aimed to evaluate the potential of SRI to boost rice yields and conserve water for resource-poor farmers in Panama.

CHAPTER 1. Literature Review

1.1. Introduction

Rice (*Oryza sativa*) is the staple food for more than half of the world's population, yet by 2030, global rice production must double to meet demand (Food and Agriculture Organization, 2006), placing greater stress on already threatened land and water resources. Rice production in many developing countries is constrained by variable rainfall, low inherent soil fertility and the rising cost of agricultural inputs (IAASTD, 2008; Stocking, 2003). Climate change is predicted to increase the variability of rainfall patterns, which will have a major impact on rice production in Latin America and the Caribbean and other rice dependent regions (Nelson et al., 2009). Among the most vulnerable to climate change are smallholder farmers, who constitute the poor and very poor in rural communities. Their land holdings are concentrated in areas with highly-weathered soils (Ultisols, Alfisols and weathered Inceptisols) having low inherent fertility and high phosphorus (P) fixation in Fe and Al oxides, making P one of the main constraints to crop production (Namé and Villarreal 2004). To meet future rice needs while preserving environmental resources, farmers need low-input, water conserving systems that can lead to stable, locally produced rice supplies on low-fertility tropical soils (IAASTD, 2008).

In this literature review, I first provide some background information on the system of rice intensification (SRI), tropical soils, soil P, the effect of agronomic practices on P availability and biological P transformations. Throughout, I discuss possible mechanisms whereby intermittent flooding and organic fertilization, as components of SRI, modify soil properties and biological

P cycling in a manner that may increase P uptake and rice yields on low fertility soils. I also provide information on rice production in Panama, the country where my Ph.D. research was conducted, and finally outline the objectives and hypotheses of the thesis research.

1.2. The System of Rice Intensification

The System of Rice Intensification (SRI) was developed in Madagascar in the 1980s, and then adopted in parts of Asia during the early 1990s, and more recently in Africa and Latin America (Stoop et al., 2002). The adoption of SRI in Latin America has been slower than in Asia, in part due to a lack of local field trials and extension work. In 2001, Cuba became the first country in Latin America to establish SRI trials (Perez, 2002). Since then, the system has been tested in several other countries including Brazil, Costa Rica, Ecuador, Peru, and now Panama (Chang, 2008; CIIFAD, 2010; Gehring et al., 2008). Most of the data so far are from isolated trials; more extensive and robust experimentation in Latin America is required before conclusions can be drawn about SRI's suitability in the region.

The majority of SRI studies to date have involved small field trials comparing SRI methods with conventional methods of rice cultivation. Yield differences between SRI and conventional system are highly variable and the potential of SRI to boost yields has therefore been debated at length in the peer reviewed literature (Dobermann, 2004; Hengsdijk and Bindraban, 2004; McDonald et al., 2006; Sheehy et al., 2005; Sheehy et al., 2004; Stoop and Kassam, 2005; Surridge, 2004; Uphoff et al., 2008). Proponents claim that SRI increases the physiological yield potential of rice, which can increase yield by 50-

100%. The “SRI controversy” stemmed from reports of SRI yields in Madagascar as high as 20 t ha^{-1}. These yields were considered to be erroneous based on theoretical models of the photosynthetic capabilities of rice and lead to major criticism of SRI from the rice research community (Dobermann, 2004; Sheehy et al., 2005; Sheehy et al., 2004). Critics argue that yield increases reported with SRI were related to a decline in Fe toxicity to rice plants and restricted to the highly ferralitic soils of Madagascar (McDonald et al., 2006). A meta-analysis of 40 studies comparing SRI with the conventional system concluded that SRI had no potential to increase yields outside of Madagascar (McDonald et al., 2006). However, these authors reported yield differences ranging from a 22% yield increase to a 61% yield reduction with SRI in regions outside Madagascar and did not provide an explanation for the wide variability in yield response to SRI (McDonald et al., 2006)

The SRI method uses early transplanting (seedlings <15 days old), wide row spacing (>25 cm), organic fertilizer use and intermittent wetting and drying of the soil rather than the prolonged flooding practiced in conventional rice paddy systems (Stoop et al., 2002). Some researchers suggest that SRI has the potential to increase yield in highly-weathered soils with low nutrient availability and low potential for rice production, but has little potential to increase yields in more favourable soil conditions where rice producers often achieve the yield potential using conventional systems (Hengsdijk and Bindraban 2004; Dobermann 2004). Highly-weathered soils tend to have extremely low concentrations of plant-available P forms (Tiessen, 1998; Walker and Syers, 1976) and P is commonly the limiting nutrient to crop production. The mechanism for improved crop growth and yield with SRI remains unclear; however, it is hypothesized that the soil management in SRI increases soil P availability in highly-weathered soils.

1.3. Tropical soils and phosphorus

The inherent fertility of tropical soils depends on their parent material, weathering status, soil organic matter (SOM) content, and land use history. Two widespread orders of weathered tropical soils are the Alfisols and Ultisols. Ultisols are associated with regions subject to greater rainfall and weathering than Alfisols and thus are more acidic and have lower concentrations of Ca, K, and Mg (Van Wambeke, 1992). Both soil orders are dominated by low activity clays (kaolinite) and generally have low concentrations of soil organic carbon and associated nutrients (N, P and S). The warm climate and frequent, heavy rains in the humid tropics accelerate the leaching and depletion of base cations from soils, including Ca, Na, Mg and K. Silica is depleted at a faster rate than Al, resulting in a enrichment of the parent material in Al (Ahn, 1993). Oxides of Fe and Al are resistant to weathering and predominate, along with minerals like kaolinitic clay and quartz sand. As the weathering process proceeds, soils become more enriched in Fe and Al oxides, more acidic and therefore have a higher P fixation capacity.

Not all tropical soils are highly-weathered or have low fertility. For example three classes of relatively fertile soils found in the tropics are Andosols, Gleysols and Luvisols. Andosols are soils of volcanic origin, rich in cations and fertile for agricultural production. However, tropical Andosols can also be rich in colloidal weathering products such as allophane, imogolite, and ferrihydrite, giving them a high P fixing capacity. Gleysols are formed under waterlogged conditions and are commonly used for flooded rice production in the tropics.

Luvisols have developed horizons with a leached clay layer rich in cations and are relatively fertile and suitable for agricultural production (Sanchez, 1976).

Many forms of organic and inorganic P exist in soils, each differing in their availability to plants. Chemical fractionation procedures can be used to quantify the amount of P present in these organic and inorganic pools. The Hedley procedure is a widely accepted method used to separate plant available P forms from refractory forms (Hedley et al., 1982). The most biologically available P, soluble orthophosphate (HPO_4^{2-}), is first removed with an anion exchange resin. Depending on the soil properties, relatively little soluble orthophosphate (< 20 mg kg^{-1}) is usually present in the soil at one time (Paul, 2007). The amount of soluble P in soil solution is affected by adsorption-desorption processes and soil pH. The optimum availability of orthophosphate is at pH 6.5. Labile organic ($NaHCO_3$-P_o) and inorganic P ($NaHCO_3$-P_i), fixed to soil surfaces are removed using $NaHCO_3$. This P pool is also considered available for uptake by living organisms. Another commonly used extract used to determine the quantity of biologically availability P in non-calcareous soil is Mehlich-3 extract (Mehlich, 1984). Phosphorus added to soil with organic fertilizers, (animal manure and green manure) can increase $NaHCO_3$-$P_{o,}$ whereas mineral P addition increases $NaHCO_3$-P_i (Singh et al., 2007). Microbial P is extracted after microbial cells are lysed with $CHCl_3$ and known as $CHCl_3$-P. Organic and inorganic P that is fixed more strongly to Fe and Al components of soil surfaces are removed with NaOH and are known as NaOH-P_o and NaOH-P_i respectively. This component is important in weathered tropical soils that have a high concentration of P-fixing Al and Fe oxides. The occluded P (HCl-P) of weathered soils is extracted using HCl.

The most chemically stable forms of organic P (H_2SO_4-P_o) and relatively insoluble inorganic P (H_2SO_4-P_i) are dissolved by oxidation and acid digestion.

A common misconception about tropical soils is that they have a low total P content. Total P in slightly weathered and highly weathered soils can range from 90-1300 mg P kg^{-1} and 60-1400 mg P kg^{-1}, respectively (Sharpley et al., 1987). Total P in the surface horizons of soils on Barro Colorado Island in Panama is between 315 and 1114 mg P kg^{-1} (Dieter et al., 2010). In that study phosphorus concentrations were generally lower in tropical soils developed from marine sediments and greatest on soils derived from andesite (Dieter et al., 2010). As mentioned above, highly weathered soils such as Acrisols and Ferralsols have high concentrations of Fe and Al-oxides that fix P strongly and a large proportion of the soil P may be held in the sparingly soluble NaOH extractable pool. Organic P forms in highly-weathered soils on average represent 26% of the total P (Sharpley et al., 1987) with up to 494 mg P kg^{-1} reported in Panama under lowland tropical forest (Turner and Engelbrecht, 2010). Phosphorus acquisition by plants growing in highly-weathered soils is dependent on the turnover of biologically available P from organic forms, namely $NaHCO_3$-P_o and microbial P (Oberson et al., 2001).

1.4 Agronomic factors that influence soil properties and P availability for rice production

1.4.1 Water Regime

In traditional methods of irrigated lowland rice cultivation, soils are inundated during the vegetative and maturation phases. It is generally thought that better rice yields are achieved in flooded soils because flooding eliminates water stress, weed pressure and creates favorable soil conditions (pH, available nutrients) (Ahn, 1993). There are several mechanisms by which flooding influences soil P availability. In many soils, P uptake is improved by flooding compared to aerobic soils (Huguenin-Elie et al., 2003). This may be due to a decrease in tortuosity causing a 10 to 100-fold increase in P diffusion and the reductive dissolution of Fe oxides under flooded conditions. Under flooding conditions, insoluble Fe^{3+}-P are reduced to more soluble Fe^{2+}-P. In many soils, this reaction is enough to increase the soil solution P concentration to a level that is adequate for rice production (>5mg kg^{-1}) (Dobermann and Fairhurst, 2000). However, Ponnamperuma (1972) found that little P is released from clay soils high in Fe-oxides compared to sandier soils with low Fe-oxide content. Conversely, soil flooding can also increase P sorption capacity in highly weathered soils with a low P saturation of amorphous Fe oxides. When these soils are flooded, there is an initial increase in soluble inorganic P and organic P due to the reductive dissolution of Fe^{3+} oxides (Shahandeh et al., 1994; Zhang et al., 2003). As reduction proceeds, crystalline Fe (dithionite extractable) is converted to amorphous Fe (oxalate extractable, Fe-ox) resulting in an increase in soil P sorption capacity compared to aerobic soils. In soils with high Fe concentration, non-oxalate extractable Fe compounds with extremely high P-fixing capacity, such as viviante, can also be formed, severely reducing P desorption. The P availability in flooded soils is correlated the ratio of amorphous Fe bound P to amorphous Fe (P-ox/Fe-ox) (Zhang et al., 2003). Thus, depending on the P-ox/Fe-ox ratio, the negative consequences of flooding may out weigh the positive (Zhang et al., 2003)

Under prolonged flooding conditions, the soil becomes anoxic and reducing conditions prevail due the activity of anaerobic bacteria. The reduction of Fe and Mn oxides begins within a few days of flooding (Patrick and Delaune, 1972). The extent of the reduction process is related to SOM content, because organic matter provides a carbon source for anaerobic bacteria. Generally, Fe^{3+} is the most important mineral to be reduced and Eh values equilibrate around the Fe^{3+}-Fe^{2+} system. Lowland rice production on acidic ferralitic soils is often limited by Fe toxicity, due to the high level of soluble Fe^{2+} generated by flooding in these soils (Fageria et al., 2008; Sahrawat, 2004). As SRI systems are flooded intermittently, Fe reduction is constrained by the return of aerobic soil conditions, which led Dobermann (2004) to suggest that the decline in Fe toxicity is responsible for higher rice yields in SRI than conventional paddies on ferralitic soils. The concentration at which Fe becomes toxic to rice depends on the availability of other soil nutrients, particularly P. The interactions between low soil P fertility and Fe toxicity on rice P nutrition and Fe toxicity are complex. Low soil P fertility can increase the uptake of Fe by plants from the soil solution by reducing the oxidizing capacity of their roots. In addition, large concentrations of Fe in the soil solution may reduce soil P availability and also interfere with the plant P uptake (Fageria et al., 2008).

Flooding also affects soil pH, which can be neutralized to pH 6.5-7.2 about one month after flooding and remains near-neutral until the soil dries (Ahn, 1993). In acidic soils, the pH increases due to the release OH^- ions as $Fe(OH)_3$ is reduced to $Fe(OH)_2$. In alkaline soils, the pH is reduced as the partial pressure of CO_2 increases the concentration of H^+ ions. This increase in pH is important in acidic soils that are at risk of Al toxicity because the exchangeable Al is precipitated within two weeks of flooding at pH 5.5 (Ahn, 1993).

The water regime may play an important role in regulating the microbially-mediated release of P from organic sources into the plant available pool. Maximum productivity and decomposition occurs under intermittent periods of inundation as aerobic decomposition of organic matter proceeds at a higher rate than under anaerobic conditions (Acharya, 1935; Kirk, 2004). Under continuous flooding, organic fertilizer increases the moderately stable organic P fraction, whereas, in intermittently flooded soils, organic fertilizer addition increases the labile organic P fractions and is correlated significantly with an increase in microbial P (Yang et al., 2006). This increase in labile organic P is closely related to improved P uptake by rice in intermittently flooded conditions, compared to continuously flooded soils (Yang et al., 2006). However, aerobic soil conditions increase organic matter decomposition, which is considered a negative consequence of intermittent flooding. Soil organic matter is important in maintaining the fertility of tropical soils because it contributes to the cation exchange capacity and variable charge in low-activity clay soils (Tiessen et al., 1994). Under flooded conditions decomposition rates are lower, resulting in a net accumulation of organic matter which can improve soil fertility (Sahrawat, 2003).

Continuous flooding may have a negative effect on root development and nutrient absorption. Root respiration is inhibited under anoxic condition, leading to slower root growth. Barison et al. (2003) found that rice plants grown under intermittently flooded conditions had a greater root biomass and roots extended to a greater depth in the soil profile compared to plants grown under continuously flooded conditions. Research by Yang et al. (2004) showed that continuous flooding had adverse effects on root active absorption area and root surface phosphatase activity, which decreased the total plant phosphorus uptake compared to the intermittently flooded conditions. Some researchers have suggested that SRI has the potential to increase yields in soils with low nutrient availability because aerobic soil conditions promote root growth (Dobermann, 2004; Hengsdijk and Bindraban, 2004).

Water regime also affects the availability of other essential plant nutrients, particularly N. Under continuously flooded conditions, urea or NH_4-based fertilizers and N mineralized from organic matter remain in the NH_4 form due to the anoxic soil conditions (Ponnamperuma, 1972). However, under intermittent flooding conditions, gaseous losses of N_2O can occur during the flooding and drying cycles, because nitrification occurs during the aerobic period and denitrification during flooding (Huang et al., 2007). Intermittent flooding may also contribute to NO_3 leaching below the root zone although there is no information on this for SRI systems.

1.4.2. Fertilization

In addition to water regime, soil P availability can be increased by adding inorganic and organic soil amendments. Single and triple superphosphate and ammonium phosphate are commonly used mineral P fertilizers for paddy rice, with optimum rates of application around 20-40 kg P_2O_5 ha^{-1}. In acidic soils, such as Ultisols, rock phosphates can also be used as P fertilizers, because soil conditions aid P dissolution from this sparingly soluble fertilizer source (Name and Villarreal, 2004a). Phosphorus fertilization of highly weathered soils is a problem because much of the P from mineral fertilizer is strongly fixed to the Fe and Al oxides, so large amounts of mineral P fertilizer are needed to saturate P fixation sites and eventually raise the available soil P concentrations to sufficient level for crop production (Sanchez, 1976). This may be too costly for resource-poor farmers in developing countries.

As resource-poor farmers in developing countries have limited access to mineral fertilizers, they rely on locally available organic manures and composts to supply plant nutrients. In highly-weathered soils, organic fertilizer can be more effective than mineral P fertilizer at increasing soil P availability because P is cycled through the microbial biomass, preventing Fe and Al fixation by maintaining nutrients in a biologically available form (Nziguheba et al., 1998). Organic fertilizers supply P and an energy source for microbes that produce phosphatase enzymes capable of mineralizing plant-available P from the organic P pool. The microbial biomass acts as a reservoir of biologically available P that can be released for plant uptake (Singh et al., 1989; Turner et al., 2006). In SRI, the use of organic fertilizer, in combination with aerobic soil conditions, could potentially increase the size of the microbial P pool and the rate of organic P turnover and in turn improve P availability to crops, compared to flooded systems that use mineral P fertilizer only (Randriamiharisoa et al., 2006; Song et al., 2007; Turner and Haygarth, 2001).

Organic fertilizer can also affect the soil P supply to plants by several other mechanisms. When organic fertilizer is added to the soil, the increase in plant P uptake can exceed the amounts of P released from the organic fertilizer, indicating that organic matter addition also increases the availability P from non-labile pools. It is thought that organic acids and humic substances released by microbes and produced during organic matter decomposition solubilize the P bound to Fe and Al oxides (Wu et al., 2007). Also, organic acids such as citrate, malate and oxalate can compete for adsorption sites on Fe and Al oxides thus reducing the amount of P that is sorbed onto these surfaces (Haynes and Mokolobate, 2001).

Organic fertilizer also buffers soil pH, adjusting it to near-neutral releasing P from sparingly soluble pools (Seng et al., 2004). In addition, organic fertilizer has a liming effect on the soils and can reduce harmful Al and Fe toxicity (Haynes and Mokolobate, 2001). The decrease of soluble Al and Fe is attributed to precipitation reactions at higher soil pH, leading to the formation of non-toxic organic-Al and Fe complexes (Seng et al., 2004). A reduction in soluble Al and Fe concentration in the soil solution also increases P availability to plants by reducing the amount of P that is precipitated into insoluble Al and Fe oxides (Haynes and Mokolobate, 2001).

Grain yield responses to organic fertilizer may only occur after several years of application. Lee et al. (2009) showed that, in a high fertility Korean soil, in the first few years of organic fertilization in combination with NPK, there was no yield increase compared to the system using only NPK. However, after 10 years, a yield response to organic fertilization was observed and after 25 years, yields in treatments receiving only organic fertilizer were comparable to the treatments receiving mineral NPK fertilizers. This was attributed to an increase in

SOM and the ability of the soil to supply essential plant nutrients. The advantages of organic fertilizer over mineral fertilizer for improving P availability on highly weathered soils are often seen immediately, whereas positive results on high fertility soils may only be seen in the long-term.

1.5. Biological Phosphorus Transformations

It is clear that water management and the fertilizer source applied in rice systems affect the plant available P in soil solution and bound to soil surfaces. However, these management factors also impact soil biota known to enhance P availability and uptake.

1.5.1. Microbial P cycling

Microorganisms have an essential role in soil P transformations. Organic amendments can increase the soil microbial biomass C:P ratio thus stimulating the microbial immobilization of P (Wu et al., 2007). Microorganisms immobilize P by assimilation into cell constituents. The amount of P that is immobilized depends the C:P ratio of the organic material being decomposed and the available P in the soil solution. However, soil microbial P may be more related to inputs of high quality organic material rather than soil P levels, because microbes must maintain a balance of C:N:P in their cells for proper metabolic functioning (Oberson et al., 2001). When the organic substrate contains insufficient P to support microbial growth, soil P must be used and net immobilization of P will occur. Generally, if the substrate has a C:P ratio of <200 then net P mineralization will occur and a C:P >300 will result in net immobilization. Organic matter inputs are expected to promote faster P cycling through microbial biomass and thus P availability in the soil solution. This is because organic matter provides a substrate for microbial growth and growing cells immobilize P that is later mineralized when old cells die, lyse and release P back into the soil solution (Oberson et al., 1999).

Organically bound P becomes bioavailable through microbial P mineralization. Mineralized organic P is an important source of P for plant nutrition (Oberson et al., 2001). The phosphatase enzymes that convert organically bound P to inorganic phosphate are produced by up to 80% of the microbial population and may also be produced by plant roots in conditions of P limitation (Paul, 2007). Phosphatase activity may be higher in soils with more SOM and where P availability is limiting relative to other essential soil nutrients (C and N) (Feller et al., 1994). Thus, soil management practices that cause a decline in SOM will generally reduce phosphatase activity. However, phosphatases are extracellular enzymes that may be stabilized on soil surfaces and function as abiotic enzymes, thus some of the enzyme activity is not directly related to microbial demand. Decomposition of organic matter is generally greater in aerobic compared to flooded conditions (Kirk, 2004). Anaerobic soil conditions reduce the activity of enzymes important in the decomposition of organically bound nutrients such as phosphatases and β-glucosidase (Pulford and Tabatabai, 1988). As a consequence, the aerobic conditions of SRI may promote microbial and enzyme activity and increase the mineralization of P from SOM (Dobermann, 2004).

Wetting and drying cycles can rapidly change the soil osmotic potential, which is expected to release microbial P accumulated from decomposition of organic matter into the soil solution (Song et al., 2007). When soil is flooded, the oxygen supply rapidly reaches zero and aerobic bacteria die or go into a dormant state. In a controlled wetland microcosm experiment, Song et al. (2007) observed a release of PO_4 during a rewetting period following a drying period. This was in part attributed to cell lysis caused by the change in osmotic potential. Turner and Haygarth (2001) also observed an increase in soil organic P during rewetting periods that followed soil drying. This increase in organic P was correlated with a decrease in microbial bound P (Turner and Haygarth, 2001). Song et al. (2007) observed a change in phosphatase activity from 1.4 nmol min^{-1} g^{-1} in the initial period when soils were wet, to 12.4 nmol min^{-1} g^{-1} in the drying period, which was sustained into the following rewetting period. Intermittent flooding in combination with organic matter addition in SRI may be an alternative, biologically mediated, way to increase P availability in soils when flooding is not possible or poses a risk of Fe toxicity.

1.5.2. P solubilization and acquisition

Under conditions of P limitation, plant roots and rhizosphere microorganisms may produce organic acids that behave as chelating agents, forming complexes with Fe and Al (Paul, 2007). Rice roots can increase the availability of soil P by decreasing soil pH through excretion of low molecular weight organic acids such as citrate (Kirk, 2004). Phosphate-solubilizing microorganisms are thought to convert insoluble PO_4 into soluble P by acidification, chelation and exchange reactions, although the details of these mechanisms are still unclear (Paul, 2007). Organisms such as *Aspergillus niger* produce the organic acids citrate, oxalate and gluconate (Illmer et al., 1995). Other microorganisms, such as *Penicillium simplicissimum*, *Pseudomonas* sp. (PI18/89) and *Penicillium aurantiogriseum* are able to solubilize Al phosphate without producing organic acids. Proton release accompanying the uptake NH_4^+ has been suggested as the mechanism of P solubilization by these organisms (Illmer et al., 1995).

Arbuscular mycorrhizal fungi (AMF) may also be important for P uptake by plants in aerobic soils with low P availability because they increase the surface area for P uptake through their extensive hyphal network. There is also evidence that AMF fungi can have synergistic effects on P uptake with other P solubilizing organisms (Duponnois et al., 2005; Osorio and Habte, 2001; Souchie et al., 2006; Tawaraya et al., 2006). Arbuscular mycorrhizal fungi are obligate aerobic organisms, so prolonged flooding in rice production systems is detrimental to soil AMF populations (Ilag et al., 1987). Microbial P solubilzation and AMF are expected to play an important role in improving plant P uptake in SRI; however, the influence of water regime on P-solubilzation and AMF mediated P uptake in soils with low P fertility remains to be investigated (Randriamiharisoa et al., 2006).

1.6. Rice production in Panama

Panama has a humid tropical climate and receives from 1000-5000mm of precipitation annually, depending on the region, with a rainy season from May to December. The majority of the annual precipitation (≈ 95 %) falls in during the rainy season, making rainfed agricultural production difficult in the dry season.

Rice production in Panama is challenged by poor soil fertility, variable rainfall patterns, access to fertilizers and pest control. There are approximately 50,000 smallholder farmers in Panama cultivating a total area of 49,000 ha using either a flooded and transplanted system (yielding approximately 3 t ha^{-1}) or rainfed and direct seeded system (yielding 0.5-1.0 t ha^{-1}) (MIDA, 2009). Another 65,000 ha, mainly concentrated on relatively fertile Luvisols along the Pacific coast, are under mechanized production (49,000 ha rainfed and 16,000 ha irrigated production; average yields of 4.6 t ha^{-1}).

The SRI is a low-input technology that could boost rice production in rural Panama. Poverty is endemic, with 36% of the rural population living in poverty and 20% living in extreme poverty (Government of Panama, 2003). Smallholder farmers are concentrated in areas with highly-weathered soils (Ultisols, Alfisols and weathered Inceptisols) having low inherent fertility and high P fixation in Fe and Al oxides, making P limitation a major constraint in crop production (Name and Villarreal, 2004a). Rural Panamanian farmers have limited access to mineral fertilizers, and most rely on chicken manure and household composts to replenish soil nutrients. In many regions, such as the Azuero Peninsula and other parts of central Panama, agricultural production is also limited by variable rainfall patterns and early onset of the dry season. Farmers also find that rainfall is becoming more unreliable as well as insufficient during some months, so water supply is expected to become a more influential factor in rice production.

1.7. Conclusions and Research Directions

SRI is emerging as an economically viable and sustainable alternative to conventional rice paddy systems for rice farmers in the tropics. However, yield improvements with the SRI system compared to the conventional system appear to be regionally variable. Conventional rice production systems rely on flooding to increase P solubilization through reduction of the soil redox potential. The SRI system differs in that the soil environment is aerobic with wetting and drying cycles and organic fertilizers are applied. Under this regime, rice yield and P uptake may be improved in highly-weathered soils where P is the limiting nutrient to crop production. The mechanism for improved crop growth and yield with SRI remains unclear, although these findings suggest that the soil management aspects of SRI may improve crop growth by increasing soil P availability. Intermittent flooding induces changes in chemical and biological processes that can result in greater soluble P concentrations in soil solution, as outlined in the preceding sections.

The effects of water regime on soil P availability may be dependent on the fertilizer source applied. In highly-weathered soils, organic fertilizer can be more effective than mineral phosphate fertilizer at increasing soil P availability because P is cycled through the microbial biomass, preventing Fe and Al fixation by maintaining nutrients in a biologically available form. Research is required to improve our knowledge of the effects of water regime and fertilizer source on soil P dynamics in tropical soils with low P availability.

The objectives of this research project were: 1) to determine if soil fertility can explain the regional variability in yield response to SRI management; 2) to determine if the soil-dependent yield response to SRI is due to P fertility; 3) to investigate the effects of water regime and organic fertilization on rice production, soil nutrient supply, microbial P and soil enzyme activity in a soil with low P availability in Panama; and, 4) to evaluate of the potential of SRI to increase rice yields while reducing water consumption for resource-poor farmers in Panama.

The following research questions and hypotheses were addressed and tested:

1) Does soil fertility explain the variability in yield response to SRI? I hypothesized that yield improvements with SRI compared to the conventional system are greater in low fertility soils.

2) Is nutrient uptake and plant growth greater in an organically fertilized system under aerobic soil conditions compared to a minerally fertilized system under continuously flooded conditions and is this effect dependent on soil properties? I hypothesized that rice biomass would be greater in the organic-aerobic system in the low fertility soils and that intermittent flooding and organic fertilizer would increase soil P availability and plant P uptake. I also hypothesize that in the moderate to high fertility soils, where available P is not a growth limiting factor, rice biomass would be greater in the flooded-mineral system or similar between the two systems.

3) How do the interactive effects on water regime and fertilizer source influence rice production and soil P dynamics? I hypothesized that rice production would be limited primarily by P availability, and that plant P uptake and yield would be greatest when composted cow manure is applied in combination with intermittently flooded soil conditions. I also hypothesized that microbial C, N and P, soil enzyme activities and available soil P would be greater when compost is applied in under intermittently flooded soil conditions.

4) Can SRI increase rice yields and conserve water for resource-poor farmers in Panama? I hypothesized that rice yields would be higher in SRI compared to the farmers' conventional system that uses continuous flooding and that SRI will use less water than the conventional system.

Chapter 2. Soil fertility and the yield response to the System of Rice Intensification: A meta-data analysis

2.1. Abstract

The system of rice intensification (SRI) is a low-input rice (*Oryza sativa* L.) production system that differs from conventional systems in several ways: seedlings are transplanted earlier and are more widely spaced, organic fertilizer is often used in addition to mineral fertilizer, and soils are irrigated intermittently rather than flooded for long periods. The yield benefits of SRI compared to conventional systems can be substantial, yet are regionally variable and have been the subject of considerable debate, due partly to a lack of mechanistic understanding. Here I show that soil properties may in part explain the variability in yield response to SRI. A meta-analysis of data from 72 field studies where SRI was compared to conventional systems indicates that yields increased significantly (P<0.0001) when SRI was implemented on highly-weathered infertile soils rich in iron and aluminum oxides (Acrisols and Ferralsols), but there was no difference in yield between SRI and conventional systems in more fertile soils favourable for rice production (Gleysols, Luvisols, Fluvisols). The yield difference between SRI and conventional rice production therefore appears to be related in part to soil properties linked to weathering. This should help resolve the debate about the value of SRI and allow research to be targeted towards understanding the biological and chemical processes in soils under SRI management.

Key words: System of Rice Intensification, Highly weathered soils, Marginal soils, Low-input rice production

2.2. Introduction

Rice (*Oryza sativa* L.) is the staple food for more than half of the world's population, yet by 2030, global rice production must double to meet demand (Food and Agriculture Organization, 2006), placing greater stress on already threatened land and water resources. The rising cost of fertilizers produced using fossil fuel, agricultural inputs and transportation also contribute to the increasing food insecurity in rice dependent areas. To meet future rice demand while preserving environmental resources, new low-input solutions that can lead to stable, locally produced rice supplies are necessary (IAASTD, 2008).

SRI has been used as a method to increase yield and reduce water and mineral fertilizer consumption (Barison, 2003; Randriamiharisoa et al., 2006). Developed in Madagascar in the 1980s, SRI was adopted in parts of Asia during the early 1990s, and more recently in Africa and Latin America. The SRI method relies on early transplanting, wide row spacing, organic fertilizer use and intermittent wetting and drying of the soil rather than the prolonged flooding practiced in conventional rice paddy systems (Stoop et al., 2002). Most SRI studies so far have involved small field trials comparing SRI methods with conventional methods of rice cultivation. Yield differences between the SRI and conventional system are highly variable and the potential of SRI has therefore been debated at length in the peer reviewed literature (Dobermann, 2004; Hengsdijk and Bindraban, 2004; McDonald et al., 2006; Sheehy et al., 2005;

Sheehy et al., 2004; Stoop and Kassam, 2005; Surridge, 2004; Uphoff et al., 2008). Proponents claim that SRI increases the physiological yield potential of rice, which can increase yield by 50-100% . The “SRI controversy” stemmed from reports of SRI yields in Madagascar as high as 20t ha^{-1}. These yields were considered to be erroneous based on theoretical models of the photosynthetic capabilities of rice and lead to major criticism of SRI in general from the rice research community (Dobermann, 2004; Sheehy et al., 2005; Sheehy et al., 2004). Critics argue that yield increases reported with SRI were related to a decline in iron toxicity to rice plants and restricted to the highly ferralitic soils of Madagascar (McDonald et al., 2006). A previous meta-analysis of 40 studies comparing SRI with the conventional system concluded that SRI had no potential to increase yields outside of Madagascar (McDonald et al., 2006). However, these authors reported yield differences ranging from a 22% yield increase to a 61% yield reduction with SRI in regions outside Madagascar; they did not provide an explanation for the wide variability in yield response to SRI (McDonald et al., 2006).

Some researchers suggest that SRI has the potential to increase yield in marginal soils with low nutrient availability and low potential for rice production, but has little potential to increase yields in more favourable soils where rice is already grown near the yield potential (Dobermann, 2004; Hengsdijk and Bindraban, 2004). This seems likely, because soil biological contributions to soil fertility and improved microbial turnover of organic P under aerobic soil conditions may more important in highly-weathered low fertility soils where P is often the limiting nutrient to crop production (Randriamiharisoa et al., 2006; Turner et al., 2006).

The objective of this study was to determine (1) whether SRI has a positive effect on rice yields in regions other than Madagascar and (2) if soil fertility can explain some of the regional variability in yield response to SRI management.

2.3. Materials and Methods

I collected yield data on SRI experiments and trials from peer reviewed and non-peer reviewed publications, reports and conference proceedings (n = 72, Table 1). Only data that fulfilled the following criteria were retained for analysis: (1) the SRI treatment used intermittent flooding and drying and an early planting date (rice seedlings were less than 15 days old at transplanting), whereas the conventional treatment had continuously flooded soils and a later planting date (seedlings were more than 20 days old at transplanting); (2) the SRI and conventional treatments were grown in the same season and the same location; and (3) each treatment was replicated at least three times during the study. In total, 81 SRI–Conventional system comparisons were collected; 72 were included and 9 were not included because they did not meet the criteria outlined above. Of the 40 data points used in the previous analysis by Macdonald et al. (2006), 29 were included and 11 were not included because they did not meet the previously stated criteria (n=5) or they were cited as personal communication. Treatment means (Table 1) were the average yield of each rice variety when replicated plots existed at a single site. In studies testing several varieties, values in Table 1 represent the average yield of all varieties grown at a site or the average yield of varieties grown on multiple farms in the same farming area. I chose to include studies that had not been peer-reviewed since there were only six peer reviewed studies available at the time (Latif et al., 2005; Sheehy et al., 2004; Sinha and Talati, 2007; Thakur et al., 2009; Vijayakumar et al., 2005 ; Zhao et al., 2009). So far, SRI has been mainly a grass-roots agricultural movement and there have been only a limited number of studies at major research institutions; most of the existing reports on SRI therefore come from local non-governmental and agricultural organizations. Given the stringent criteria for the inclusion of data in this analysis, I feel that the data set is strengthened by including non-peer reviewed sources, which allows us to examine the effects of SRI on rice yield over a broader range of geographic regions and soil types.

Most studies did not provide information on soil properties, so the soil type at each site was determined by entering the latitude and longitude into the ISRIC-WISE global dataset of derived soil properties on a 0.5 x 0.5 degree grid using ARC-GIS software. Soils were then grouped on the basis of their fertility and potential for rice production (Driessen et al., 2001; Sanchez, 1976). Low fertility soils were highly weathered soils rich in iron and aluminum oxides, namely Acrisols, Ferralsols and Dystric Cambisols. The moderate fertility soils (Andisols, Luvisols, Regisols, Vertisols and Cambisols) were moderately weathered soils with a greater potential for agricultural production. Young alluvial soils and soils considered ideal for rice production (Fluvisols and Gleysols) were classified as having high fertility. While there is some uncertainty associated with using this general system of soil identification and grouping, we consider it a necessary tradeoff in taking the first step to examine the relationship between soil fertility and yield response to SRI at the global scale using the currently existing data. The soil types determined by the ISRIC map were compared to the soils information available from 22 field studies to validate the accuracy of the predicted soil types (Bangladesh Rice Research Institute (BRRI), 2000; Barison, 2003; Gypmantasiri, 2002; Latif et al., 2005; M S Swaminathan Research Foundation (MSSRF), 2002; Nissanka and Bandara, 2004; Randriamiharisoa and Uphoff, 2002; Shengfu et al., 2002; Vijayakumar et al., 2005).

The effect size of SRI management was calculated as the natural logarithm of the response ratio (lnRR) of SRI yield to conventional yield:

$$\ln RR = \ln(X/Y)$$

where X is the yield under SRI management and Y is the yield under conventional management (Hedges et al., 1999). The response ratio is commonly used to describe the effect size in meta-analyses testing the response of a treatment. The effect size, expressed as the lnRR, was positive when SRI produced greater rice yield than the conventional system and negative when there was lower yield in SRI than the conventional system. The lnRR is appropriate for meta-analysis because it provides a dimensionless measure of effect sizes that can be used to compare among studies (Hedges et al., 1999). The normality of the data was confirmed by examining Q-Q plots and using the Shapiro-Wilk test ($\alpha < 0.5$). Simple statistics (mean and t-test) were used to describe the performance of SRI relative the conventional system in countries with more than two data points. The effect of soil fertility (low, moderate and high) on the lnRR was evaluated using the ANOVA procedure of SPSS statistical software (SPSS version 15.0, Chicago, IL). The model (lnRR = soil fertility group) indicated a significant ($P<0.05$) effect of soil fertility, so a post hoc mean separation test was performed (Least Significant Difference (LSD), $\alpha = 0.5$).

2.4. Results and Discussion

The results of 72 field trials comparing SRI and conventional rice production systems are summarized in Table 1. Overall, the mean lnRR was 0.20 and the 95% confidence interval ranged from 0.11 and 0.29, indicating that SRI had a positive effect on rice yields. Yield responses were grouped by country to determine if there were regions outside of Madagascar where SRI may have a positive effect on yield. The lnRR ranged from −0.54 in the Philippines to 1.11 in Myanmar (Fig. 1). The lnRR in Indonesia, India and Madagascar were significantly greater than zero, indicating a yield benefit from SRI compared to the conventional system (Fig.1). Other countries with positive lnRR values were Iraq, Sri Lanka, Iran, Nigeria, Gambia and Myanmar (Fig. 1). The lnRR in studies from Thailand, Laos, China and Bangladesh did not differ significantly from zero, indicating no detectable difference in rice yield between SRI and conventional systems in these countries (Fig. 1).

A previous meta-analysis of 40 SRI trials concluded that SRI had no significant positive effect on yields in countries other than Madagascar (McDonald et al., 2006). The current study presents meta-analysis of a larger data set (72 SRI trials) and demonstrates that there are countries other than Madagascar, namely India and Indonesia, where SRI has a significant, positive effect on rice yield. However, there is no significant negative effect of SRI on yield in most other countries (Fig. 1). Both Thailand and the Philippines had mean lnRRs < 0, although the means were not significantly difference from zero (P=0.083, df= 4 and P=0.263, df =1 respectively; t-test) (Fig. 1). These results suggest that the introduction of SRI could increase or maintain rice yields over a broad range of geographic and climatic conditions.

Next I assessed whether the regional variability found in the yield response to SRI could be explained by soil fertility. The soil type predicted by the ISRIC soil map agreed with soil information available in 22 of the reports. Of the 72 studies, only 15 provided soil texture information and seven provided soil pH. Soils with low pH (≤5) had been classified as low fertility Acrisols and neutral pH (≥6) clay soils had been classified as Gleysols by the ISRIC soils map. The mean rice yields in SRI were 5.8, 7.0 and 7.7 t ha^{-1} in low, moderate and high fertility soils, respectively. In the conventional systems, rice yields were on average 4.3, 6.1 and 7.4 t ha^{-1} in the low, moderate and high fertility soils (Table 1). The rice yields therefore agreed with the soil fertility groupings, because lower yields were found in the low fertility soils, higher yields were found in the moderate fertility soils and the highest yields in the high fertility soils.

The LnRRs were highly variable among soil types, likely due to the wide range of climatic conditions associated with studies included in the meta-analysis. When grouped by soil fertility, the mean LnRR of the high fertility soils (n=19) was −0.014 with the 95% confidence interval ranging from −0.07 to 0.10 (Fig. 2). In the moderate fertility soils (n=17), the mean LnRR was 0.18 and the 95% confidence intervals were −0.04 and 0.40 (Fig. 2). The mean LnRR of the low fertility soils (n=36) was 0.31 and the 95% confidence intervals were 0.16 and

0.45. There ANOVA showed that there was a significant effect of soil fertility on lnRR (*P*=0.026). Low and high fertility soils were significantly different (LSD, *P*=0.007), whereas the moderate fertility soils were not different from the low (LSD, *P*=0.114) and high (LSD, *P*=0.330) fertility soils. The mean lnRR of the low fertility soils was significantly different from zero (t-test, df=35, *P*<0.0001) whereas the mean lnRR of the medium and high fertility soils were not significantly different from zero (t-test, df=16, *P*=0.096 and df=18, *P*=0.745, respectively). Data from peer-reviewed sources (n=8) followed a similar trend as the complete data set. The average LnRR of the high fertility soil group (n=4) was 0.02 whereas the average LnRR of the low fertility soil group (n=3) was 0.29. These results show that SRI has a positive effect on rice yields in low fertility soils, but no measurable effect on yields in moderate to high fertility soils. The adoption of SRI implies greater use of organic fertilizers than in conventional systems, so SRI could be viewed as a low input alternative with the potential to improve yields on low fertility soils while maintaining yields and conserving resources on moderate to high fertility soils.

Global rice yields must increase by 50% in the next 20 years to meet the projected demand of the world's growing population (Food and Agriculture Organization, 2006). Much of the increased demand will occur in areas with low fertility soils, such as the highly weathered Acrisols and Ferralsols that are found in about two-thirds of the world's humid tropics (Olaleye et al., 2001). By examining a larger number of field trials than considered previously (McDonald et al., 2006), we demonstrate that SRI increases rice yields in regions other than Madagascar, namely in areas of Indonesia and India, where rice is the staple food.

In most other countries, there is generally no yield loss in SRI compared to the conventional system. Furthermore, differences in soil fertility and potential for rice production can explain in part the regional variability in yield response to SRI. We found that SRI increases rice yields on low fertility soils, and has no effect on yields in moderate to high fertility soils where yields are already high (about 7–10 t ha^{-1}). This agrees with the ideas outline in critical assessment of SRI by Dobermann (2004). In the context of augmenting food security while preserving natural resources, we suggest that SRI has the greatest potential to increase rice production on marginal soils, and thus could be an appropriate low-input technology for resource-poor farmers. Also, in areas where water is limited, the adoption of SRI may conserve water without sacrificing yields.

The mechanisms involved in the yield improvements with SRI on low fertility soils remain poorly understood. Low base cations is a key criterion in the classification of Acrisols and Ferralsols, and strongly-weathered soils tend to be extremely low in available forms of P (Tiessen, 1998; Walker and Syers, 1976). Here I posit four possible mechanisms whereby SRI modifies soil properties in a manner to increase rice yields on low fertility soils: (1) aerobic conditions increase microbial activity, rates of organic fertilizer decomposition, organic P turnover and P availability in low P soils (Nziguheba et al., 1998; Oberson et al., 2001; Turner and Haygarth, 2001; Turner et al., 2006); (2) aerobic conditions favour root growth and increase nutrient acquisition by organically fertilized rice (Barison, 2003; Dobermann, 2004; Stoop et al., 2002); (3) wetting-drying cycles create aerobic conditions that reduce accumulation of toxic $Fe^{2+}$and Mn^{2+} (Olaleye et al., 2001); and (4) Low potential soils may have high drainage or permeability making them unsuitable for flooding. Further research on the chemical and biological mechanisms involved in yield improvements with SRI on low fertility soils is required to provide a scientific basis for agronomic recommendations and predictions of the long-term sustainability of this novel rice production system.

2.5. Conclusion

There is significant evidence that (1) SRI increases rice yields in regions other than Madagascar and (2) SRI increases rice yields on low fertility soils and has no effect on yields in moderate to high fertility soils. The results of this meta-data analysis should be considered as preliminary and replicated field trials with detailed soil fertility data are needed to improve our confidence in the yield differences between SRI and conventional rice production systems. The biological and chemical mechanisms that lead to increased rice yields on these low fertility soils remain to be elucidated. Although the scientific debate over SRI continues, more than a million farmers around the world have now adopted the system (CIIFAD, 2010). I suggest that the minimum data set to be provided by future field studies comparing the SRI and conventional system should include data on soil fertility class, texture, pH, macronutrient availability, fertilizer use, and standard deviation of the mean yield value.

Acknowledgements

We thank individuals who provided data for the meta-analysis, Rosa Orlandini and Joanna Hobbins (Walter Hitschfeld Geographic Information Centre) for their help with GIS, Rick Condit (STRI) for statistical advice, and anonymous reviewers for comments on the manuscript. Financial support for this work was from the Natural Sciences and Engineering Research Council of Canada.

Table 1. Soil types, soil fertility group and rice yields from field experiments where SRI was evaluated against the conventional method. The yield difference was calculated as SRI Yield – Conventional Yield and the natural logarithm of the response ratio (lnRR) was ln(SRI Yield/Conventional Yield).

Location	Source	Soil Type (FAO)	Soil Fertility Group	SRI Yield t ha^{-1}	Conventional Yield	Yield Difference	lnRR
Madagascar (Anjomakely)	(Randriamiharisoa and Uphoff, 2002)	Ferralic Cambisol	Low	10.4	3.0	7.4	1.24
Madagascar (Anjomakely)	(Randriamiharisoa and Uphoff, 2002)	Ferralic Cambisol	Low	6.4	2.0	4.4	1.14
Myanmar (Kachin)	(Kabir, 2006)	Orthic Acrisol	Low	6.4	2.1	4.3	1.11
Gambia (Sapu)	(Ceesay, 2002)	Gleyic Luvisol	Moderate	5.3	1.8	3.5	1.07
Madagascar (Morondova)	(Randriamiharisoa and Uphoff, 2002)	Ferralic Cambisol	Low	6.0	2.1	3.9	1.04
Madagascar (Morondova)	(Randriamiharisoa and Uphoff, 2002)	Ferralic Cambisol	Low	6.8	2.8	4.0	0.88
Nigeria (Sabongida)	(Khalifa, 2006)	Eutric Regosol	Moderate	5.8	2.9	2.9	0.69
Indonesia (Central Sulawesi)	(Sato, 2006)	Orthic Acrisol	Low	7.1	3.8	3.3	0.62
India (Uttarakahan)	(The Peoples Science Institute, 2007)	Dystric Cambisol	Low	5.2	2.8	2.4	0.62
Indonesia (South Sulawesi)	(Sato, 2006)	Orthic Luvisol	Low	7.8	4.3	3.5	0.61
India (Hamchal Pradesh)	(The Peoples Science Institute, 2007)	Dystric Cambisol	Low	5.3	2.9	2.4	0.60
Indonesia (Nusa Tengarra)	(Sato, 2006)	Orthic Acrisol	Low	6.6	3.6	3.0	0.60
Iran (Mazandaran)	(Larijani, 2007)	Calcic Cambisols	Moderate	8.8	5.6	3.2	0.45
Indonesia (Sukamandi)	(Gani et al., 2002)	Orthic Acrisol	Low	7.5	4.9	2.6	0.43
Indonesia (West Sumatra)	(Gani et al., 2002)	Dystric Fluvisol	Low	5.3	3.5	1.8	0.41
India (Balrampur)	(Sinha and Talati, 2007)	Dystric Cambisol	Low	6.3	4.2	2.1	0.40
Indonesia (Sukamandi)	(Gani et al., 2002)	Orthic Acrisol	Low	6.9	4.7	2.2	0.38
India (Orissa)	(Thakur et al., 2009)	Orthic Acrisol	Low	6.4	4.5	1.9	0.35
Indonesia (Sukamandi)	(Gani et al., 2002)	Orthic Acrisol	Low	7.7	5.5	2.2	0.33
China (Hangzhou)	(Zhao et al., 2009)	Eutric Gleysol	High	7.08	5.11	2.0	0.33
Indonesia (West Nusa Tenggara)	(Gani et al., 2002)	Vertic Luvisol	Moderate	5.9	4.3	1.6	0.32
Indonesia (Sukamandi)	(Gani et al., 2002)	Orthic Acrisol	Low	7.7	5.7	2.0	0.30
Indonesia (Sukamandi)	(Gani et al., 2002)	Orthic Acrisol	Low	8.3	6.4	1.9	0.26
Bangladesh (Burichang)	(Das, 2003)	Eutric Gleysol	High	7.0	5.4	1.6	0.26
Indonesia (Sukamandi)	(Gani et al., 2002)	Orthic Acrisol	Low	8.4	6.5	1.9	0.25
Indonesia (Sukamandi)	(Gani et al., 2002)	Orthic Acrisol	Low	8.4	6.5	1.9	0.25
Madagascar (Beforona)	(Barison, 2003)	Xanthic Ferralsol	Low	6.3	4.9	1.3	0.24
Indonesia (Bali)	(Gani et al., 2002)	Ochric Andosol	Moderate	7.3	5.7	1.6	0.24
Indonesia (West Nusa Tenggara)	(Gani et al., 2002)	Vertic Luvisol	Moderate	7.1	5.7	1.4	0.22
Indonesia (West Sumatra)	(Gani et al., 2002)	Dystric Fluvisol	Low	4.7	3.8	0.9	0.21
Indonesia (South Sulawesi)	(Gani et al., 2002)	Vertic Luvisol	Moderate	8.0	6.5	1.5	0.21
India (Coimbatore)	(Vijayakumar et al., 2005)	Pellic Vertisol	Moderate	7.0	5.7	1.3	0.20
Laos (Pakcheng)	(Schiller, 2004)	Orthic Acrisol	Low	5.6	4.6	1.0	0.20
Indonesia (East Java)	(Gani et al., 2002)	Vitric Andosol	Moderate	8.9	7.4	1.6	0.19
Indonesia (North Sumatra)	(Gani et al., 2002)	Dystric Fluvisol	Low	6.1	5.0	1.1	0.19
Bangladesh (Comilla)	(Bangladesh Rice Research Institute (BRRI), 2000)	Eutric Gleysol	High	5.3	4.4	0.9	0.19
India (Pondicherry)	(M S Swaminathan Research Foundation (MSSRF), 2002)	Dystric Regosol	Low	6.4	5.4	1.0	0.18
China (Yantze River)	(Shengfu et al., 2002)	Eutric Gleysol	High	12.2	10.2	2.0	0.17

Table 1. (continued).

Location	Source	Soil Type (FAO)	Soil Fertility Group	SRI Yield t ha^{-1}	Conventional. Yield t ha^{-1}	Yield Difference	lnRR
Indonesia (Central Java)	(Gani et al., 2002)	Mollic Andosol	Moderate	7	5.9	1.1	0.16
Laos (Vientiane)	(Schiller, 2004)	Gleyic Acrisol	Low	7.5	6.5	1	0.15
Indonesia (West Nusa Tenggara)	(Gani et al., 2002)	Eutric Fluvisol	High	7.4	6.5	0.9	0.13
Bangladesh (Debidwar)	(Das, 2003)	Eutric Gleysol	High	7	6.2	0.9	0.13
Thailand (Chiang Mai)	(Gypmantasiri, 2002)	Orthic Acrisol	Low	2.3	2.1	0.3	0.11
Indonesia (South Sulawesi)	(Gani et al., 2002)	Orthic Luvisol	Moderate	6.5	5.8	0.7	0.11
India (Jhalda)	(Sinha and Talati, 2007)	Ferric Luvisol	Low	4.2	3.8	0.4	0.11
Sri Lanka (Hinguraggoda)	(Nissanka and Bandara, 2004)	Chromic Luvisol	Moderate	7.6	6.9	0.7	0.10
Laos (Phonengam)	(Schiller, 2004)	Gleyic Acrisol	High	3.6	3.3	0.3	0.09
China (Jiangsu)	(Shao-hua et al., 2002)	Calcaric Gleysol	High	9.9	9.1	0.8	0.08
Iraq (Najaf)	(Hameed and Jaber, 2007)	Calcaric Fluvisol	High	5.5	5.1	0.3	0.07
Indonesia (Central Java)	(Gani et al., 2002)	Pellic Vertisol	Moderate	8.0	7.6	0.4	0.05
China (Jiangsu)	(Shao-hua et al., 2002)	Eutric Gleysol	High	9.3	9.1	0.3	0.03
China (Nanjing)	(Shao-hua et al., 2002)	Eutric Gleysol	High	11.7	11.5	0.3	0.02
Indonesia (West Java)	(Gani et al., 2002)	Dystric Nitosol	Low	5.5	5.4	0.1	0.02
China (Guangdong)	(Sheehy et al., 2004)	Eutric Gleysol	High	7.2	7.2	−0.1	−0.01
China (Nanjing)	(Shao-hua et al., 2002)	Eutric Gleysol	High	7.8	8.3	−0.5	−0.06
Nepal (Bhairahawa)	(Evans et al., 2002)	Dystric Regosol	Low	5.4	5.7	−0.3	−0.06
China (Jiangyin)	(Shao-hua et al., 2002)	Eutric Gleysol	High	8.4	8.9	−0.5	−0.06
Bangladesh (Comilla)	(Latif et al., 2005)	Eutric Gleysol	High	7.1	7.6	−0.5	−0.07
China (Nanjing)	(Shao-hua et al., 2002)	Eutric Gleysol	High	9.8	10.6	−0.7	−0.07
Ivory Coast (M'be)	(Stoop, 2002)	Ferric Acrisols	Low	3.7	4.0	−0.3	−0.08
China (Hunan)	(Sheehy et al., 2004)	Eutric Gleysol	High	6.7	7.4	−0.7	−0.10
Thailand (Chiang Mai)	(Gypmantasiri, 2002)	Orthic Acrisol	Low	4.4	4.8	−0.5	−0.10
Bangladesh (Vangurapara)	(Latif et al., 2005)	Eutric Gleysol	High	6.0	6.8	−0.8	−0.12
Laos (Vientiane)	(Schiller, 2004)	Gleyic Acrisol	Low	4.1	4.7	−0.6	−0.14
Bangladesh (Matiara)	(Latif et al., 2005)	Eutric Gleysol	High	5.9	7.0	−1.1	−0.17
Philippines (Los Banos)	(Rickman, 2002)	Orthic Luvisol	Moderate	3.0	4.1	−1.1	−0.30
Laos (Savannakhet)	(Schiller, 2004)	Ferric Acrisol	Low	3.9	5.7	−1.8	−0.38
Indonesia (East Java)	(Gani et al., 2002)	Vitric Andosol	Moderate	8.0	12.5	−4.5	−0.45
Thailand (Chiang Mai)	(Gypmantasiri, 2002)	Orthic Acrisol	Low	2.6	4.2	−1.6	−0.47
Thailand (Mae Taeng)	(Gypmantasiri, 2002)	Orthic Acrisol	Low	3.2	5.1	−2.0	−0.48
Thailand (San Sai)	(Gypmantasiri, 2002)	Eutric Fluvisol	High	3.3	5.4	−2.1	−0.48
Philippines (Los Banos)	(Rickman, 2002)	Orthic Luvisol	Moderate	1.4	3.1	−1.7	−0.77
		Mean		6.5	5.5	1.1	0.20
		Standard Error		0.2	0.3	0.2	0.05

Figure 1. The natural logarithm response ratio (lnRR) of rice yield in SRI and conventional systems grouped by country. The mean lnRR and standard error are shown for countries with more than 2 data points. A reference line is shown at zero (——) and the mean lnRR of the complete data set (- - -) (n=72) and its 95% confidence intervals (·········) are show. The significance of each mean from zero is shown (t-test; *, α < 0.05; ** α < 0.001; ns, not significant).

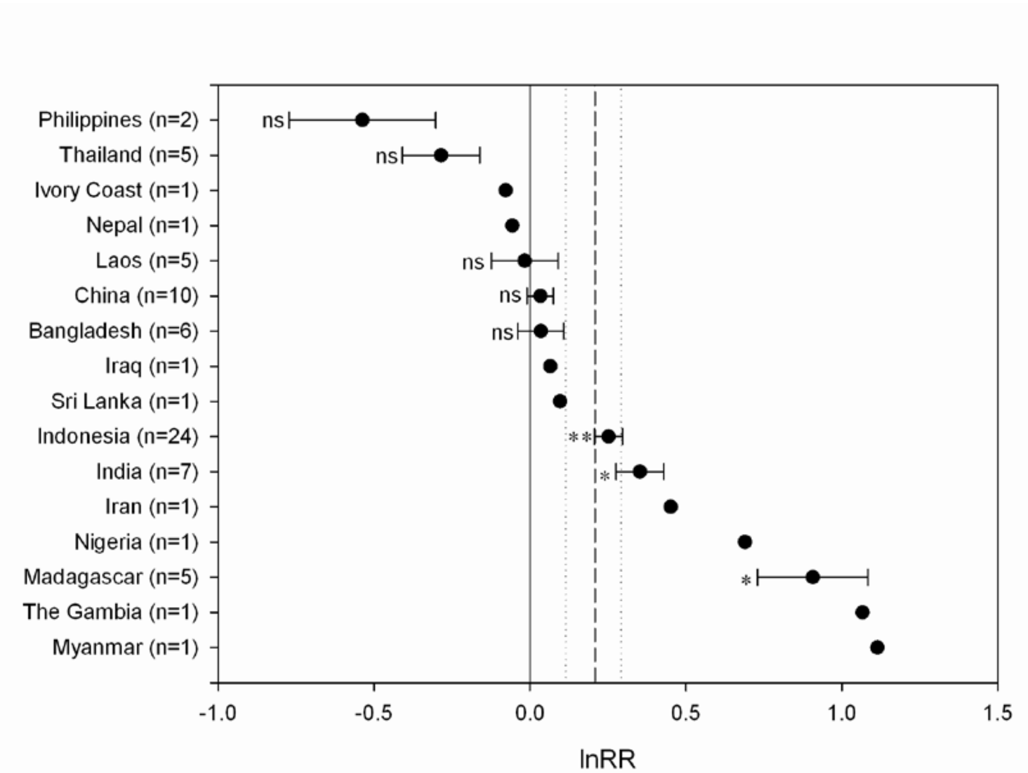
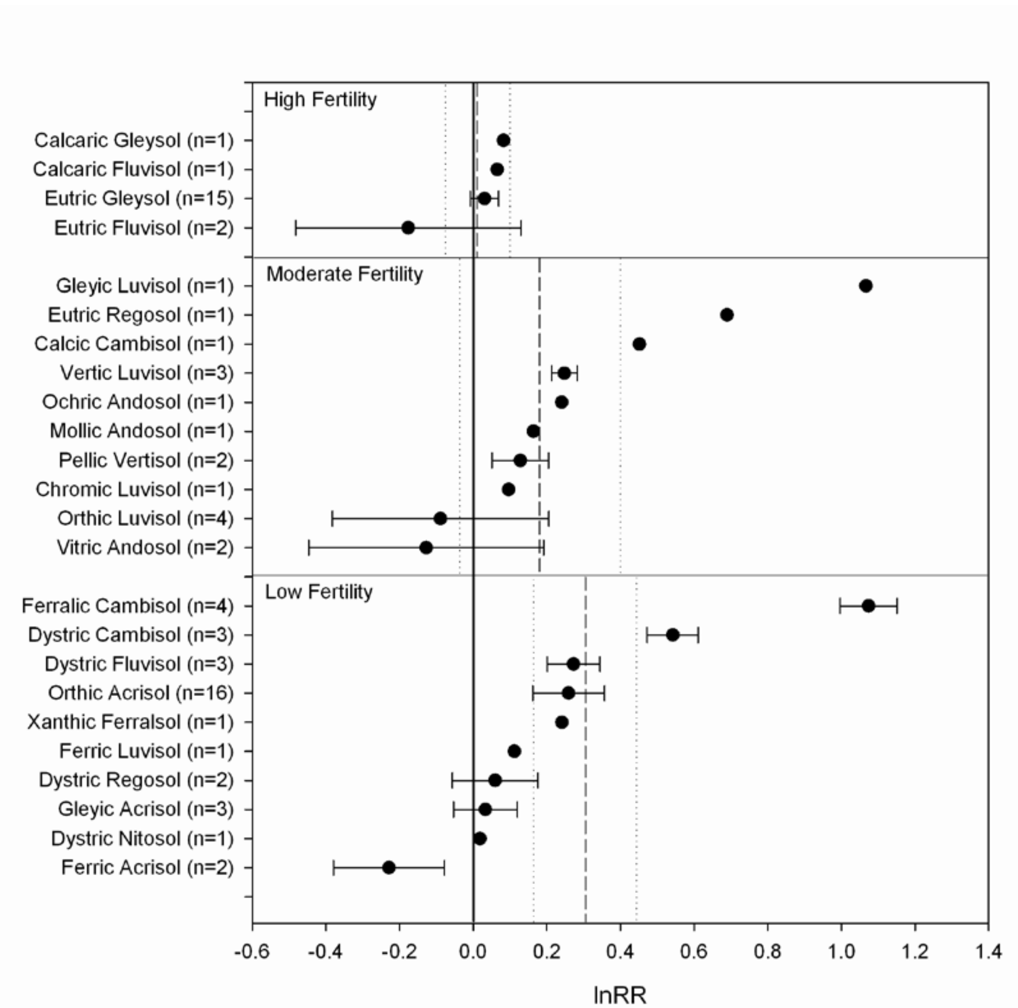


Figure 2. The natural logarithm response ratio (lnRR) of rice yield in SRI and conventional systems. Values are the mean and standard error for each soil type. Soils were assigned to fertility groups, namely high (n=19), moderate (n=17) and low (n=36) fertility. A reference line is shown at zero (——) and mean lnRR (· · ·) and 95% confidence intervals (········) are shown for each soil fertility group.



Connecting Paragraph to Chapter 3

In Chapter 2, a meta-data analysis of previous SRI vs. conventional system trials to showed that SRI significantly increases rice yield on low-fertility soils and has no effect on yields in moderate to high fertility soils. The analysis was conducted using a world-wide data set and a general system of soil identification and grouping, and was considered a first step to examine the relationship between soil fertility and yield response to SRI at the global scale. The next step was to validate these results in a greenhouse study to determine the biological and chemical mechanisms involved in the soil dependant yield response to SRI and identify directions for future research.

Chapter 3. The effect of water regime and fertilizer source on phosphorus availability for rice production in tropical soils of Panama: A greenhouse study

3.1. Abstract

Rice production in developing countries is constrained by variable rainfall, low inherent soil fertility, and the rising cost of agricultural inputs. Rice production systems, such as the System of Rice Intensification, that use intermittent flooding and some organic fertilizer may be a viable alternative to conventional rice production systems that use continuous flooding and mineral fertilizer only. Soil properties, particularly P availability, are expected to control rice production in highly weathered soils. My objective was to determine how water regime and fertilizer source influence the plant-soil nutrient dynamics in the organically fertilized aerobic systems (AO), based on SRI soil management, compared to systems that use continuous flooding and only mineral fertilizer (CM) in a wide range of tropical soils. This was investigated in a greenhouse study with six Panamanian soils ranging in texture from sandy loam to clay and having Mehlich-3 extractable P (M3P) concentrations between 3.2 and 30.8 mg M3P kg^{-1} (low-P to medium-P fertility). Rice plants were grown for 50 days and aboveground and belowground biomass, plant nutrient uptake, soil nutrient availability, microbial P and soil enzymes activities were measured. A significant (P<0.05) correlation between M3P and rice biomass in the AO system indicated the importance of plant-available P for rice growth. Ultisols and Inceptisols with ≤ 7.1 mg M3P kg^{-1} showed greater rice biomass, plant P uptake and an increase in M3P concentration

and microbial P when managed as an AO system, compared to the CM system. In soils with higher M3P concentrations (Gleysols, Mollisols and Andisols), rice biomass was greater in the CM than the AO system. In conclusion, the AO system is recommended for augmenting rice P nutrition on highly-weathered soils with low-P fertility.

3.2. Introduction

Rice production in the developing countries is constrained by variable rainfall, the rising cost of agricultural inputs, and low inherent soil fertility (Stocking, 2003). In Panama, resource-poor farmers are concentrated in areas with highly-weathered soils, mostly Ultisols, Alfisols and weathered Inceptisols, having low inherent fertility and high P fixing Fe and Al oxides. Such soils are dominated by low activity clays (kaolinite) and have low soil organic carbon and associated nutrients (N, P and S). Thus, P availability is a major constraint to rice production on highly-weathered soils in Panama (Namé and Villarreal, 2004a). Furthermore, resource-limited farmers in Panama rely on locally produced amendments such as chicken manure and household composts for P and other essential plant nutrients. Thus, low-input agricultural solutions that are accessible to resource-limited farmers and productive on low-fertility soils are required to ensure stable, locally produced rice supplies in Panama (IAASTD, 2008).

The System of Rice Intensification is an emerging system to improve rice production on highly-weathered tropical soils. The SRI is characterized by early transplanting, wide row spacing, organic fertilizer use and intermittent flooding, and was found to increase yields in some studies (Barison, 2003; Sheehy et al., 2004; Sinha and Talati, 2007). A meta-analysis of 72 experiments from 16 countries comparing SRI to the conventional system (continuous flooding and mineral fertilizer) found that SRI increased yields in low-fertility soils, whereas yields were similar in SRI and the conventional system on moderate and high fertility soils (Turmel et al., 2011). Results from Panamanian on-farm trials with highly-weathered soils found that rice yields were 47% higher with SRI than the conventional system (Turmel et al., 2010). The mechanism for improved crop growth and yield with SRI in highly weathered soils remains unclear. Given that P is generally the limiting nutrient to crop production on highly-weathered soils, the soil management aspects of SRI may improve crop growth by increasing soil P availability in highly-weathered soils.

In highly-weathered soils, organic fertilizer can be more effective than mineral phosphate fertilizer at increasing soil P availability. This is because P is cycled through the microbial biomass, preventing Fe and Al fixation by maintaining nutrients in a biologically available form (Nziguheba et al., 1998). The microbial biomass acts as a reservoir of nutrients that can be released for plant uptake (Singh et al., 1989; Turner et al., 2006). In SRI, the use of organic fertilizer, in combination with soil aeration, could potentially increase the microbial biomass P and the rate of organic P turnover compared to flooded conditions and in turn P availability to crops (Randriamiharisoa et al., 2006; Song et al., 2007; Turner and Haygarth, 2001)

There are also several mechanisms by which flooding influences soil P availability. Phosphorus uptake can be improved by flooding due to a decrease in tortuosity, which increases P diffusion to the roots and the reductive dissolution of Fe oxides under anaerobic conditions (Huguenin-Elie et al., 2003). However, in highly weathered soils with low P saturation of amorphous Fe oxides, flooding has been shown to increase the soil's P sorption capacity. When these soils are flooded, there is an initial increase in soluble inorganic P and organic P due to the reductive dissolution of ferric oxides (Shahandeh et al., 1994; Zhang et al., 2003). If reducing conditions continue, crystalline Fe (dithionite extractable Fe) is converted to amorphous Fe (oxalate extractable, Fe-ox) resulting in an increase in soil P sorption capacity compared to soils that were not flooded. Non-oxalate extractable Fe compounds, such as viviante, can also be formed, severely reducing P desorption. The amount of P that becomes available after soil flooding is correlated to the ratio of amorphous Fe bound P to amorphous Fe (P-ox/Fe-ox) (Zhang et al., 2003). Thus in soils with a low P-ox/Fe-ox ratio, the negative consequences of flooding, may out weigh the improved P availability to the roots due to diffusion effects (Zhang et al., 2003).

As a first step, a greenhouse experiment to evaluate the effects of farming systems on soil P availability for rice production was conducted because a number of soils could be tested simultaneously under controlled environmental conditions. The objective of this research was to determine if an organically fertilized system with intermittent flooding (AO) could increase soil P availability and plant P nutrition compared to a system that uses mineral fertilizer and continuous flooding (CM). I also aimed to determine if there were soil-specific responses to the two systems in terms of nutrient availability and plant growth. The two systems were compared in a greenhouse study with six soils from rice-growing regions of Panama having low, medium and high fertility and varying widely in M3P and Fe-oxide concentrations. I hypothesized that rice biomass will be greater in the AO system in the low fertility soils because intermittent flooding and organic fertilizer will increase the M3P concentration, which will enhance plant P uptake. In the moderate to high fertility soils, where available P was not the major growth limiting nutrient, rice biomass will be greater in the CM system or similar between the two systems.

3.3. Methods

3.3.1. Soil collection

Soil (0-20 cm depth) was collected from 6 locations in the rice growing regions of Panama. Details about these locations, including previous land use, elevation and precipitation are given in Table 1. I identified low fertility soils (Calabacito, Bella Vista) as being a highly weathered Inceptisol and Ultisol with < 5 mg M3P kg^{-1}. The moderate fertility soils were a moderately weathered Inceptisol (El Coco) and an Andisol (Alanje) with high Al content and 5 – 20 mg M3P kg^{-1}. The high fertility soils were Inceptisols with a low weathering status (Tocumen and Rio Hato) and had >20mg M3P kg^{-1}. Other soil physico-chemical properties are provided in Table 2.

3.3.2. Experimental set-up

The study used a randomized factorial design with two factors: soil (six different Panamanian soils) and system (AO and CM). The AO system was based on SRI management and used intermittent flooded and some organic fertilizer and the CM system was modelled after the conventional system that uses continuous flooding and mineral fertilizer only. Each treatment was replicated four times and there were 48 experiment units in total.

The experimental unit was a plastic pot (33 cm diameter, 65 cm tall) fitted with a tap at the bottom to control water drainage. The bottom of each pot was filled with 0.5 L of sand and 0.5 L of gravel, which was then covered with a water permeable geotextile to facilitate drainage. Each pot was filled with a depth of soil of approximately 26 cm with 22 L of soil (air-dried and sieved through 4 mm mesh prior to use). Fertilizer was mixed with soil prior to flooding. Pots with the CM treatment were fertilized according to IRRI recommendations for conventional irrigated rice production (Dobermann and Fairhurst, 2000). In the AO treatment, 50% of the P requirements were supplied by air dried composted cow manure (14.7 g total N kg^{-1}, 5.4 total P kg^{-1} and 20.0 g total K kg^{-1}) ground to pass through a 1 cm^2 sieve and the remaining NPK requirements were met with mineral fertilizer (ammonium nitrate, triple super phosphate and potassium chloride). In this manner, both treatments received equal inputs of macronutrients.

Pots were irrigated two weeks before transplanting. Pots with the CM treatment were flooded with 10 L of water so that they had 3-5cm of standing water on the soil surface and AO pots were watered with 5 L. The taps on the CM pots were closed to maintain flooded conditions and the taps on the AO were open to allow drainage. All pots received approximately 0.5 L of water daily to maintain soil moisture near field capacity (approximately 80-100% water holding capacity) in the AO treatment and a layer of water 3-5cm deep in the CM treatment.

Rice (*Oryza sativa* var. IDIAP 38) seed was sown in a transplant tray with pre-fertilized potting soil. Seedlings were transplanted singly into each pot at 10 d after emergence. At the time of transplanting, seedlings were at the three-leaf stage. Plants were grown in a greenhouse with plastic covering that had approximately 85% light transmittance and an average daily temperature of 26°C.

3.3.3. Soil Analysis

A soil subsample was collected from each pot at 0, 20 and 35 d after transplanting using a 1.5cm diameter soil probe inserted to a depth of 15 cm. Soil samples were analysed for available nutrients (Al, Cu, Fe, K, Mn, N, P and Zn) and pH (1:2 soil:deionized water slurries). Soil NO_3 and NH_4 were extracted, immediately after sampling from moist soil with 2 M KCl (1:5 dry soil:solution) and analyzed colorimetrically with a QuickChem 8500 (Hatch Ltd. Loveland, CO, USA). Available Al, Cu, Fe, K, Mn, P and Zn were extracted from air-dry soil with Mehlich-3 solution (1:10 dry soil:solution) and extracts were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES 2100, PerkinElmer, Waltham, MA, USA). Moist soil from each pot was also analyzed for microbial P by the hexanol fumigation method using anion exchange resin strips (Turner and Romero, 2010). Soil phosphatase and β-glucosidase activity were assayed on moist soil using 4-methylumbelliferone-linked fluorogenic substrates in acetate buffer with fluorometric detection (Turner and Romero, 2010).

3.3.4. Plant Sampling and Tissue Analysis

Plant samples were collected at the mid-tillering stage. Aboveground samples were the shoots, cut with scissors at the soil surface, and belowground samples were roots, separated from the soil in each pot by washing over a 1 cm^2 mesh screen. Plant samples were washed with deionized water, dried at 60°C for 48 h and then weighed. Samples were then ground with a mechanical grinder to pass a 2 mm mesh screen. Samples were digested in H_2SO_4 and 30% H_2O_2 solution with $LiSO_4$ and Se catalyst (Parkinson and Allen, 1975). Extracts were analysed for Cu, Fe, K, and Zn using atomic absorption spectroscopy (Perkin-Elmer model 2380, Waltham, MA, USA) and for N and P colorometrically using the Lachat Instruments QuickChem Method 13-115-01-1-B for Phosphorus and Method 13-107-06-2-A for Total N (Hach Ltd. Loveland, CO). Tissue S was analysed by combustion using a Thermo-Finnigan Flash 1112 elemental analyzer with a thermal conductivity detector (Thermo Fischer Scientific, Waltham, MA). The nutrient concentrations in tissue (mg kg^{-1} tissue) at mid-tillering were compared to the critical nutrient concentration at which a yield reduction of 5-10% is generally observed (Dobermann and Fairhurst, 2000). The response ratio (lnRR) of the AO biomass compared to the CM biomass calculated as ln(AO biomass / CM biomass).

3.3.5. Diagnosis and Recommendation Integrated System (DRIS) Analysis

The nutrient balance in rice shoots was further examined with the DRIS model, which calculates nutrient deficiencies based on crop-specific ideal nutrient ratios (Ramakrishna et al., 2009). The DRIS norms for rice were used to compute the DRIS indices for N, P, K and S (Counce and Wells, 1986). DRIS indices were calculated with Excel software using the equations of Walworth and Sumner (1988). Considering the analysis contains nutrient A through N:

$$\text{A index} = \frac{f(A/B) + f(A/C) + f(A/D + ... + f(A/N)}{n}$$

B index $= \dfrac{-f(A/B)+f(B/C)+f(B/D+...+f(B/N)}{n}$

N index $= \dfrac{-f(A/N)-f(B/N)+f(N/C)+...+f(N/M)}{n}$

where *A/B* is the ratio of the concentrations of nutrient A and B in the plant tissue, n is the number of nutrients and *f (A/B)* is the function of the form:

$$f(A/B)=\left(\frac{A/B}{a/b}-1\right)\frac{1000}{CV} \text{ where } A/B \geq a/b \text{ or}$$

$$f(A/B)=\left(1-\frac{a/b}{A/B}\right)\frac{1000}{CV} \text{ where } A/B < a/b$$

where a/b is the crop specific DRIS normal ratio and CV is the coefficient of variation associated with that normal ratio. Nutrients that are in balance will have DRIS indices close to zero and those are deficient or in excess, compared to other nutrients, will have negative and positive values, respectively.

3.3.6. Statistical Analyses

All soil and plant nutrient data were tested for normality using the Shapiro-Wilk test and homogeneity of variances using likelihood ratio by modelling variances with the Satterthwaite adjustment. Data were normalized using a log transformation if necessary. The effect of soil (six soils), system (AO and CM) and system*soil interactions on soil available nutrients, plant biomass and plant nutrient concentrations was analysed using the Proc Mixed function of SAS (SAS statistical software, version 9.0 for Windows,(SAS Institute, 2002). System means of each soil type were compared using the Slice function. Relationships between soil available nutrients, the response ratio (lnRR) of rice production systems, DRIS indices and biomass evaluated with Pearson correlation analysis and the restricted maximum likelihood (REML) method.

3.4. Results

3.4.1. Soil fertility and nutrient dynamics

The rice production system had a significant effect on soil fertility and nutrient dynamics in the six Panamanian soils tested in this study. The initial soil pH ranged from 4.1 (Calabacito) to 5.7 (Tocumen) (Table 2) and the pH tended to increase in the CM treatment and decline in the AO treatment over the course of the experiment (Fig. 1). In all soils, the pH after 35 d was significantly (P<0.05) greater in the CM system than the AO system (Fig. 1). Among the most notable changes in pH was in the Coco soil, where the pH declined from 5.1 to 4.4 in the AO system and rose to 6.0 in the CM system after 35 d under greenhouse conditions.

The pattern of N transformations and availability differed among the soils and the systems and there was a significant soil*system interaction (P<0.0001). In the Alanje, Tocumen and Rio Hato soils with the AO treatment, all available N was in the NO_3 form at transplanting (Fig. 2). In the Calabacito, Bella Vista and Coco soils, at least half the available N was still in the NH_4 form at the time of transplanting. In the CM system, the available N levels were similar across all soils (100mg N kg^{-1}) at transplanting, except in the Bella Vista soils that had 156 mg N kg^{-1}. Most soils had NH_4 as the dominant source of available N, except the Alanje and Tocumen soils where 21% and 34% of available N was in the NO_3 form, respectively. In the AO system, available N was depleted in the Coco, Tocumen and Rio Hato soils by 35 d after transplanting, whereas the Alanje, Calabacito and Bella Vista soils still had high available N concentrations (>50 mg N kg^{-1}). In the CM system, available N remained in the NH_4 form after 35 d and available N concentration increased (to 238 mg N kg^{-1}, Bella Vista soil), decreased (to 32 mg N kg^{-1}, Tocumen soil) or increased slightly (by 14 mg N kg^{-1}, on average) in the remaining soils after 35 d.

Soils contained from 3.2 to 30.8 mg M3P kg^{-1} and values in Calabacito and Bella Vista soils were below the critical level of 5 mg M3P kg^{-1} (Fig. 3). In the Calabacito and Bella Vista soil, M3P was significantly greater in the AO than the CM system after 35 d, whereas in the Rio Hato soil, M3P was significantly greater with the CM system. In the remaining soils there was no difference in available P between the systems.

Mehlich-3 extractable K (M3K) concentrations ranged from 82 mg K kg^{-1} (Rio Hato) to 455 mg K kg^{-1} (Bella Vista) (Fig. 3). In the Coco, Alanje and Rio Hato soils, the M3K concentration was significantly greater in the CM system than the AO system. There was no difference in M3K concentration between AO and CM systems in the Calabacito, Bella Vista and Tocumen soils.

Mehlich-3 extractable Fe was significantly higher with the CM system than the AO system in most soils except Tocumen (Fig. 3). In the Calabacito, Bella Vista and Coco soils, concentrations were >1500 mg M3Fe kg^{-1}. Extractable Al concentration was significantly greater in the AO system than the CM system in the Calabacito, Bella Vista and Alanje soil, but not in the remaining soils. Available soil Cu was significantly greater in the AO system than the CM system in most soils, except Tocumen (Fig. 3). In the Calabacito, Bella Vista and Coco soils, available soil Cu was reduced to <0.1 mg Cu kg^{-1} in the CM system by 35 d after transplanting. There was a significant system*soil effect on available soil Zn. Available soil Zn was significantly higher in Calabacito and Bella Vista soils in the AO system, and higher in Rio Hato soil in the CM system, with no difference between the remaining soils.

Microbial biomass P was significantly higher in the AO system than the CM system in the Calabacito, Bella Vista and Coco soils (Fig. 4). The microbial P for the remaining soils was highly variable and not significantly different from zero (data not shown). Soil phosphatase activity was significantly different among soils but there was no significant system effect (Fig. 5). Phosphatase activity was highest in Bella Vista, Calabacito, Alanje and Rio Hato soils (5.7 nmol $g^{-1}min^{-1}$) and lowest in Coco and Tocumen soils (3.0 nmol $g^{-1}min^{-1}$). A significant increase in β-glucosidase in the AO system compared to the CM system (P=0.024) was found in the Coco soil. Similar to phosphatase activity, β-glucosidase activity also differed among soils.

3.4.2. Plant biomass

The AO and CM treatments had significant effects on plant biomass and nutrient accumulation in the six soils tested. Aboveground plant biomass ranged from 1.9 to 10 g in the AO system and 0.75 to 18.2 g in the CM systems at 54 d after emergence (Fig. 6). Aboveground biomass was significantly (P<0.05) greater in the AO system than the CM system in the strongly-weathered Calabacito and Bella Vista soils. There was no difference between the systems in the Coco soil. Greater aboveground biomass was found with the CM system than the AO system in the Alanje, Tocumen and Rio Hato soils (Fig. 6). Fewer differences were observed in belowground components, but there was significantly greater root biomass in the CM system than the AO system in the Alanje, Tocumen and Rio Hato soils and higher root density in the CM system than the AO system in the

Tocumen soil (data not shown). The response ratio (lnRR) of biomass to the AO system was highly correlated with available soil P (P<0.0001) (Fig. 7).

3.4.3. Tissue nutrients

In both Calabacito and Bella Vista soils, the aboveground tissue N concentration was higher in the AO system than the CM systems (Fig. 6). In the Coco, Tocumen and Rio Hato soils, tissue N concentration was higher in the CM system and in the Alanje soil, there was no difference between the two systems. Plants in the Bella Vista soil and the CM system had tissue N concentration below the critical level (2.5% N) suggested by Dobermann and Fairhurst (2000). In contrast, plants in the Coco and Rio Hato soil under the AO system showed N deficiency based on tissue N concentration.

In the Calabacito and Bella Vista soils, tissue P concentration was deficient (< 0.1%; Dobermann and Fairhurst, 2000) in the CM system (Fig. 6). With the AO system, the P concentration was significantly increased and was above the critical P tissue concentration. For the remaining soils, there was no difference between the two systems and all the tissue P concentrations were above the critical level.

Tissue K concentrations were above the critical level for deficiency (K>1.5%, Dobermann and Fairhurst 2000) in all soils and system combinations (Fig. 6). In the Calabacito soil tissue K concentration was greater in the AO than CM system, and in the Tocumen soil, the K concentration was greater in CM than the AO system. Tissue S concentration approached the critical concentration (0.1%, Dobermann and Fairhurst 2000) in the Calabacito, Alanje and Coco soils.

Plants grown in the Coco soil had significantly higher tissue S concentration in the AO system, while in all remaining soils there was no significant difference in tissue S concentration between systems.

Tissue Fe concentration was higher with the CM system in the Calabacito soil (Fig. 6). In the remaining soils there was no difference in the tissue Fe concentration between the systems. In Calabacito CM, Bella Vista CM and AO, Coco CM and Tocumen CM, tissue Fe concentration approached or exceeded the critical level for potential Fe toxicity (Dobermann and Fairhurst, 2000). Tissue Cu and Zn concentrations were above the critical concentration (Dobermann and Fairhurst, 2000) in all soil and system combinations (Fig. 6).

3.4.3. DRIS analysis

DRIS analysis was used to determine which nutrients were likely limiting biomass accumulation and the DRIS nutrient indices are shown in Table 3. The DRIS model indicated that P was the most limiting nutrient in all soil-system combinations with the exception of the AO system in the Rio Hato soil, where N was the most limiting nutrient. The DRIS P indices for the Calabacito and Bella Vista soils were significantly more negative in the CM than the AO system, indicating more severe P limitation in the CM system. The absolute value of the DRIS P index was negatively correlated with aboveground biomass (r=-0.44, REML, P=0.026).

In the Rio Hato soil, N was the most limiting nutrient in the AO system. Indices for N were also negative in both systems in the Tocumen soil, indicating that N was also deficient. However, there was no significant correlation between the DRIS N index and available soil N. The results of the DRIS analysis showed that K was not deficient in any of the soil*system combinations, which agrees with the results that K was above the critical tissue concentration in all soil*system combinations (Fig 3). The S index was significantly more negative for Alanje AO than Alanje CM and the S indices were slightly negative for Calabacito AO and Rio Hato CM. The results for DRIS indices for S are strongly weighed by the relationship with N, and the model indicated that in the above treatments S was in short supply compared to the N.

3.5. Discussion

The effects of AO vs. CM system on plant biomass, nutrient uptake and soil nutrient dynamics were dependent on the soil in which they were implemented. The results of this greenhouse study supported my hypothesis that the AO management practices of intermittent flooding and the use of organic fertilizer have positive effects on rice biomass, soil P availability, and plant P uptake in strongly weathered tropical soils with low M3P concentrations (Calabacito, Bella Vista) compared to high-input practices (flooding and mineral fertilizer). The DRIS analysis confirmed my assumption that P was the limiting nutrient (observed in five of the six soils studied) and was useful in detecting system effects on P deficiency. Also, the DRIS P index was correlated with aboveground biomass. Also, supporting my hypothesis, I found that in soils with a higher soil P availability such as Gleysols, Molisols and Andisols (Rio Hato, Tocumen and Alanje), rice biomass accumulation was greater with high-input management (flooding and mineral fertilizer). Furthermore, the significant negative correlation between soil P and the response ratio indicated that the differing response to production system is largely controlled by soil P status. The results of this greenhouse study support the results of the previous meta-data analysis of worldwide SRI studies (Turmel et al., 2011) and further suggest that the reason SRI has been successful in increasing yield in low fertility soils such as highly-weathered Inceptisols and Ultisols is related to an increase in soil P availability and improved rice P nutrition. This mechanism suggested by the current study should be evaluated under field conditions and individual systems components (water regime and fertilizer source) should be evaluated in a factorial design.

3.5.1. Low fertility soils (Calabacito and Bella Vista)

Phosphorus is often the limiting nutrient for crop production in highly-weathered soils that have low P saturation and high P fixing Fe and Al oxides. The results of the current study supported my hypothesis that AO system will increase M3P and microbial P, compared to the CM system. This indicates that aerobic soil conditions and organic fertilization increased the biologically available P pool. Phosphorus uptake has previously been shown to increase in SRI, a system that uses an aerobic intermittently flooded water regime in combination with organic fertilizer, compared to a continuously flooded system that uses mineral fertilizer (Barison, 2003).

In strongly-weathered tropical soils, rich in P-sorbing Fe and Al oxides, organic fertilizers can be more effective than mineral fertilizers at supplying plant available P over time (Nziguheba et al., 1998; Turner et al., 2006). This is because as organic fertilizers promote microbial growth that retains P in the biologically available P pool and also produce organic ions that compete for Fe and Al oxide adsorption sites (Nziguheba et al., 1998). The results of the current study supported my hypothesis that in the AO system, both the microbial P and M3P were higher than the CM system, indicating that the aerobic soil conditions and organic fertilization increased the biologically available P pool. However, I found no evidence that the AO system increased phosphatase enzyme activity. I found that β-glucosidase activity was higher in the AO system in the Coco soil only, likely because this soil is extremely low in soil organic carbon, and the organic fertilizer addition was able to boost β-glucosidase activity above background levels.

Maximum productivity and decomposition occurs under intermittent periods of inundation as aerobic decomposition of organic matter proceeds at a higher rate than under anaerobic conditions (Acharya, 1935; Kirk, 2004). Under continuous flooding, organic fertilizer has been found to increase the moderately stable organic P fraction, whereas in intermittently flooded soils, organic fertilizer addition increased the labile organic P fractions and was correlated significantly with an increase in microbial P (Yang et al., 2006). The findings of the current study are consistent with the observations of Yang el al. (2006). This increase in labile organic P is closely related to improved P uptake by rice in intermittently flooded conditions, compared to continuously flooded soils (Yang et al., 2006). However, in this study, I did not investigate the effect of management practices on P availability from specific soil P pools. Further research is required to determine the effect of water regime and fertilizer source on plant available P from organic and biological sources compared to P supplied from weathering and dissolution.

The soil pH increased substantially with CM system, but, it did not improve soil P availability or reduce the soluble Fe in the low fertility soils. Likely the P provided by the manure and increase in organic P mineralization and competition for sorption sites with organic ions in the organically fertilized AO system, discussed above, was the dominant factor controlling M3P concentration/supply. Nitrification rates are often lower in acidic soils than neutral soils (Sahrawat, 1982) which may explain why, in the acidic Calabacito and Bella Vista soils, less available N was converted to NO_3 than the soils with higher pH (Tocumen and Rio Hato). None of the soils were critically low in K availability (Dobermann and Fairhurst, 2000).

Plant biomass increases in aerobic systems with organic fertilization in low fertility soils may also be related to a decline in Fe toxicity in high iron soils (McDonald et al., 2006). Our results show that tissue Fe reached potentially toxic concentrations in the Calabacito and Bella Vista (low P fertility) soils and available soil Fe was significantly higher under the reducing soil conditions of the CM system. Low soil P fertility has been shown to increase the plant uptake of Fe from soil solution by reducing the oxidizing capacity of roots. In turn, high Fe in the soil solution can also interfere with the plant uptake of P (Fageria et al., 2008). Future research should examine the interactive effects of water regime and fertilizer source on soil P–Fe interactions and plant nutrition.

Other researchers have also suggested that SRI has the potential to increase yields in soils with low nutrient availability by promoting root growth in aerobic conditions (Dobermann, 2004; Hengsdijk and Bindraban, 2004). I did not observe an increase in root biomass in the AO system, although the root system was likely constrained due to the limitations of greenhouse pots.

3.5.2. Moderate fertility soils (Coco and Alanje)

The DRIS indices indicated that P was the limiting nutrient in both the AO and CM systems (Table 2). This was due to low soil P availability in these soils, linked to the high concentration of P-fixing Fe-oxides (Coco) and Al-oxides (Alanje). The poor growth in the Alanje soils under AO management may be also attributed to the high soil Al concentration. Aluminum toxicity is common in soils of volcanic origin with high Al and low pH (Takahashi and Shoji, 2002). Flooding in the CM system increased the pH compared to the AO system, which probably decreased Al availability (Sahrawat, 2007).

Lower available N and K in the AO system occurred in the sandier soils (El Coco and Rio Hato), which may have been due to leaching of soluble NO_3 and K. There may have been excessive leaching of N and K from these soils in the AO system because the pots could drain whereas the CM pots were sealed. The loss of N could also be attributed to gaseous losses during flooding and drying cycles involving nitrification during the aerobic period and denitrification during the flooded period. Nonetheless, it is unclear by which mechanism N was lost or if this loss was an artefact of the pot set-up rather than an effect of the system. This study should be repeated at the field scale to evaluate N cycling in the AO and CM systems under realistic conditions.

3.5.3. High fertility soils (Tocumen and Rio Hato)

In the Rio Hato and Tocumen soils, both P and N limitation were important. The results of the DRIS analysis differed from the comparison of critical nutrient concentrations because the DRIS system compares optimal ratios of nutrients rather than only critical concentrations. The soil P and tissue P concentration were both above critical levels, however the DRIS analysis indicated that in relation to the other nutrients, P was still limiting in all soil and system combinations except in Rio Hato AO were N was limiting. In contrast to the low fertility soils, soil P and plant P uptake were higher in the CM system compared to the AO system. This agrees with my hypothesis and other studies that have shown that P availability increases under flooding conditions due to Fe bound P solubilization and increased P diffusion to the root (Huguenin-Elie et al., 2003). In the Rio Hato and Tocumen soils, soil mineral N and tissue N concentrations were lower in AO than the CM system. As discussed above, this may be due to the rapid conversion of available N to NO_3 and excessive leaching of NO_3 in these sandy textured soils. Also, denitrification may occur during wetting and drying in the AO system due to increased supply of soluble C and ample NO_3 in the soil. Soil N may also have been depleted in the CM system because there was greater biomass production and plant N uptake. Also, it should be noted that a yield response to organic fertilizer is not always seen in the first years of application. Lee et al. (2009) showed that in a high fertility Korean soil, there was no positive yield response to organic fertilization compared to complete mineral fertilizer but after 10 years a yield response to organic fertilizer application was observed and after 25 years yields in treatments receiving only organic fertilizer were comparable to the minerally fertilized yields.

3.6. Conclusion

This study demonstrated the importance of site-specific management for low, medium and high fertility soils. The AO system tested would be beneficial for resource-poor farmers farming highly weathered Inceptisols and Ultisols in

Panama because it relies on organic fertilizer, which is locally available and intermittent flooding, which could conserve on-farm water resources, reduce iron toxicity and increase plant P nutrition and growth. In contrast, the use of continuous flooding and mineral fertilizer are appropriate to optimize rice production in medium and high fertility soils in Panama.

The results of this study suggest that SRI, a system that uses intermittent flooding and organic fertilization, may be an effective way to improve rice P nutrition in low-fertility soils using low-input methods accessible to resource-poor farmers. Field experiments should be conducted to validate the results of this greenhouse study. Detailed work on the interactions between soil Fe and P is needed to understand the interactive effects of organic fertilization and flooding on plant P nutrition and Fe toxicity. Further research is also required to determine the effect of SRI management practices on soil N dynamics in the field.

Table 1. Location, precipitation, elevation and previous land use at soil collection sites in Panama.

Site	**Latitude**	**Longitude**	**Precipitation** (mm)	**Elevation** (m)	**Land Use**
Calabacito, Veraguas	8'14'50"	81'04'57"	2515	90	Grain/pasture
Bella Vista, Chiriqui	8'36'00"	82'14'00"	5633	740	Grain/pasture
El Coco, Cocle	8'25"00"	80'21'10"	1480	9	Grain/pasture
Alanje, Chiriqui	8'23'45"	82'33'30"	2340	32	Grain/Horticulture
Tocumen, Panama	9'03'40"	79'23'30"	1903	22	Grain
Rio Hato, Cocle	8'21'00"	80'10'00"	1508	55	Irrigated grain

Table 2. Soil class and properties of the Panamanian soils used in the greenhouse experiment.

Location	Soil Class	pH	Total C	Total N	Clay	Silt	Sand	Fe-ox	Mn-ox	Al-ox
			-- $g\ kg^{-1}$ ----------------------------------							
Calabacito,Veraguas	Ultisol	4.1	16.8	1.4	531	334	136	3.5	0.1	3.5
Bella Vista,Chiriqui	Inceptisol	4.6	39.8	4.9	535	335	131	12.8	14.1	13.5
El Coco, Cocle	Inceptisol	5.1	11.5	1.0	187	211	602	3.1	5.0	1.7
Alanje, Chiriqui	Andisol	5.4	51.7	4.9	75	516	360	6.6	4.1	45.0
Tocumen, Panama	Mollisol	5.7	17.5	1.8	310	505	185	13.3	7.8	1.9
Rio Hato, Cocle	Inceptisol	5.4	9.0	0.9	247	225	529	3.9	3.7	1.1

Table 3. DRIS index values for aboveground tissue nutrient concentration ratios at 35 days after transplanting. The AO system had intermittent flooding and some organic fertilizer, while the CM system was under continual flooding with mineral fertilizer only. Larger negative and positive values indicate a greater degree of nutrient deficiency or over-supply. Significant difference between the systems are indicated (***, $P<0.0001$; **, $P<0.001$; *, $P<0.05$).

Site	System	N		P		K		S	
Calabacito	AO	16.6	***	-37.8	***	22.6		-1.3	
	CM	87.7		-122.9		32.6		2.6	
Bella Vista	AO	15.0		-37.7	**	19.1	***	3.6	
	CM	27.1		-85.5		44.3		14.1	
Coco	AO	-13.1	***	-35.2		24.8		23.5	
	CM	18.8		-50.3		19.1		12.4	
Alanje	AO	18.3		-32.4		26.7		-12.6	*
	CM	19.5		-54.4		35.8		-0.9	
Tocumen	AO	-4.4		-10.3		9.8	*	4.9	
	CM	-1.0		-15.7		15.8		1.0	
Rio Hato	AO	-15.3	***	-1.1		14.0		2.4	
	CM	-1.4		-8.6		13.5		-3.4	

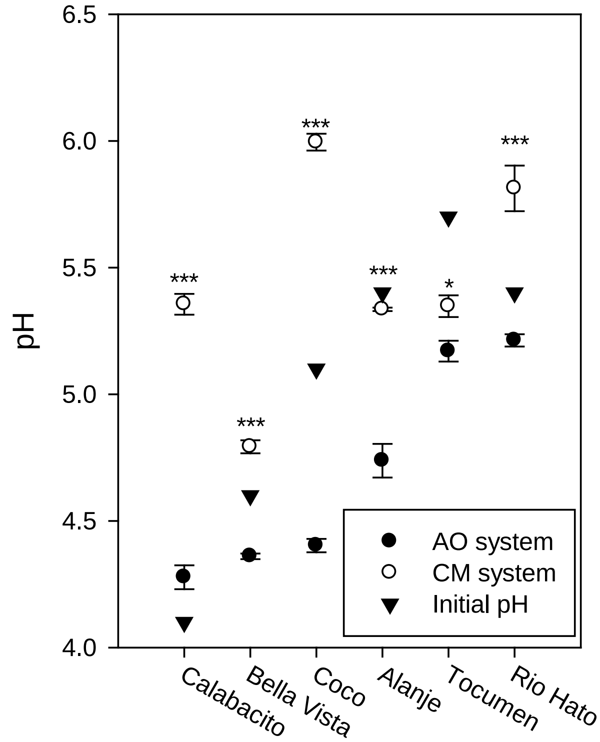


Figure 1. Soil pH measured after 35 d of rice growth in a greenhouse study with 6 Panamanian soils. The AO system had intermittent flooding and some organic fertilizer, while the CM system was under continual flooding with mineral fertilizer only. The initial soil pH is also shown. Significant difference between the two systems are shown (***, $P<0.0001$; *, $P<0.05$).

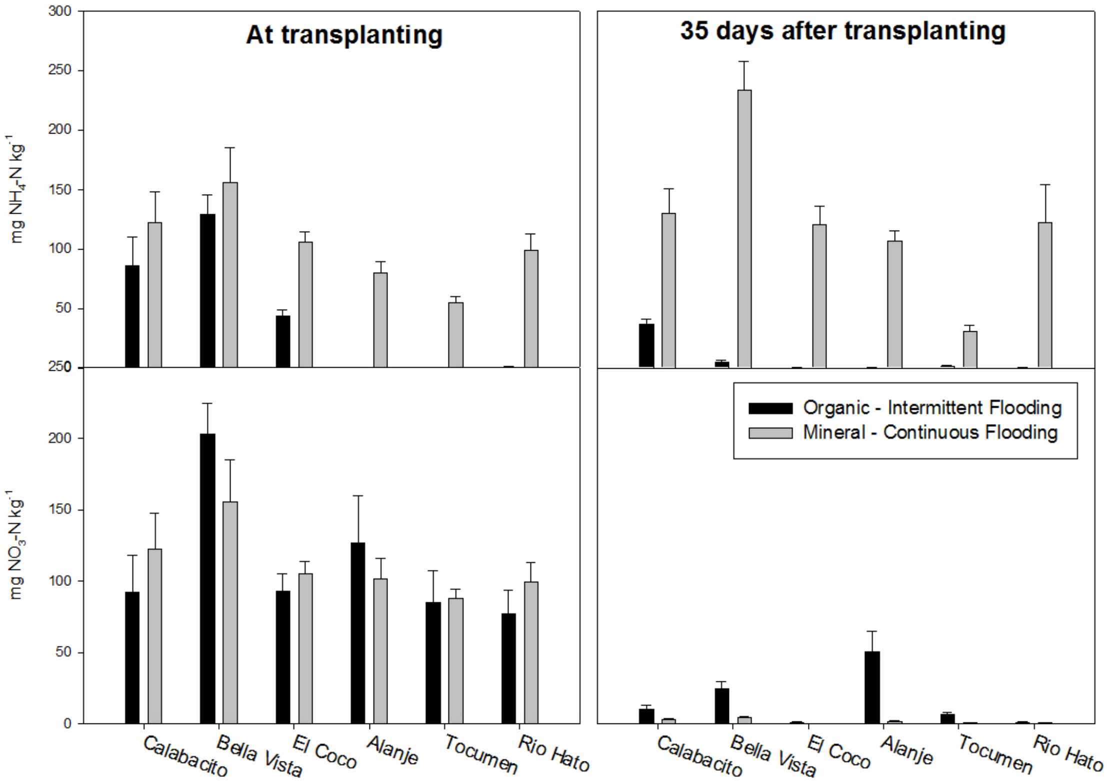


Figure 2. Soil NO_3-N and NH_4-N concentrations at transplanting and 35 d after transplanting in 6 Panamanian soils in a system with organic fertilization and intermittent flooding and another system using mineral fertilizer and continuous flooding.

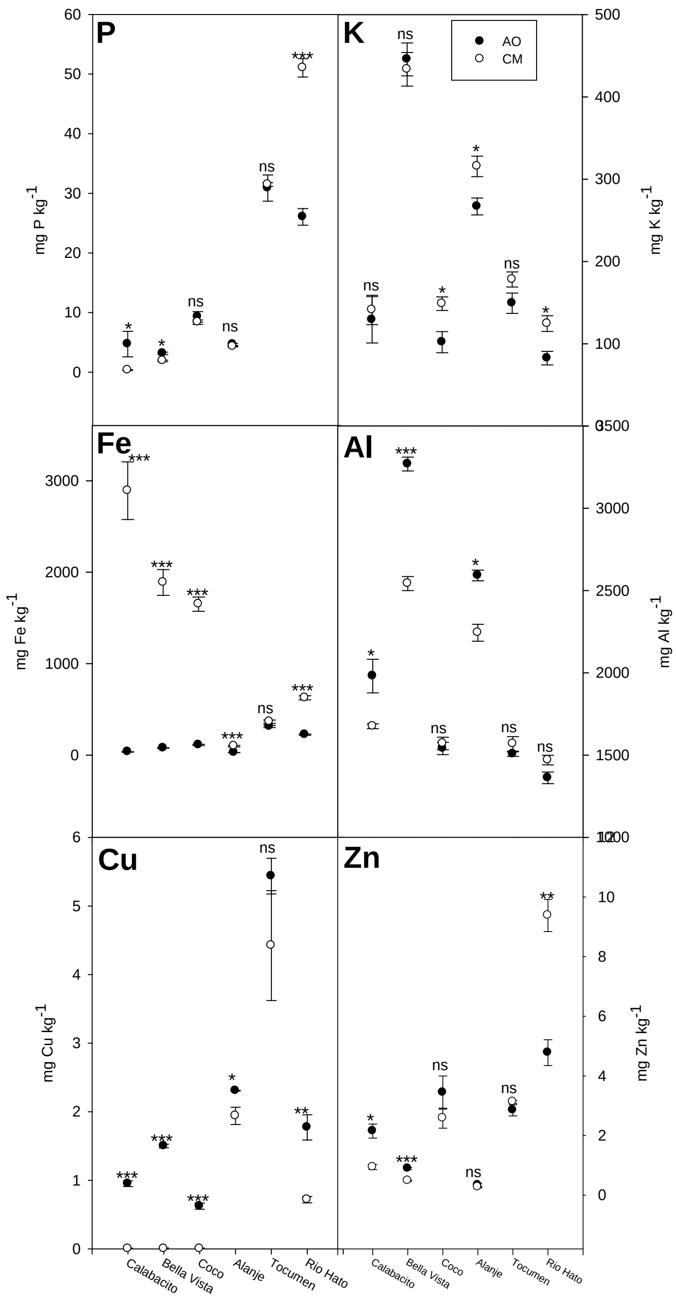


Figure 3. Mehlich extractable soil nutrients 35 days after transplanting. Nutrient concentrations in the AO and CM systems are shown for the six soils tested in the study ordered by increasing soil P fertility. The AO system had intermittent flooding and some organic fertilizer, while the CM system was under continual flooding with mineral fertilizer only. Significant differences between the two systems are shown (***, P<0.0001; **, P<0.001; *, P<0.05; ns, not significant).

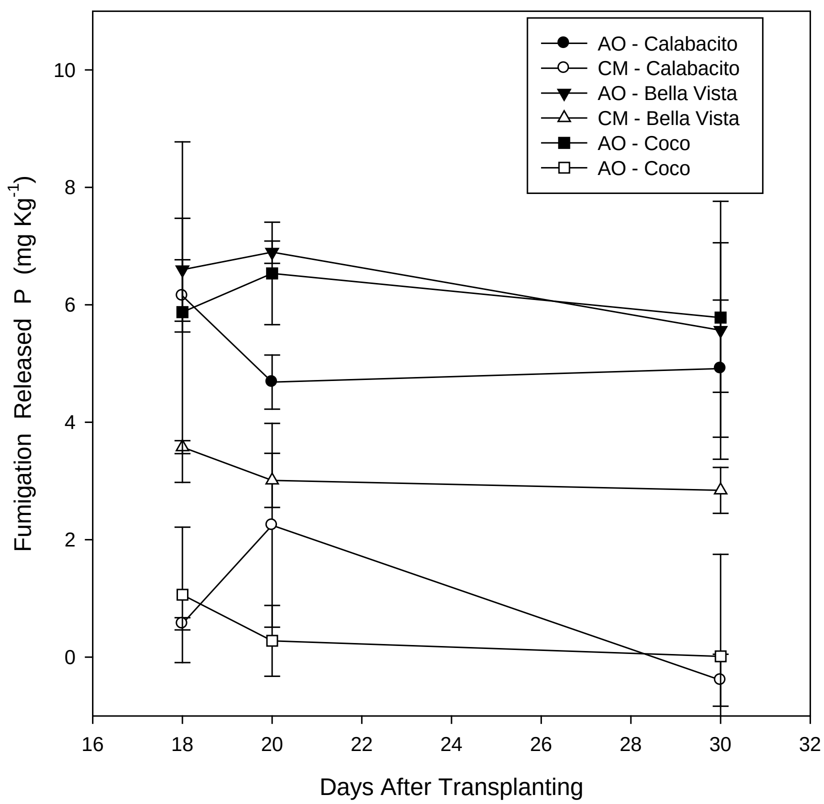


Figure 4. Fumigation released P (microbial P) measured 18, 20 and 30 days after rice transplanting in the Calabacito, Bella Vista and Coco soils with AO and CM systems. The AO system had intermittent flooding and some organic fertilizer, while the CM system was under continual flooding with mineral fertilizer only.

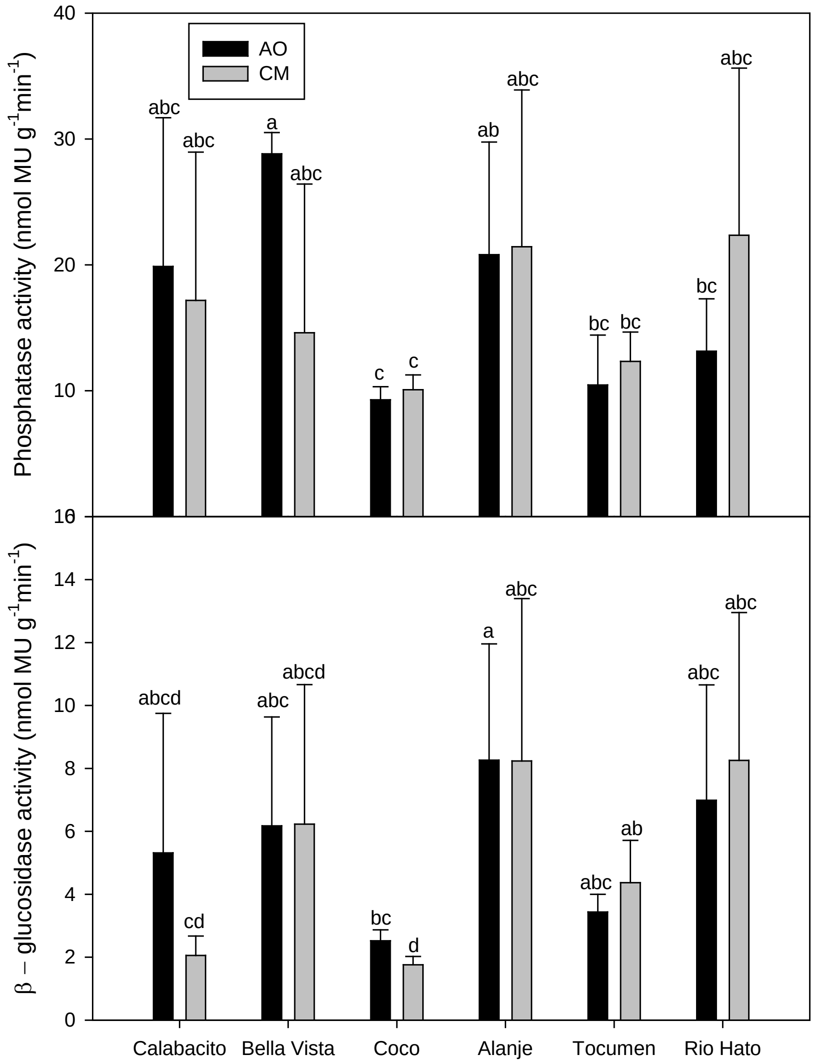


Figure 5. Soil phosphatase and β-glucosidase activity measured 30 days after transplanting. The AO system had intermittent flooding and some organic fertilizer, while the CM system was under continual flooding with mineral fertilizer only. Different letters indicate difference between soils and systems (LSD, $\alpha = 0.05$).

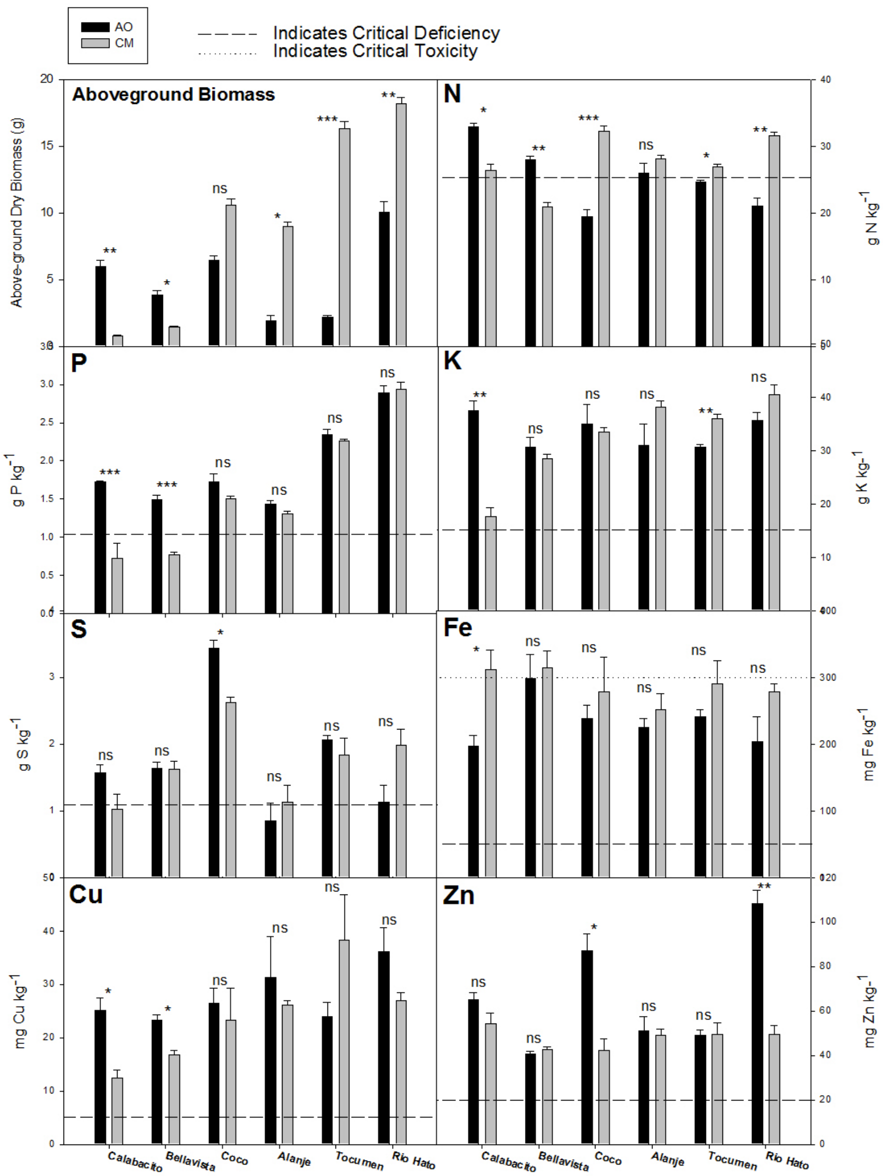


Figure 6. Aboveground biomass and nutrient concentrations in rice tissue measured after 35 d of rice growth in a greenhouse study with six Panamanian soils with two water and fertilizer management regimes (AO and CM, described in Fig. 1). Critical tissue nutrient levels for deficiency and toxicity were based on Dobermann and Fairhurst (2000). Significant differences between the AO and CM systems are indicated (***, P<0.0001; **, P<0.001; *, P<0.05; ns, not significant).

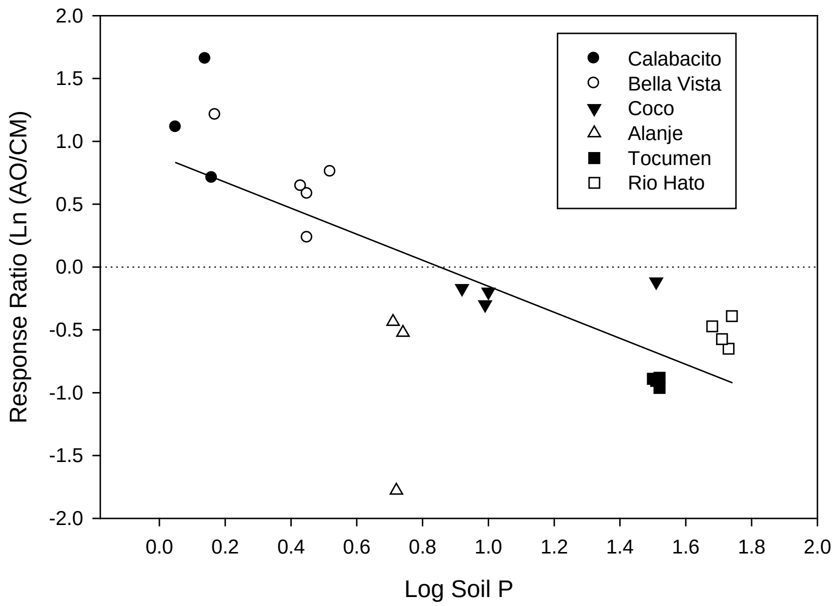


Figure 7. The relationship between the response ratio (rr) to the system that received organic fertilizer and intermittent flooding (AO) compared to the system that received mineral fertilizer and continuous flooding (CM) (response ratio (rr) = ln(AO biomass/CM biomass) and the log transformed Mehlich-3 extractable P concentration is shown for the six soils tested in this study. A positive rr represents response to the AO system and a negative rr represents a negative response to the AO compared to the CM.

Connecting Paragraph to Chapter 4

In Chapter 3, a greenhouse study with six distinct Panamanian soils showed that in soils low P availability, rice growth and P uptake were greater with a system using organic fertilizer and intermittent flooding (based on SRI) than a system using only mineral fertilizer and continuous flooding. The next step was to conduct a factorial design experiment to investigate the interactive effects on water regime on plant-soil P dynamics and grain yield under field conditions. The Coco soil was chosen for the field experiment because it is a moderately weathered low fertility soil with low P availability where P is the limiting nutrient to crop production. I also selected the Coco soil because the results from the greenhouse study showed that, while the Coco soil has high concentrations of Fe (3.1g Fe kg^{-1}), plant grown in the Coco soils did not accumulate potentially toxic Fe concentrations under flooding conditions, which could confound the effects of water regime on P uptake and yield.

Chapter 4. Composted cattle manure improves the nutrient balance and yield of rice in a tropical soil with low phosphorus availability in Panama

4.1. Abstract

A field experiment was conducted in Panama on a moderately weathered tropical Inceptisol (Dystric Fluvisol) with low phosphorus (P) availability to determine the effects of water regime and fertilizer source on rice production and soil nutrient availability. The experiment was conducted over two harvests in one year and used a factorial design to evaluate the effects of water regime (continuously flooded vs. intermittently flooded), composted cow manure (compost) (0 and 13.5 t ha^{-1}), and mineral fertilization (none, NK and NPK) on plant–soil nutrient dynamics. The nutrient concentration in rice grain and straw was measured at maturity. The nutrient balance and potential nutrient limitations (N, P, K) were evaluated with the Diagnostic and Recommendation Integrated System (DRIS). Measured soil properties included available N, P and K, microbial biomass C, N and P and the activity of hydrolytic enzymes involved in C, N and P turnover. In the first season, P was the most limiting nutrient for rice production and yields were greater with NPK + compost than NPK alone in the intermittently flooded (6.6 t ha^{-1} vs. 4.9 t ha^{-1}) and continuously flooded (6.8 t ha^{-1} vs. 6.2 t ha^{-1}) soils. In the second season, N was the most limiting nutrient and yields were greater in the continuously flooded (5.2 t ha^{-1}) than intermittently flooded (2.7 t ha^{-1}) soils when no compost was applied.

When compost was applied, crop nutrient balance improved and no significant yield difference was observed in the intermittently flooded (4.4 ± 1.3 t ha^{-1}) and continuously flooded (5.4 ± 1.0 t ha^{-1}) soils. Compost increased available soil P,

microbial P, phosphomonoesterase activity and plant P uptake under both water regimes; however, greater increases were measured under intermittently flooded conditions. Organic fertilizers like composted cow manure may help to maintain crop nutrient balance and yields in water-conserving rice production systems that are intermittently flooded following establishment on soils with low P fertility.

4.2. Introduction

Climate change is predicted to create greater variability in rainfall patterns, which will have a major impact on rice production in Panama and other countries in Latin America and the Caribbean (Nelson et al., 2009). Rice production in Panama is already challenged by poor soil fertility, variable rainfall patterns, access to fertilizers and pest control. There are approximately 50,000 smallholder farmers in Panama cultivating a total area of 49,000 ha^{-1} using either a flooded and transplanted system (yielding approximately 3 t ha^{-1}) or rainfed and direct seeded system (yielding 0.5-1.0 t ha^{-1}) (MIDA, 2009). Smallholder farmers are concentrated in areas with weathered soils (Ultisols, Alfisols, and weathered Inceptisols) having low inherent fertility and high P fixation capacity, making P limitation a major constraint on crop production (Namé and Villarreal, 2004a). To ensure future rice yields, farmers will require water-conserving rice production systems that also are productive in low fertility soils. Preliminary research on the System of Rice Intensification (SRI), a water conserving system, supports the view that intermittent flooding and organic fertilization can improve P uptake and rice yields in low P fertility soils (Barison, 2003; Sinha and Talati, 2007; Turmel et al., 2011; Turmel et al., 2010). However, the predicted benefits of intermittent flooding and organic fertilizers on rice production and soil fertility remain to be verified under field conditions in Panama.

The interactive effects of soil water regime and fertilizer source on P availability in weathered tropical soils is poorly understood. Soil water regime is an important factor affecting P mobility and uptake by plants. Soil P mobility is improved by flooding due to an increase in tortuosity, which increases P diffusion by 10 to 100-fold (Huguenin-Elie et al., 2003). The reductive dissolution of Fe oxides in flooded soils may increase P availability, but can also increase the reactive surface area of reduced Fe compounds, leading to P fixation (Patrick and Khalid, 1974). In soils with low P saturation of amorphous Fe-oxides, Zhang et al. (2003) demonstrated that flooding decreased P availability by forming Fe compounds with great P-fixing capacity, outweighing the positive effects of flooding on P diffusion to roots.

The effect of flooding on soil P availability may be dependent on the fertilizer source applied. In highly-weathered soils, organic fertilizer can be more effective than mineral phosphate fertilizer at increasing soil P availability because P cycles through microbial biomass, thereby avoiding fixation by Fe and Al oxides (Nziguheba et al., 1998; Turner et al., 2006). Yang et al. (2006) compared soil P availability, plant P uptake and rice yields from organic and mineral fertilizers under continuous and intermittent flooding conditions. When organic fertilizer was used, soil P and rice yields were greater in the intermittent flooding regime

The objective of this research to determine the interactive effects of water regime and composted cow manure (hereafter referred to as compost) on rice production and soil nutrient supply in a low P Inceptisol in a rice producing region of Panama. The study was based on the following hypotheses: (1) rice production will be limited primarily by P availability, (2) plant P uptake and yield will be greatest when compost is applied to soil that is intermittently flooded, and (3) microbial C, N and P, soil enzyme activities and available soil P will be greater when compost is applied to soil that is intermittently flooded than continuously flooded.

4.3. Methods

4.3.1. Experimental site and land preparation

The field experiment was carried out at the Panama Agriculture Research Institute's experimental station in El Coco, located in the province of Cocle, Panama (8°25'00"N, 80°21'10"W, elevation 50m). This area is in the humid tropics and receives about 1070 mm of precipitation annually with a rainy season from May to December. About 95 % of the annual precipitation falls during the rainy season. The dry season is also generally windier and has a slightly higher average temperature (30°C) than the rainy season, which has an average temperature of 27°C. Land use in the El Coco region is mainly irrigated rice production and pasture. The soil is an Isohyperthermic Aeric Endoaquept (Inceptisol, USDA; Dystric Fluvisol, FAO classification) with moderately weathered fluvial-marine sediment as parent material. Soil texture was 145 g kg^{-1} clay, 205 g kg^{-1} silt and 644 g kg^{-1} sand in the top 10 cm and after 20 cm 393 g kg^{-1} clay, 202 g kg^{-1} silt and 405 g kg^{-1} sand. The clay fraction is dominated by kaolinite and has low CEC of 6.2 cmol kg^{-1}. Initial soil chemical and physical properties in the top 15 cm are shown in Table 1.

The experiment was conducted on land that was left fallow for seven years. The field was prepared by tilling existing vegetation (native grasses) into the soil. Topsoil (top 15 cm) was first removed so that the subsoil could be levelled and principal walls constructed. Topsoil was then redistributed evenly over the main plots. Soil was flooded and then tilled, individual plot walls were constructed and soil was levelled manually in each plot before applying experimental treatments.

4.3.2. Experimental design and agronomic management

The experimental design was a randomized complete block split-split plot design with 4 replicates. The main plot effect was water regime (continuously flooded or intermittently flooded), the first split plot effect was compost (0 and 13 t ha^{-1} compost) and the second split plot effect was mineral fertilizer (none, NK and NPK). Each plot was 6 m x 4 m in size. Main plots were separated by a 0.5 m wide wall and a 0.75 m dyke. The irrigation system was installed with 5 cm diameter PVC tubing, providing an independent source of irrigation to each plot. Continuously flooded plots were irrigated daily while the intermittently flooded plots were irrigated approximately every three days, depending on rainfall.

The first growing season was from 15 October 2009 to 22 February 2010 and the second field season was from 12 March 2010 to 22 July 2010. The first two months of the first season were in the rainy season and the last two months were in the dry season. In the second season, seedlings were transplanted at the end of the dry season and the final two months were in the rainy season. Plots were maintained in the same location in the field for these two consecutive growing seasons, so fertilizer applications in the split plot and split-split plot were identical in both growing seasons.

The compost plots were fertilized with 0 or 13.5 t ha^{-1} (dry weight) of compost with approximately 40% moisture, 13.7 g N kg^{-1}, 14.2 g P kg^{-1} and 2.9 g K kg^{-1} (dry weight). Compost was surface applied approximately 1 week before transplanting. All mineral fertilizer was surface broadcast. The NK and NPK plots received 100 kg N ha^{-1} (urea, $CO(NH_2)_2$) and 40 kg K ha^{-1} (potassium chloride, KCl) divided in three parts: 30% was applied at transplanting, 40% was applied 35 d after transplanting (DAT) and the remaining 30% was applied 60 DAT. All NPK plots received 25 kg P ha^{-1} (triple superphosphate) at transplanting.

Rice nurseries were established in plastic seeding trays and fertilized with a complete fertilizer containing NPK and micronutrients. Seedlings were transplanted at the three-leaf stage, 15 d after emergence. Seedlings were transplanted singly in a square pattern with a spacing of 25 cm between each neighbouring plant in both directions.

All plots were weeded by hand during the first three weeks after transplanting. Three weeks after transplanting, plots were weeded once using a manually pushed weeding tool with a rotating blade. Glyphosate was applied to control weeds and volunteer rice from the previous crop two weeks before the second crop was transplanted. Weed control in the second season was achieved using the same methods as above.

4.3.3. Soil collection and analysis

Surface samples (0-15 cm) were collected from each plot by compositing five random cores per plot. Soil samples were collected before transplanting (0 d) and 33, 75 and 120 d after transplanting (DAT), before the split fertilizer applications. Soil samples were analysed for available nutrients (NO_3, NH_4, P, K) and pH. Soil NO_3 and NH_4 was measured by extracting field-moist soil in 2 M KCl immediately after collection. Extracts were analyzed using a QuickChem 8500 (Hach Ltd. Loveland, CO, USA). Soil available P and K were measured by extracting air dried soil in Mehlich-3 solution and analyzing extracts by inductively coupled plasma optical emission spectrometry (ICP-OES 2100, Perkin Elmer, Waltham, MA, USA) (Mehlich, 1984). Total soil C and N was determined on air dried soil at 0 and 120 DAT of the first growing season and again at 120 DAT of the second growing season using a Flash EA 1112 NC soils analyzer (Carlo-Erba, Milan, Italy). Amorphous Al, Fe, and Mn were determined on the air dried soil samples (on initial soil samples collected before installing treatments) by oxalate extraction and extracts were analysed by ICP-OES (2100, PerkinElmer, Waltham, MA, USA) (Schoumans, 2000).

Soil biological parameters were measured on fresh soil collected 33 and 75 DAT. Microbial P was determined by the hexanol fumigation method and shaking soil for 24 h with anion exchange resin strips. Microbial C and N were determined using the chloroform fumigation method. Soil enzyme assays (phosphomonoesterase, phosphodiesterase, β-glucosidase and *N*-acetyl-β-glucosidase) were conducted using 4-methylumbelliferone-linked substrates in acetate buffer and analysed fluorometrically (Turner, 2010).

4.3.4. Plant collection and analysis

Plant biomass samples were collected by harvesting six plants at random (avoiding plot edges) from each plot at the tillering stage (33 DAT), at panicle formation (75 DAT) and at physiological maturity (approximately 120 DAT). Whole plants (shoots and roots) were sampled by excavating an area of approximately 25 cm^2 and 30 cm in depth. Aboveground samples were separated at the soil surface and roots were washed from the soil. Unsampled areas (1 m^2 quadrats) were maintained in each plot for grain yield sampling at maturity (3 quadrats per plot = 16 plants in total). Grain was harvested using a simple threshing machine and cleaned manually to remove straw debris. Grain samples were sun dried until they reached 14% moisture content and then weighed. Grain weights were expressed on a 14% moisture content basis. Aboveground and belowground biomass samples were washed with deionised water and dried at 60°C for 48h and then weighed. Samples were then ground with a mechanical grinder to pass through a 2 mm^2 sieve and digested in H_2SO_4 and 30% H_2O_2 solution with $LiSO_4$ and Se catalysts (Parkinson and Allen, 1975). Extracts were analysed for K using atomic absorption spectroscopy (Perkin-Elmer model 2380, Waltham, MA, USA) and for P and N colorometrically using the Lachat Instruments QuickChem Method 13-115-01-1-B for P and 13-107-06-2-A for Total N (Lachat Instruments). Total nutrient uptake was calculated as: nutrient uptake (kg ha^{-1}) = grain biomass (kg ha^{-1}) x nutrient content (g kg^{-1}) + straw biomass (kg ha^{-1}) x nutrient content (g kg^{-1}).

4.3.5. Diagnosis and Recommendation Integrated System (DRIS) analysis

Plant nutrient balance was examined with the DRIS model, which calculates nutrient limitations based on crop specific ideal nutrients ratios (Ramakrishna et al., 2009). The DRIS norms for rice were used to compute the DRIS indices for N, P, K (Counce and Wells, 1986). DRIS indices were calculated using the following equations (Walworth and Sumner, 1988):

Considering the analysis contains nutrient A through N:

$$\text{A index} = \frac{f(A/B) + f(A/C) + f(A/D + ... + f(A/N)}{n}$$

$$\text{B index} = \frac{-f(A/B) + f(B/C) + f(B/D + ... + f(B/N)}{n}$$

$$\text{N index} = \frac{-f(A/N) - f(B/N) + f(N/C) + ... + f(N/M)}{n}$$

Where *A/B* is the ratio of the concentrations of nutrient A and B in the plant tissue, n is the number of nutrients and *f (A/B)* is the function of the form:

$$f(A/B) = \left(\frac{A/B}{a/b} - 1\right)\frac{1000}{CV} \text{ where } A/B \geq a/b \text{ or}$$

$$f(A/B) = \left(1 - \frac{a/b}{A/B}\right)\frac{1000}{CV} \text{ where } A/B < a/b$$

Where a/b is the crop specific DRIS normal ratio and CV is the coefficient of variation associated with that normal ratio. Nutrients that are in balance will have DRIS indices close to zero and those are deficient or over-supplied, relative to other nutrients, will have negative and positive values, respectively.

4.3.6 Statistical Analyses

All statistical analyses were performed using the SAS System (SAS Institute, 2002) and the JMP interface of SAS (SAS Institute, 2008). All soil and plant data were tested for normality using the Shapiro-Wilk test and for homogeneity of variances using likelihood ratio by modelling variances with the Satterthwaite adjustment. Data were normalized using a log transformation if necessary. Data were analysed using the Proc Mixed function testing for water regime, compost and mineral fertilizer effects and their interactive effects. Means were separated using Least Significant Differences with the Tukey adjustment. Pearson correlation analyses were performed with the soil nutrients, microbial nutrients and enzyme activity and soil nutrients, total plant nutrient uptake and grain yield.

4.4. Results

4.4.1. The effect of water regime and fertilizer source on grain yield, plant nutrient uptake, and nutrient limitation

Water regime, compost and mineral fertilization had significant effects on plant nutrient uptake, grain yield and nutrient balance.

4.4.1.1. Grain yield

In the first season, grain yield ranged from 6.8 t ha^{-1} in the flooded regime with compost and NPK fertilizers to 3.5 t ha^{-1} in the intermittently flooded unfertilized treatment (Table 2). As with macronutrient uptake, yields were lower in the second field season and ranged from 5.4 t ha^{-1} in the flooded regime with compost and NPK fertilization to 1.2 t ha^{-1} in the intermittently flooded unfertilized treatment (Table 3). In both the first and second season, yield was positively affected by compost (P=0.01) and the NK fertilizer treatment (P=0.0004).

However, in the second season yield was also affected significantly by the water regime ($P<0.0001$) and there was a significant interaction between water regime and compost ($P=0.037$). Similar to P uptake, yield was greater with compost in the intermittently flooded soil, whereas, there was no effect of compost on grain yield in the flooded soil. Grain yield in the first season was strongly correlated with tissue P concentration at 33 DAT ($P<0.0001$). The DRIS balance ($P<0.0001$) and was also correlated with tissue K ($P=0.001$), soil P at 33 DAT ($P=0.007$) and 75 DAT ($P=0.01$) and soil N at 33 DAT ($P=0.01$) and negatively correlated with soil K at 75 DAT ($P=0.005$). The second season's yield was also correlated with tissue P ($P=0.0001$) and tissue N ($P=0.02$) at 33 DAT and the DRIS nutrient balance ($P=0.01$) and was negatively correlated with soil K ($P<0.0001$).

4.4.1.2. Plant nutrient uptake

In the first field season, N uptake ranged from 150 kg N ha^{-1} in intermittently flooded water regime with compost and NPK fertilization to 68 kg N ha^{-1} in the intermittently flooded water regime without fertilizers (Table 1). Nitrogen uptake was lower in the second field season, from 136 kg N ha^{-1} in the flooded water regime with compost and NK fertilization to 11 kg N ha^{-1} in the intermittently flooded unfertilized treatment (Table 3). The NK and NPK fertilizer treatments increased significantly the uptake of N in both the first ($P=0.005$) and second ($P<0.0001$) field seasons (Tables 2 and 3).

Phosphorus uptake ranged from 28 kg ha^{-1} in the flooded water regime with compost and NK fertilization to 11 kg ha^{-1} in the intermittently flooded unfertilized treatment in the first season (Table 2). As with N uptake, P uptake was lower in the second field season and ranged from 21 kg ha^{-1} in the flooded water regime with compost and NPK fertilizer to 3.2 kg ha^{-1} in the intermittently flooded unfertilized treatment. In the first field season, compost had a significant positive effect on P uptake whereas in the second field season P uptake was positively affected by flooding (P<0.0001) and mineral NK treatment (P=0.0001). There was also a significant interaction between water and compost on P uptake in the second field season (P=0.0019). Phosphorus uptake was greater with organic fertilization in the intermittently flooded soil, whereas, there was no effect of organic fertilization on P uptake in the flooded soil.

Potassium uptake ranged from 169 kg ha^{-1} in the intermittently flooded water regime with compost and NPK fertilizers to 79 kg ha^{-1} in the intermittently flooded unfertilized treatment in the first field season (Table 2). As with N and P uptake, K uptake was generally lower in the second field season and ranged from 153 kg ha^{-1} in the flooded regime with organic and NK fertilizer to 19 kg ha^{-1} in the intermittently flooded unfertilized treatment. There was no effect of the treatments on K uptake in the first field season, whereas in the second field season there was a significant positive effect of the NK fertilizer treatment on K uptake (P=0.0004).

4.4.1.3. DRIS analysis

In the first field season, DRIS analysis revealed that P was the most limiting nutrient across all treatments (Table. 4). Compost decreased the severity of the P limitation significantly (P=0.0036, Table. 4). Mineral P fertilizer also reduced P limitation in treatments without compost (P<0.0001, Table. 4). The overall nutrient balance followed the same pattern: P nutrition was improved by compost application (*P*=0.0019) and the application of a complete NPK fertilizer in plots without compost (*P*<0.0001, Fig. 4).

In the second field season, N was more limiting than P and K for rice production in the compost-amended plots (*P*=0.0009) and plots receiving NPK or no mineral fertilizer (*P*=0.0003) (Table 4). The nutrient balance was positively affected by compost addition (*P*=0.0007) and complete NPK fertilization in plots without compost (*P*=0.0119).

4.4.2. The effect of water regime and fertilizer source on soil fertility

Water regime and fertilizer sources (compost and mineral) had significant (*P*<0.05) effects on soil nutrient availability, nutrients in microbial biomass and soil enzyme activity in the first and second season. There was no effect of the treatments on soil pH after the first season. Following the second season of rice production, the pH increased by 0.4 units to pH 5.9 in treatments that received mineral NK and NPK and by 0.3 units to pH 5.8 in treatments that did not receive mineral fertilizer. There was no effect of compost on soil pH (data not shown).

4.4.2.1. Soil nutrient availability

Soil macronutrient availability was affected significantly by water regime and fertilizer source. Available soil N (NO_3 plus NH_4) was increased by flooding (3 of 6 sampling dates), the addition of compost (4 of 6 sampling dates), and mineral N fertilizer (3 of 6 sampling dates) (Fig. 1). There was a consistent response of available soil N to mineral fertilizer addition in both the flooded and intermittently flooded water regimes. In the first field season, N was initially increased by compost and mineral N fertilizer and at the time of panicle initiation (75 DAT) flooding also increased soil N availability (Fig. 1). At the beginning of the second field season, N fertilizer increased available soil N and later in the season (75 DAT) soil N was increased by flooding and compost (Fig. 1). By the end of the second season (120 DAT), only compost had a significant positive effect on the soil N availability (Fig. 1).

Available soil P (Mehlich-3 extractable P) was influenced by water regime, compost and mineral fertilizer. In contrast to available soil N, available soil P declined significantly in the continuously flooded plots. Soil P was increased significantly by compost application in both field seasons. By the end of the first season, available soil P in the organically fertilized plots was above the critical level for rice production (5 mg P kg^{-1}) and after the second application of compost in the second season, exceeded the soil P level required to achieve maximum rice yields (10 mg P kg^{-1}) (Dobermann and Fairhurst, 2000). Mineral NK and NPK fertilizer also had a significant effect on available P, but to a lesser extent than the compost and available P levels remained below 5 mg kg^{-1} when with only mineral NPK fertilizer was applied (Fig. 1).

Water regime and mineral fertilizer had no effect on the soil available K (Mehlich-3 extractable K). Compost had a negative effect on available soil K in the first season only (120 DAT, Fig. 1).

The initial soil organic C concentration was low (13g organic C kg^{-1}) and did not change after the first field season. However, by the end of the second season, the water regime x compost interaction had a significant (P=0.015) effect on soil organic carbon (Fig. 2). Compost increased soil organic C under flooded soil conditions but had no effect under intermittently flooded soil conditions (Fig. 2)

4.4.2.2. Soil microbial nutrients

Soil microbial C, N and P concentrations were significantly (*P*<0.05) greater under intermittently flooded soil conditions than the flooded conditions at almost all sampling dates (Fig. 3). At 33 DAT, the water regime x compost interaction affected microbial C. Under flooded conditions microbial C was greater without compost and under intermittently flooded conditions there was no effect of compost. At 75 DAT in the first season and 33 DAT in the second season (Fig. 3) microbial C was significantly greater under intermittently flooded soil conditions than flooded conditions (*P*=0.0006 and 0.0043 respectively).

Similarly, microbial N was greater in intermittently flooded soil conditions (Fig. 3). At panicle formation in the first season, (75 DAT Fig. 3) microbial N was also affected significantly by mineral fertilization. In the first field season, microbial N was increased by the addition of N and K and further increased by the addition of P. This indicates that P may have been the limiting nutrient before N for microbial growth in the first field season.

Microbial P concentration was increased significantly under intermittently flooded soil conditions at three of the four sampling dates (first season 33 and 75 DAT and second season 75 DAT, Fig. 3). At panicle formation in the second season (75 DAT), microbial P was also greater in the compost-amended plots than those that did not receive any compost and was also strongly correlated with available soil P (*P*=0.0001).

4.4.2.3. Soil enzyme activity

Soil enzyme activities were affected by water regime, organic fertilization and mineral fertilization (Fig. 4). There were no significant effects of the treatments on phosphomonoesterase activity in season 1. However in the second season, soil phosphomonoesterase activity was stimulated by the addition of N and K mineral fertilizer 33 DAT and 75 DAT. Significant effects of N and K fertilization on phosphodiesterase was activity were also detected 75 DAT in the first season. Phosphodiesterase activity was also positively affected by intermittently flooded soil conditions (75 DAT) and by compost (33 DAT) in the second season (Fig. 4). An interactive effect between the mineral and compost treatments was observed (P=0.005) 75 DAT in the second season. When N and K were added the phosphodiesterase activity was only greater in the absence of organic fertilizer. Both phosphomonoesterase and phosphodiesterase activity were correlated with soil N (P=0.001, 0.003) and microbial N (P=0.002 and 0.002) at 75 DAT in season 1. In the second season at 33 DAT phosphodiesterase was negatively correlated with soil P (P=0.01)

Water regime and compost had significant effects on β-glucosidase activity. β-glucosidase activity was significantly greater under intermittently flooded soil conditions at the time of panicle formation (75 DAT) in first and second season and was increased by compost addition at panicle formation (75 DAT) in season 1 (Fig. 4). β-glucosidase activity was positively correlated with soil P 75 DAT in the first (P=0.036) and second (P=0.0001) season and with soil organic C and total soil N in the second season (P=0.025 and 0.029). Also, in the second season at 75 DAT, there was a strong negative correlation between β-glucosidase and available soil N (*P*<0.0001).

Compost stimulated *N*-acetyl-β-glucosaminadase activity in the first season 33 DAT. A positive effect of flooding and an interactive effect of organic and mineral fertilizer on *N*-acetyl-β-glucosaminadase activity was also observed 33 DAT in the second season (Fig. 4). When compost was applied, the *N*-acetyl-β-glucosaminadase activity was greater in the NK than the NPK mineral fertilizer treatment (Fig. 4). *N*-acetyl-β-glucosaminadase was positively correlated with soil P at 33 DAT (*P* = 0.035) and SOC at 75 DAT (*P*=0.0003) in the first season and with SOC at 33 and 75 DAT in season 2 (*P*=0.023, and 0.014 respectively).

4.5. Discussion

In highly weathered soils, P is often the limiting nutrient to crop production due to the large concentration of P fixing Fe and Al-oxides (Ahn, 1993). Organic fertilizers can be more effective than mineral P fertilizers at supplying plant available P because they increase P maintained in the organic and microbial P pool that is protected from fixation by Fe and Al-oxides (Nziguheba et al., 1998; Yang et al., 2006). In support of my hypothesis, I found that in the first field season of this study, P was the most limiting nutrient in all treatments and soil P availability and plant P uptake was greater in treatments with compost than treatments receiving mineral fertilizers only. Yields were also significantly greater with compost addition suggesting that the increased P availability from compost was responsible for boosting yields in the first season. In the first season, grain yield was significantly correlated with soil P availability, whereas in the second season, soil available P exceeded the critical level and P limitation declined and grain yield was no longer correlated with soil P availability. These results support my hypothesis that compost can improve plant P nutrition and boost yields under P limiting soil conditions.

Maximum productivity and decomposition occurs under intermittent periods of inundation as aerobic decomposition of organic matter proceeds at a greater rate than under anaerobic conditions (Acharya, 1935; Kirk, 2004). I hypothesized that the intermittently flooded water regime in combination with compost addition would increase the microbial P pool and soil P availability. The results of the current study showed that soil P availability and microbial C, N and P were greater under intermittently flooded soil conditions than continuously flooded conditions; however, fertilization with compost had less of an effect on microbial nutrients, and a significant increase in microbial P due to compost addition was not observed until the end of the second season. I found that there was less accumulation of SOM under intermittently flooded conditions, confirming that the mineralization of compost was more rapid under intermittently flooded soil conditions. I also found mixed effects of flooding on soil enzyme activity. Phosphodiesterase and β-glucosidase activites were negatively affected by flooding, agreeing with the results of Pulford and Tabatabai (1988). However, I also found that phosphomonoesterase activity was not affected by flooding and *N*-acetyl-β-glucosaminadase activity was stimulated by flooding, which agrees with the results of Mentzer et al. (2006). They suggested that enzyme activity can be stimulated by flooding due to the release of soluble carbon compounds. This may explain why *N*-acetyl-β-glucosaminadase activity, an enzyme that is involved in chitin degradation, was correlated with

SOC and its activity was greater under flooding conditions where the SOC content was greater. Phosphodiesterase and phosphomonoesterase activity, responsible for the release of phosphate from organic P, were also stimulated by the addition of mineral N, which may explain the increase in soil P when mineral N fertilizer was added to the compost-amended plots.

Yang et al. (2006) reported an increase in labile organic P following organic fertilization, which was correlated with greater P uptake and yields in intermittently flooded conditions, compared to continuously flooded soils. This is consistent with my hypothesis, and I found that available soil P, microbial nutrients and phosphodiesterase activity were greater in the intermittently flooded water regime. However, contrary to my hypothesis, I found that the increase in soil available P in the intermittently flooded soil did not translate into greater plant P uptake in the intermittently flooded, compared to the flooded water regime. This was likely because the compost supplied sufficient available P to exceed the critical P levels (>5 mg P kg^{-1}) in both intermittently flooded and flooded water regimes.

In the first season, I found that when compost was used in combination with urea-N fertilizer, yields in the intermittently flooded system were comparable to the flooded system; however, when compost was not used, yields were greater with flooding. Since the P supply was not limiting in the second season, the positive effects of the compost may also be related to increased N supply or soil water holding capacity. Management of N in intermittently flooded systems may be the greatest challenge as I found that, in the second season of this study, N became the limiting nutrient to rice production and was more deficient in the treatments that received P inputs from mineral or compost sources. The decrease in rice yields in the second season was due in part to the lower solar radiation at the end of the season and to a declining level of available soil N. Soil N availability and plant N uptake was lower in the second season than the first season, most notably in the intermittently flooded water regime. This may have been due to an increase in soil N loss from denitrification from flooding and drying cycles in the intermittently flooded water regime (Huang et al., 2007). In the second season, compost addition improved yields and soil N availability with the intermittently flooded water regime, whereas there was no effect of compost on yield in the flooded water regime. This may indicate that compost may be important in supplying plant N in the intermittently flooded water regime because it gradually releases N through mineralization.

The pattern of available soil K levels matched the pattern of crop removal of K, and available soil K pools in the unfertilized plots were likely replenished by indigenous sources. The decrease in soil K availability in the plots receiving compost was likely due to increased removal of N and P in those plots, which meant that plant K requirements were higher and the available K pool was depleted.

4.6. Conclusions

Organic fertilization is an important factor in maintaining yields in water conserving rice production systems that do not use continuous flooding. Compost (composted cow manure) increased soil P availability, plant P uptake and yields in a weathered tropical soil in both intermittently flooded and continuously flooded water regimes. Compost may also boost yields in water-conserving rice systems by increasing the supply of plant available N. Intermittently flooded soils may be more susceptible to N losses, and future research should focus on developing nutrient and water management regimes to improve N use efficiency in water conserving rice production systems.

Table 1: Initial soil chemical properties ǂ

pH	Total C	Total N	Available P	Available K	Oxalate extractable Fe	Oxalate extractable Mn	Oxalate extractable Al	CEC
(H_2O)	-----------g kg^{-1}-----------		------------------------mg kg^{-1}-----------------------					cmol kg^{-1}
5.5	13.0	1.0	4.3	90.6	3.1	5.0	1.7	6.2

ǂ Soil surface samples were collected before installing treatments by compositing 10 random cores (0-15 cm).

Table 2: First field season means and standard deviation for total N, P and K from straw and grain at 120 DAT and grain yield. Plots were intermittently flooded or continuously flooded (Flooded), with and with compost (13.5 t ha^{-1} composted cow manure) and with NK, NPK or no mineral fertilizer. ANOVA results are shown and significant *P* values (<0.05) are marked (*).

		N kg ha^{-1}		**P** kg ha^{-1}		**K** kg ha^{-1}		**Grain Yield** t ha^{-1}	
		Compost	**No compost**	**Compost**	**No compost**	**Compost**	**No compost**	**Compost**	**No compost**
Intermittently	**NPK**	150 ± 60	136 ± 34	25.5 ± 4	14.4 ± 10	169 ± 69	134 ± 17	6.6 ± 0.8	4.9 ± 1.9
Flooded	**NK**	151 ± 82	132 ± 56	21.1 ± 7	16.4 ± 7	155 ± 79	122 ± 38	6.2 ± 1.7	5.6 ± 1.5
	None	123 ± 39	68 ± 27	17.5 ± 5	11 ± 4	137 ± 32	79 ± 31	4.8 ± 1.3	3.5 ± 0.8
Flooded	**NPK**	134 ± 30	106 ± 43	24.7 ± 2	20.3 ± 1	156 ± 58	108 ± 43	6.8 ± 0.2	6.2 ± 0.3
	NK	121 ± 16	107 ± 34	28.1 ± 4	13.8 ± 7	126 ± 16	109 ± 44	6.5 ± 0.3	5 ± 1.4
	None	81 ± 8	91 ± 16	19 ± 2	14.3 ± 8	114 ± 10	109 ± 13	5.2 ± 0.5	4.8 ± 1.1

ANOVA	N *P*		P *P*		K *P*		Grain Yield *P*	
Water	0.0907		0.2122		0.0893		0.4804	
Compost	0.0673		0.0004	*	0.1004		0.011	*
Water*Compost	0.4873		0.9339		0.5374		0.583	
Fertilizer	0.0051	*	0.0536		0.0742		0.0004	*
Water*Fertilizer	0.7541		0.9967		0.3634		0.3536	
Compost*Fertilizer	0.854		0.7112		0.85		0.89	
Water*Compost*Fertilizer	0.0937		0.1895		0.1606		0.344	

Table 3: Second field season means and standard deviation for total N, P and K from straw and grain at 120 DAT and grain yield. Plots were intermittently flooded or continuously flooded (Flooded), with and with compost (13.5 t ha^{-1} composted cow manure) and with NK, NPK or no mineral fertilizer. ANOVA results are shown and significant *P* values (<0.05) are marked (*).

		N kg ha^{-1}		**P** kg ha^{-1}		**K** kg ha^{-1}		**Grain Yield** t ha^{-1}	
		Compost	**No compost**	**Compost**	**No compost**	**Compost**	**No compost**	**Compost**	**No compost**
Intermittently flooded	**NPK**	100 ± 41	52.4 ± 19	17.6 ± 6	7.4 ± 3	109 ± 50	54.3 ± 26	4.4 ± 1.3	2.7 ± 0.7
	NK	81 ± 37	48.7 ± 29	16.5 ± 3	8.2 ± 4	97 ± 50	47.1 ± 28	4.3 ± 0.8	3.1 ± 1
	None	39 ± 25	11.4 ± 3	11.7 ± 6	3.2 ± 2	65 ± 40	18.9 ± 5	2.7 ± 0.9	1.2 ± 0.5
Flooded	**NPK**	105 ± 18	114.5 ± 42	21.1 ± 4	16.5 ± 5	120 ± 28	119.8 ± 24	5.4 ± 1	5.2 ± 0.7
	NK	136 ± 54	62.9 ± 26	18.8 ± 1	14.6 ± 5	153 ± 51	74.9 ± 38	5.3 ± 0.8	4.8 ± 0.8
	None	54 ± 19	39.1 ± 22	14.4 ± 5	10.7 ± 5	95 ± 40	56.5 ± 28	3.8 ± 1.2	3.5 ± 1
ANOVA		*P*		*P*		*P*		*P*	
Water		0.659		<.0001 *		0.9156		<.0001 *	
Compost		0.162		0.1093		0.2068		0.0041 *	
Water*Compost		0.077		0.0019 *		0.0927		0.0366 *	
Fertilizer		<.0001 *		0.0001 *		0.0004 *		<.0001 *	
Water*Fertilizer		0.426		0.4062		0.7852		0.8228	
Compost*Fertilizer		0.208		0.5083		0.2481		0.9756	
Water*Compost*Fertilizer		0.16		0.5784		0.4314		0.8128	

Table 4: Diagnostic and Recommendation System (DRIS) index values for N, P and K for the first and second seasons. Negative values indicate nutrient deficiency and positive values indicate a nutrient over supply in relation to other nutrients. The nutrient balance is the sum of the absolute DRIS indices. Plots were intermittently flooded or continuously flooded (Flooded), with (Comp) and without (No C.) compost (13.5 t ha^{-1} composted cow manure) and with NK, NPK or no mineral fertilizer. ANOVA results are shown and significant *P* values (<0.05) are marked (*).

		First Season								**Second Season**							
		N		**P**		**K**		**Balance**		**N**		**P**		**K**		**Balance**	
		C.	**No C.**	**C.**	**No C.**	**C.**	**No C.**	**C.**	**No C.**	**C.**	**No C.**	**C.**	**No C.**	**C.**	**No C.**	**C.**	**No C.**
Intermittently flooded	**NPK**	52	77	-83	-117	31	40	166	235	-39	4	32	-36	7	31	70	44
	NK	59	172	-89	-251	31	79	179	502	-62	110	56	-195	6	85	92	190
	None	38	156	-58	-250	21	94	117	500	-64	-67	40	-17	24	85	85	161
Flooded	**NPK**	7	38	-32	-82	25	43	65	164	-64	-70	55	59	9	11	89	114
	NK	7	118	-35	-206	28	88	70	412	-66	28	56	-92	10	64	94	115
	None	26	104	-54	-185	28	80	109	370	-70	-81	37	42	33	39	99	161
ANOVA			*P*		*P*		*P*		*P*		*P*		*P*		*P*		*P*
Water			0.2909		0.4704		0.8901		0.5		0.6218		0.0145 *		0.068		0.2555
Compost			0.0002 *		0.0036 *		0.0833		0.0019 *		0.0009 *		<0.0001 *		<.0001 *		0.0007 *
Water*Compost			0.3621		0.5262		0.9934		0.4609		0.1009		0.0353 *		0.0114 *		0.1203
Fertilizer			<.0001 *		<.0001 *		<.0001 *		<.0001 *		0.0003 *		0.003 *		0.0006 *		0.0119 *
Water*Fertilizer			0.4146		0.8149		0.7915		0.8473		0.4339		0.7711		0.7699		0.468
Compost*Fertilizer			<0.0001 *		<0.0001 *		<0.0001 *		<0.0001 *		0.0003 *		0.0004 *		0.0056 *		0.0276 *
Water*Compost*Fertilizer			0.3055		0.2115		0.2319		0.2341		0.5543		0.8889		0.5051		0.6592

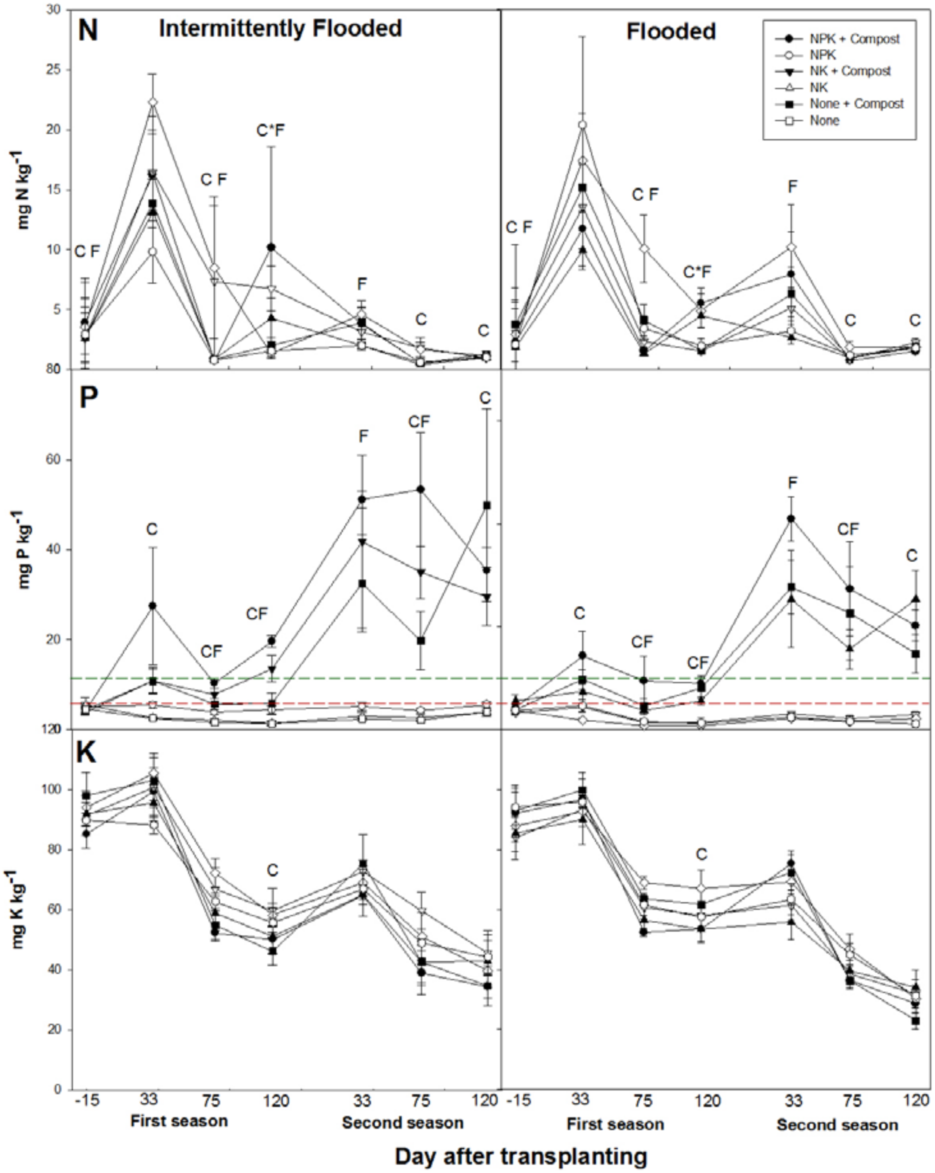


Figure 1. Available soil N, P, K means and standard errors are shown for the first (-15, 33, 75, and 120 d after transplanting (DAT)) and the second (33, 75 and 120 DAT). Critical levels of P fertility where yield reduction (<5 mg P kg^{-1}), and where no further yield response is expected (>10 mg P kg^{-1}) are shown (----) (Dobermann and Fairhurst, 2000). Plots were intermittently flooded or continuously flooded (Flooded), with and with compost (13.5 t ha^{-1} composted cow manure) and with NK, NPK or no mineral fertilizer. Significant treatment effects (*P*<0.05) from the ANOVA results are shown (C, Compost; F, mineral fertilizer).

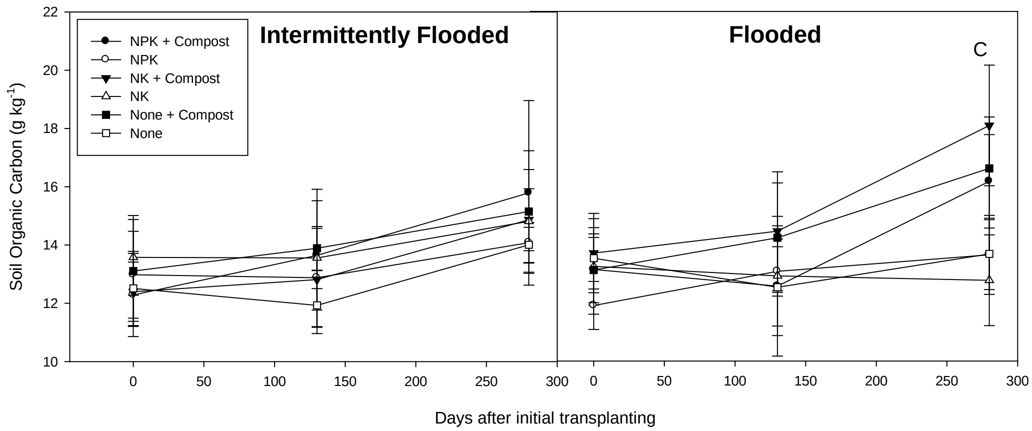


Figure 2. Soil organic carbon mean and standard errors from soil collected at the beginning and end of the first season (120 d) and at the second field season (280 d). Plots were intermittently flooded or continuously flooded (Flooded), with and with compost (13.5 t ha^{-1} composted cow manure) and with NK, NPK or no mineral fertilizer. Significant treatments effects (*P*<0.05) from the ANOVA results are shown (C, Compost).

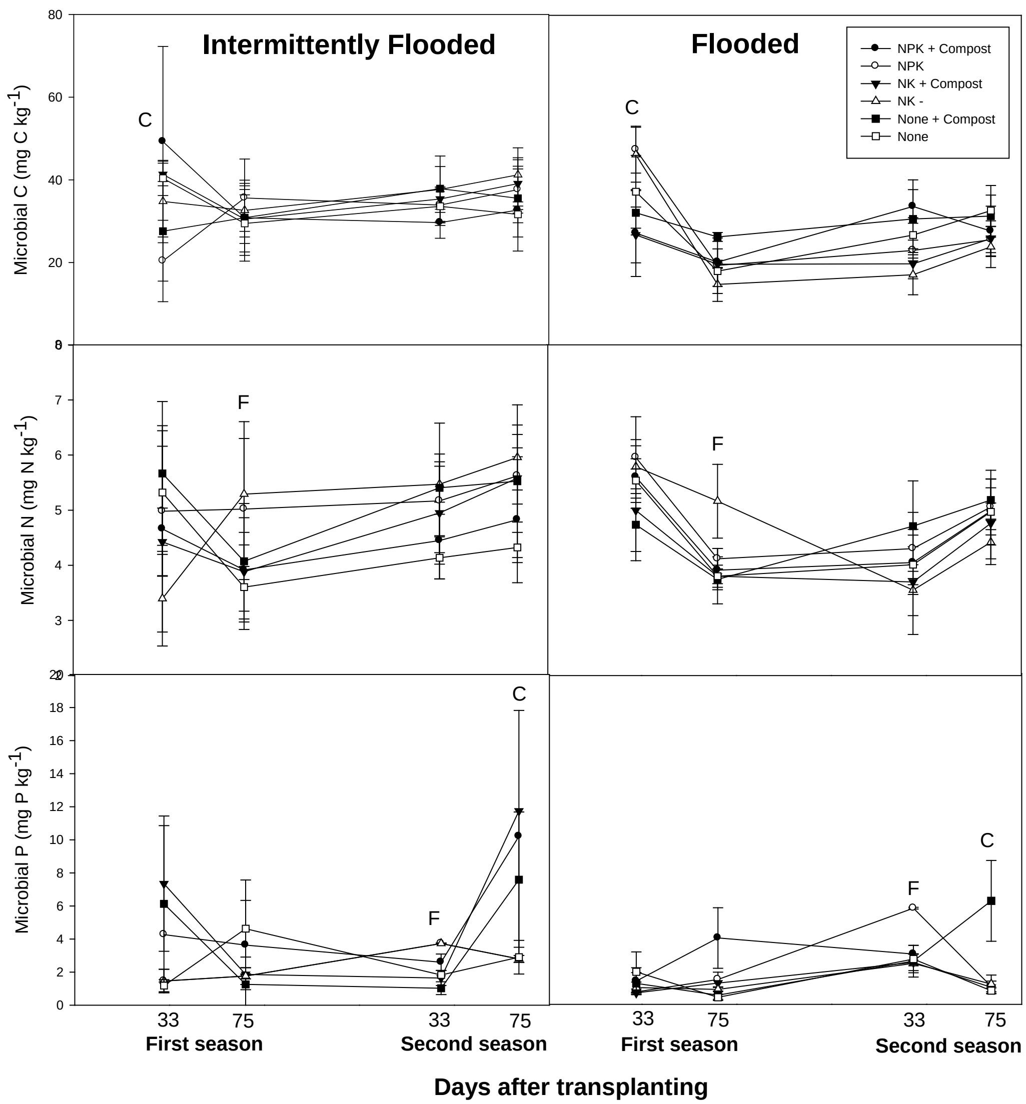


Figure 3. Microbial C, N and P means and standard errors are shown for the first and second season (33 and 75 d after transplanting). Plots were intermittently flooded or continuously flooded (Flooded), with and with compost (13.5 t ha^{-1} composted cow manure) and with NK, NPK or no mineral fertilizer. Significant treatments effects (P<0.05) from the ANOVA results are shown (C, Compost; F, mineral fertilizer).

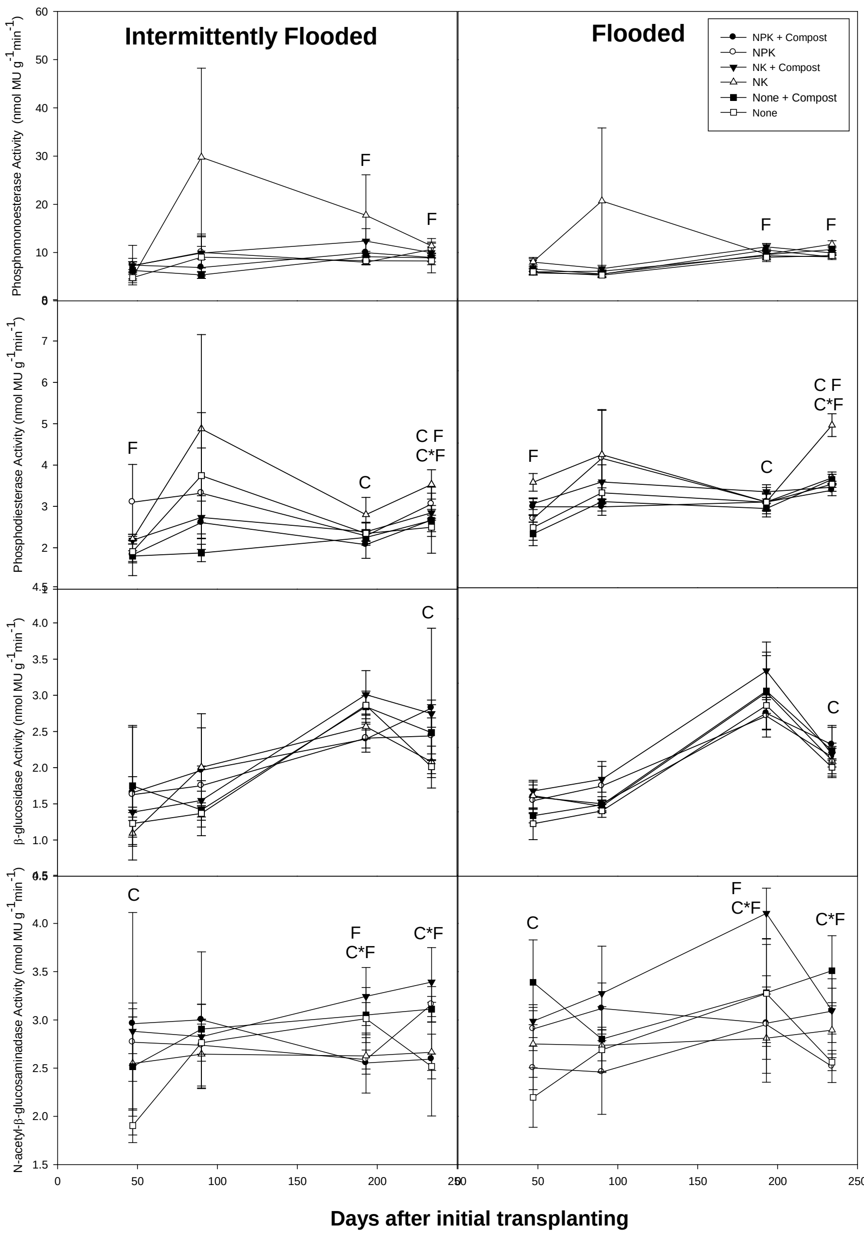


Figure 4. Soil enzyme activity means and standard errors are shown for the first and second season (33 and 75 d after transplanting). Plots were intermittently flooded or continuously flooded (Flooded), with and with compost (13.5 t ha^{-1} composted cow manure) and with NK, NPK or no mineral fertilizer. Significant treatments effects (P<0.05) from the ANOVA results are shown (C, Compost; F, mineral fertilizer).

Connecting Paragraph to Chapter 5

In Chapter 4, I found that under conditions of P limitation and water stress, rice yields were greater with composted cow manure (compost) and, when only compost was used, yields were similar under flooding and intermittently flooded conditions. These results suggest that SRI may be a suitable system for resource poor-farmers in Panama because their landholdings are mainly on weathered Inceptisols and Ultisols with low P fertility and they have limited access to mineral fertilizers and insufficient water resources for continuous flooding.

Results from experimental field stations are not always transferable to the farm because the farmers' economic and environmental conditions may be very different from those of field station. Thus, on-farm trials (10 farms) were conducted to evaluate the potential of the SRI, a low-input crop management system, to increase rice yields and reduce water consumption for resource-poor farmers in several regions of Panama.

Chapter 5. On-farm evaluation of a low-input rice production system in Panama

5.1. Abstract

On-farm trials were conducted to evaluate the potential of the System of Rice Intensification (SRI), a low-input crop management system, to increase rice yields and reduce water consumption on subsistence farms in several regions of Panama and to determine how inherent soil fertility might affect SRI yields and the yield response to SRI management in the first season of SRI management.

SRI practices increased yield by 47% on average and showed potential to increase yield by > 90%, while reducing water consumption by as much as 86%. SRI yields were correlated with available soil K and the difference between SRI and the conventional system yields was positively correlated with extractable Ca, Mg and Mn. The results of this study indicate that SRI is a promising rice production system for smallholder farmers in rural Panama farming.

Key words: Low-input agriculture; Panama; potassium; rice; soil fertility; System of Rice Intensification (SRI)

5.2. Introduction

The System of Rice Intensification (SRI) is an emerging low-input method for production of rice (*Oryza sativa* L.) that has the potential to increase crop yields while reducing the consumption of water, seed and mineral fertilizer (Barison, 2003; Randriamiharisoa et al., 2006). Developed in Madagascar in the 1980s, the first SRI experiments outside of Madagascar began in 1999, leading to its adoption in some parts of Asia, Africa and Latin America (Wang et al., 2002).

The SRI method involves early transplanting, lower plant density, use of organic fertilizer to supply all or some of the required nutrients, and intermittent wetting and drying of the soil rather than the prolonged flooding practiced in conventional rice paddy systems (Stoop et al., 2002). Some reports indicate that mineral fertilizer and water inputs can be reduced by up to 50% with SRI (Barison, 2003).

With SRI, fields can be irrigated intermittently, when they begin to dry (every 3-10 days depending on the climate and soil), in contrast to maintaining flooded paddies which are irrigated continuously. SRI has been found to increase yields significantly compared to the conventional system when implemented on strongly-weathered soils of low fertility (Acrisols and Ferralsols), and to produce relatively high yields (7-10 t ha^{-1}) in more fertile soils (Gleysols, Luvisols) (Turmel et al., 2011).

The adoption of SRI in Latin America has been slower than in Asia, in part due to a lack of local field trials and extension work. In 2001, Cuba became the first country in Latin American to establish SRI trials (Perez, 2002). Since then, the system has been tested in several other countries including Brazil, Costa Rica, Ecuador, Peru, and now Panama (Chang, 2008; CIIFAD, 2010; Gehring et al., 2008).

The majority of trials have reported positive results in terms of yields and resource-saving. Several reports indicate that weeds were a problem that reduce yields or require more labor in the SRI system (Chang, 2008; CIIFAD, 2010). Most of the data so far are from isolated trials; more extensive and robust experimentation in Latin America is required before conclusions can be drawn about SRI's suitability in the region.

The SRI is a low-input technology that could possibly boost rice production in rural Panama where poverty is endemic, with 36% of the rural population living in poverty and 20% living in extreme poverty (Government of Panama, 2003). The rural poor are mostly concentrated in areas with highly-weathered Ultisols and Alfisols, having low inherent fertility. Such soils are dominated by low activity clays (kaolinite) and have low soil organic C and associated nutrients (N, P and S). Both Ultisols and Alfisols have low cation exchange capacity, although, Ultisols are more weathered and have low concentrations of plant-available Ca, K and Mg (Van Wambeke, 1992). In many Panamanian farms, soil K fertility is further decreased because K-rich rice straw is removed at harvest.

The fertility of these tropical soils can be improved by adding nutrients (i.e. organic and mineral fertilizers) and liming (Van Wambeke, 1992). Rural Panamanian farmers have limited access to mineral fertilizers, and most rely on chicken manure and household composts to replenish soil nutrients. The advantage of applying organic fertilizers is that they supply essential N, P and K, which are the main nutrients limiting rice production, as well as other macro- and micro-nutrients.

In many regions, such as the Azuero Peninsula and other parts of central Panama, agricultural production is also limited by water availability from December through April. Farmers also find that rainfall is becoming more unreliable as well as insufficient, so water supply is expected to become a more influential factor in rice production.

This study thus was an initial evaluation of the potential of SRI practice to increase rice yields while reducing water consumption. It was undertaken on subsistence farms in five provinces across central Panama. The project provided practical information on SRI to Panamanian producers representative of the large population of smallholder households which depend on rice for part or much of their subsistence. At the same time, it sought to develop agronomic recommendations for SRI utilization based on on-farm results.

5.3. Methods

5.3.1. Farm sites

Working with a Panamanian NGO, *Patronato de Nutrición*, 10 collective farms were identified in different parts of rural Panama where subsistence farmers are producing rice as their staple food. The Patronato, with public and private funding, purchases land in areas of extreme poverty, helping local households establish the farm and operate it as a democratically self-governed community. It provides the communities with training and inputs for producing food more efficiently and sustainably, to improve household nutrition, reduce hunger, and raise incomes.

Each farm has about 5 ha of productive land, which the surrounding families farm collectively and whose harvests they share. While the land belongs to the Patronato, it collects neither a share of the harvest nor rent. Patronato agronomists visit the farms regularly to advise on agronomic practices and to bring agricultural supplies (seeds, tools, etc.). The Patronato is currently working with over 300 such farms across Panama.

The 10 farms selected are located in the country's central provinces of Veraguas, Cocle, Panama, Colon and Herrera (Figure 1). All of the farms are located in mountainous areas in the interior of the country, with the exception of one farm which is located in the lowlands (Aguas Claras 1). The number of farmers in each collective who participated in the trials ranged from 2 to 8, with a total of 46 farmers involved (Table 1).

5.3.2. On-farm trials comparing SRI to the conventional system of rice cultivation

All trials used a locally-developed rice variety, IDIAP 38, which is suitable for either flooded or aerobic soils, and which grows well in acidic soils. In each trial a plot was cultivated of approximately 10 x 10 m using SRI methods. This SRI trial plot was situated adjacent to a rice plot of equal dimensions where the conventional methods recommended currently by the government's Agriculture Department were used. This involves flooding the soil continuously throughout the growing season and transplanting seedlings at an average age of 20 d, with spacing of 20 cm and two or three seedlings per hill. The SRI methods evaluated included: transplanting single, young seedlings 10 d old with square spacing at least 25 cm; using organic fertilizer; and promoting aerobic soil conditions by flooding the plot approximately once per week and by using an SRI weeding implement.

The frequency of flooding of each plot and quantity of fertilizer used was recorded for each farm. Only organic fertilizer (average of 8 t ha^{-1} of chicken manure, household compost or waste from coffee production) was used with the exception of three farms that also used mineral fertilizer (Aguas Claras 1, 110kg-N ha^{-1}; Barrigon, 28 kg N ha^{-1}, 55 kg P ha^{-1}, 28 kg K ha^{-1}; Palmilla, 64 kg N ha^{-1}). The same amounts of fertilizer were applied to both the conventional and SRI plots in each case.

One of the main challenges in switching from a flooded to an aerobic rice production system is weed control. In Panama, continuous flooding is used primarily to control excessive weed growth, although weed growth is vigorous enough that manual weeding with a machete is still required several times during the growing season. SRI farmers in Madagascar and parts of Asia have adopted a manually-operated weeding tool with rotating blades that uproots and incorporates weeds into the soil, thus reducing the weed population and adding organic matter. As part of this study, the SRI weeding tool was evaluated to determine its effectiveness in controlling weeds in SRI. The weeding tool was used at least three times during the vegetative growth of the rice crop.

The rice grain was harvested from each plot, dried in the sun, and then weighed with a calibrated scale. Yield was calculated as grain weight/plot area.

4.3.3. Soil analysis

Before the experiment began, soil surface samples (0-10 cm) were collected from each farm by compositing 10 random cores per plot. Soil texture, soil pH and available soil nutrient concentrations were determined. Available nutrients (Ca, Cu, K, Mg, Mn, P and Zn) were extracted with Mehlich-3 solution (Mehlich, 1984). The concentration of amorphous Al and Fe (Fe-ox and Al-ox) and associated P (P-ox) were determined by oxalate extraction with detection by inductively coupled plasma optical emission spectrometry (Schoumans, 2000).

5.3.4. Statistical analysis

Statistical analysis was conducted using the JMP interface of Statistical Analysis Software (2008, SAS Institute). Soil and yield data were log transformed to normalize and reduce the scale of the data set. Correlation analysis for the soil and yield dataset was performed using the restricted maximum likelihood method.

5.4. Results and discussion

5.4.1. Grain Yield

Rice crops were planted in September 2009 and harvested in January 2010. Yields ranged from 0.61 t ha^{-1} to 7.48 t ha^{-1} in the conventional system and from 1.21 t ha^{-1} to 8.98 t ha^{-1} with SRI (Table 2). Yields were higher in SRI in 8 of the 10 farms and were similar to the conventional system in the other two farms.

In Cocuyal, La Mata and Las Lajas, yields increased by >90% with SRI, while in Barrigon, Loma, Cope and Palmilla, yields were 30% greater in SRI than the conventional system. Yields were 8% and 6% lower with SRI than the conventional system at San Juan and La Puente, respectively. Both of these sites were in the same region of Veraguas and had similar sandy soils with low base cation (Ca, K and Mg) concentrations. Thus, these results may be related to the rapid rate of water infiltration in these soils or the lower nutrient status. However, the actual reduction in yield was only 1.8 and 2.3 kg per 100 m^2 plot and was not a major economic loss given the potential water savings. The mean yield increase with SRI methods was 47% across the 10 on-farm trials in Panama.

5.4.2. Water savings

Sufficient soil moisture in the SRI plots was maintained by irrigating once or twice a week, in contrast to the conventional plots that were irrigated daily to maintain flooded conditions. In this situation, SRI management reduced water consumption by 71–86% in the on-farm trials.

Reductions in water consumption could benefit the farming communities by liberating more water for other agricultural activities, such as bean and corn production, and for aquaculture. Climate change is increasing the variability in rainfall patterns and thus it may important to have a rice production system that can succeed with less water. SRI water management may also reduce the fertilizer loss in water runoff compared to the conventional flooded system.

5.4.3. Weed control

This was not found to be a problem with SRI management. While more weed growth was observed in the SRI plots than the conventional plots (because there was no continuous flooding), farmers were able to control weeds effectively with the weeding tool.

With SRI, it was important to transplant the seedlings in straight rows, with regular spacing, so that the weeding tool could pass through the rows. Weeds growing extremely close to the rice plants still had to be removed by hand.

5.4.4. Seedling transplant

Transplanting the younger seedlings with wider spacing was not a problem in the SRI system. It took more time to plant in straight lines, but overall it was as an advantage because the weeding tool could pass readily between the rows.

The main obstacle to the adoption of SRI in large-scale rice production is the transition to low density planting. In most parts of Latin America, large-scale rice production systems use direct seeding with a high plant density, whereas the basic methodology of SRI relies on wide spacing of singly transplanted seedlings. Transplanting of rice is presently used by some small-scale and subsistence farmers in Panama, and thus SRI may be more suitable for small-scale operations. This problem could be overcome, however, by the mechanization of transplanting. A Costa Rican producer has successfully implemented SRI on a larger-scale using a mechanical transplanter adjusted for extremely low density planting (CIIFAD, 2010). Mechanical transplanters, however, are currently not common or easily obtained in Latin America.

5.4.5. Soil nutrients and yields

Soil nutrient status is a key determinant of crop yield. As with grain yield, soil nutrient status varied greatly among the farms (Table 3). Soils ranged in texture from clay to sandy clay to loamy sand. Soil pH ranged from 5.2 to 6.5, so none of the soils were below the threshold soil pH for potential aluminum toxicity (pH 4.3). The available soil P and K at several sites fell below the critical levels for rice production (5 mg P kg^{-1} and 37 mg K kg^{-1}) (Dobermann and Fairhurst, 2000; Namé and Villarreal, 2004b). Potassium deficiency is common in Panamanian soils where K fertilizer is not used (Name and Villarreal, 2004b). Low concentrations of available K occurred mainly in the sandy clay soils. Two of the sites, La Puente and San Juan, also had critically low available soil Ca and Mg. Given this wide range of soil properties and yields we attempted to find relationships that could explain both SRI and conventional yields, and the yield difference between the two systems.

Correlation analysis of soil nutrients and yield responses showed significant (P<0.05) correlations among several of the pairs (Table 4). SRI and conventional yields were significantly correlated (r=0.94), demonstrating that potential yields were site-specific and depended on inherent soil fertility, local microclimate and historical agronomic management on the farm.

SRI yield was positively correlated with available soil K (r=0.64) and both SRI and conventional yields were correlated with available soil Cu (r=0.71 and 0.70, respectively). The yield difference between SRI and conventional was correlated with available soil Ca (r=0.75), Mg (r=0.77) and Mn (r=0.71), suggesting that these nutrients may play a role in determining the yield increase in SRI compared to the conventional system.

The available soil Ca concentration was positively correlated with soil Mg (r=0.97) and soil Mn (0.66), while Fe-ox was positively correlated with extractable Ca (r=0.82) and Mg (r=0.80). These nutrients are associated with CEC on mineral surfaces, suggesting that soils with greater CEC retain and release greater quantities of plant-available macro- and micro-nutrient cations into the soil solution.

Of interest was that rice yield was not correlated with soil P fractions (Mehlich-3 or oxalate extractable), even though P was very low at many of the sites (Table 3). This may indicate that sufficient P was supplied by the addition of manures and compost throughout the growing season.

Soil biological activity is also an important factor affecting nutrient cycling and overall soil fertility that would be promoted by the aerobic soil conditions in SRI. However, in this study, soil biological parameters were not evaluated due to logistical constraints. Here I was interested in examining whether SRI methods could improve food security, helping the rural population meet their needs for rice, a staple food, while helping to preserve their water resources.

5.5. Conclusion

The results of these initial field trials with SRI methods indicate that rice yields can be substantially increased or at least maintained with reduced inputs of water and seeds on smallholder farms in Panama, using a low-external input, organically-fertilized system. The main advantages of SRI, are increased yield, water savings, and saving of labor time using the SRI weeding tool.

SRI yield was positively correlated with soil K, and both SRI and conventional system yields were correlated with soil Cu. The yield difference between SRI and the conventional system was correlated with Ca, Mg and Mn. Panamanian farmers may need to adjust their storage and handling of organic wastes to ensure that on-farm fertilizers like chicken manure and household compost supply adequate quantities of nutrients to supply the needs of rice grown under SRI conditions.

Based on the results of this initial evaluation, I conclude that SRI is a promising rice production system for smallholder farmers in rural Panama. More research is required to further elucidate the effects of soil fertility on the yield response to SRI practice. Findings from the soil biological analyses may help to illuminate the soil-crop yield relationships involved in SRI yield enhancement.

Acknowledgments

The funding for this research was provided by the International Development Research Centre and the Natural Sciences and Engineering Research Council of Canada. Norman Uphoff provided helpful comments on this manuscript.

Table 1. Names and locations of the *Patronato de Nutricion* collective farms that participated in the trials, and the number of farmers at each farm.

	Farm	Township	District	Province	Farmers
1	Aguas Claras 1	Santa Rosa	Colon	Colon	4
2	Aguas Claras 2	Tulu	Penonome	Cocle	2
3	Barrigon	Vigui	Las Palmas	Verguas	5
4	Cocuyal	El Rincon	Las Palmas	Veraguas	8
5	La Mata	San Jose	Canazas	Veraguas	4
6	La Puente	El Alto	Santa Fe	Veraguas	7
7	Las Lajas	Ciri de Los Sotos	Capira	Panama	4
8	Loma Cope	Los Cerros de Paja	Los Pozos	Herrera	7
9	Palmilla	Chigri	Penonome	Cocle	3
10	San Juan	La Yeguada	Calobre	Verguas	2

Table 2 SRI and conventional rice yields on collective farms, showing also differences between SRI and conventional yields, and response ratio to SRI (LnRR=natural logarithm for SRI yield/ conventional yield).

Farm	SRI yield (t ha^{-1})	Conventional yield (t ha^{-1})	Yield yifference (t ha^{-1})	LnRR
1	8.98	7.48	1.50	0.18
2	5.18	3.19	1.99	0.48
3	4.94	3.63	1.32	0.31
4	5.22	2.72	2.49	0.65
5	1.21	0.61	0.60	0.68
6	1.70	1.81	-0.11	-0.07
7	2.99	1.54	1.45	0.66
8	8.12	5.91	2.21	0.32
9	6.41	4.44	1.97	0.37
10	2.79	3.02	-0.23	-0.08

Table 3 Soil properties and available soil nutrients in the top 0-10 cm of soil

			Mehlich-3							Oxalate		
Farm	Texture	pH	P	K	Ca	Mg	Mn	Cu	Zn	Al-ox	Fe-ox	P-ox
			-- mg kg^{-1} --------------------------------									
1	Silty Clay	5.6	3.0	105	5275	1446	161	7	15	575	1693	29
2	Silty Clay	6.5	47.8	129	1422	148	261	3.3	3.6	483	1192	47
3	Clay	5.6	3.7	112	2131	425	87	3.0	0.9	1061	1974	7
4	Clay	5.8	26.1	165	1420	363	149	4.0	2.8	455	2001	8
5	Clay	6.4	6.3	21	1267	226	35	1.9	0.7	647	1174	9
6	Sandy Clay	5.2	44.5	13	235	20	2	3.6	3.5	622	861	27
7	Sandy Clay	5.2	0.1	32	2469	855	190	3	8	587	1749	2
8	Sandy Clay	5.8	3.8	37	1117	262	113	7	4	181	925	5
9	Loamy Sand	5.9	31.3	62	1037	225	95	3.5	1.7	1365	1019	36
10	Sandy Clay Loam	5.2	15.8	78	302	33	90	1.9	2.1	524	643	9

Table 4. Correlations among initial soil nutrients and grain yield. Yield difference is SRI yield – conventional yield, and LnRR = Ln (SRI yield / conventional yield) (restricted maximum likelihood; *, *P*<0.05; ***P*<0.001).

	P	K	Ca	Mg	Mn	Cu	Zn	Al-ox	Fe-ox	P-ox	SRI Yield	Con. Yield	Yield Dif.	LnRR
pH	0.32	0.26	0.27	0.19	0.28	-0.11	-0.32	-0.03	0.09	0.39	0.07	-0.10	0.48	0.54
P		0.07	-0.57	-0.65*	-0.37	-0.14	-0.33	0.15	-0.43	0.75*	-0.12	-0.08	-0.23	-0.28
K			0.48	0.40	0.73*	0.05	0.11	0.09	0.44	0.17	0.64*	0.61	0.52	0.16
Ca				0.97**	0.66*	0.31	0.46	0.06	0.82*	-0.14	0.49	0.34	0.75*	0.59
Mg					0.65*	0.37	0.42	0.04	0.80*	-0.26	0.51	0.35	0.77*	0.61
Mn						0.08	0.32	-0.17	0.39	-0.21	0.62	0.45	0.71*	0.48
Cu							0.62	-0.41	0.14	0.17	0.71*	0.70*	0.41	-0.17
Zn								-0.37	0.24	0.03	0.46	0.46	0.22	-0.11
Al-ox									0.20	0.30	-0.19	-0.15	-0.07	-0.01
Fe-ox										-0.26	0.26	0.12	0.62	0.61
P-ox											0.16	0.25	-0.05	-0.36
SRI yield												0.94**	0.71	-0.02
Conv. Yield													0.45	-0.33
Yield difference														0.66*

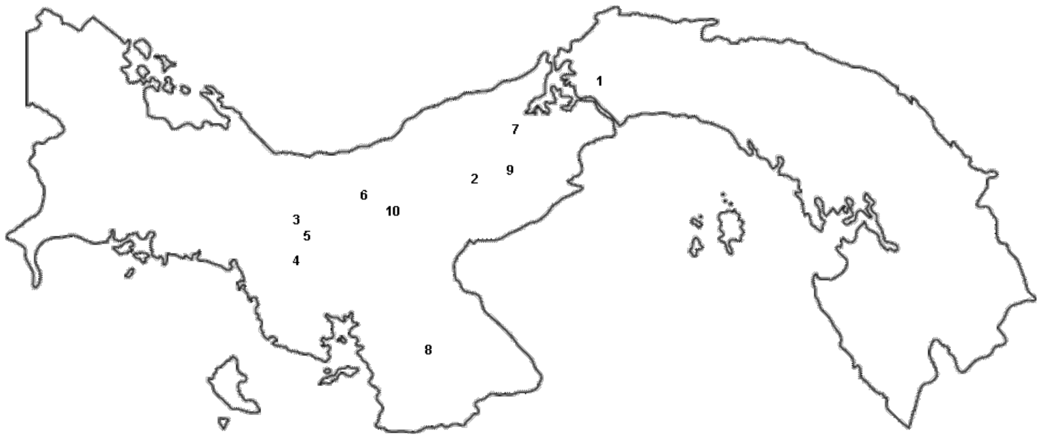


Figure 1 Map of Panama showing locations of the 10 evaluation sites. The numbers on the map represent the locations of the farms and correspond with the farm numbers given in Tables 1, 2 and 3.

General Conclusions

The objective of this research was to determine the potential of SRI to improve rice yields in low-fertility soils and the biological and chemical mechanism underlying yield improvements with SRI observed in some studies. The meta-data analysis provided significant evidence that SRI increases rice yields on low fertility soils in regions other than Madagascar and has no effect on yields in moderate to high fertility soils. These results were validated in a greenhouse study where intermittent flooding and organic fertilization, important components of SRI, improved rice growth (biomass at harvest) and P uptake in soils with low P fertility ($\leq$7.1 mg P kg^{-1}), whereas in soils with greater P fertility, a system using flooding and mineral fertilizer produced the greatest plant biomass. These results support the hypothesis that P limitation in highly weathered soils can be overcome with intermittent flooding and organic fertilization. Further work on the interactions between soil Fe and P is needed to differentiate the interactive effects of organic fertilization and water regime on plant P nutrition and Fe toxicity in highly-weathered soils.

Results from the field showed that organic fertilization is an important factor in improving crop P nutrition and yield under P-limiting conditions and maintaining yields in water conserving rice production systems that do not use continuous flooding. Compost (composed cow manure) increased soil P availability, plant P uptake and yields in a low fertility tropical Inceptisol in both intermittently flooded and continuously flooded water regimes. Compost may also boost yields in water conserving rice systems by increasing the plant available supply of N. Both greenhouse and field results suggested that intermittently flooded soils may be more susceptible to N losses and future research should also focus on developing nutrient and water management regimes to improve N use efficiency in water conserving rice production systems.

On-farm trials showed that SRI methods were effective. Rice yields increased substantially (8 of 10 farms) or were at least maintained (remaining 2 farms) with reduced inputs of water on smallholder farms in Panama, using an intermittently flooded, organically-fertilized system. The main advantages of SRI for farmers in Panama are: possibility of increased yield, water savings, and saving of labour time, using the SRI weeding tool. Based on the results of this initial evaluation, we conclude that SRI is a promising rice production system to improve crop P nutrition and yields and conserve water for smallholder farmers in rural Panama.

Contribution to knowledge

The research conducted in this thesis provides the following important contributions to knowledge:

- This was the first study to focus on the soil fertility aspect of the System of Rice Intensification (SRI). This work contributed to resolving the controversy over the yield benefits of SRI by showing that soil properties in part control the yield improvements with SRI and the greatest yield improvements with SRI are found in low fertility soils (Acrisols, Ferralsols).
- The soil-dependent yield response to SRI is in part controlled by P fertility and plant growth is greater in a system using organic fertilization and intermittent flooding than a system using mineral fertilizer and continuous flooding when soil available P $\leq$7.1 mg P kg^{-1}.
- This the first report of the interaction between fertilizer source and water regime in low fertility tropical soils. I showed that fertilization with composted cow manure reduces crop P limitation and increase yields in tropical soils with low P availability under both intermittently flooded and continuously flooded conditions. Composted cow manure increased available soil P, microbial P, phosphomonoesterase activity and plant P uptake under both water regimes, and greater increases were measured under intermittently flooded conditions. This is consistent with the hypothesis that organic fertilization would promote biological P recycling.
- Composted cow manure can improve crop nutrient balance and yields in tropical soils under an intermittently flooded water regime under N limiting conditions.
- This was the first detailed study about SRI conducted in the Americas. Evidence from on-farms trials showed that SRI can improve yield and conserve water resource for resource poor-farmers in Panama.

Future research directions

The research presented in this thesis took the initial steps to explain the influence of soil fertility on yield improvements in the System of Rice Intensification and the interactive effects of fertilizer source and water regime on rice production in low fertility tropical soils. Here I suggest directions for further research that were identified during the course of this work.

- In the future, more SRI studies with detailed soils information may be available and it would be worthwhile to conduct a meta-analysis of the effects of specific soil properties on the yield response to SRI.

- Future work should look at the differences in microbial communities between systems that use intermittent flooding vs. continuous flooding. It would be of interest to investigate the effects of water regime and fertilizer source on the mycorrhizal fungal activity and P uptake by rice, particularly in soils with low P fertility.

- Future work should examine the interactions between soil P and Fe in flooded soils with low P availability and high Fe content.

- This work focused on tropical soils where yield was limited by soil P availability. Future work should also look at the effect of SRI on rice yields where yield is limited by other factors such as N, soil salinity and metal toxicity.

- Further research is also required to develop nutrient and water management regimes to improve N use efficiency in water conserving rice production systems.

References

Acharya C.N. (1935) Studies on the anaerobic decomposition of plant materials. III. Comparison of the course of decomposition of rice straw under anaerobic, aerobic and partially aerobic conditions. Biochemical Journal 29:1116-1120.

Ahn P.M. (1993) Tropical soils and fertilizer use. Longman Group UK Limited, Essex.

Bangladesh Rice Research Institute (BRRI). (2000) System of Rice Intensification: A new approach to raise the production of rice. Bangladesh Rice Research Institute, Comilla, Bangladesh.

Barison J. (2003) Nutrient-use efficiency and nutrient uptake in conventional and intensive (SRI) rice cultivation systems in Madagascar, Cornell University, Ithaca, NY.

Ceesay M.M. (2002) Experiments with the System of Rice Intensification in The Gambia: N. Uphoff, et al. (Eds.), Assessments of the System of Rice Intensification (SRI) Conference Proceedings, Sanya, China, April 1-4.

Chang J.V.G. (2008) Cultivo de arroz sistema intensificado SICA - SRI en Ecuador, Fundación para el Desarrollo Agrícola del Ecuador.

CIIFAD. (2010) http://ciifad.cornell.edu/sri/countries/index.html.

Counce P., Wells B. (1986) Rice Y-leaf nutrient analyses and midseason foliar fertilization. Communications in Soil Science and Plant Analysis 17:1071-87.

Das L. (2003) Verification and Refinement of the System of Rice Intensification (SRI) in Selected Areas of Bangladesh. SAFE Development Group, Dhanmondi, Bangladesh.

Dieter D., Elsenbeer H., Turner B.L. (2010) Phosphorus fractionation in lowland tropical rainforest soils in central Panama. Catena 82:118-125.

Dobermann A. (2004) A critical assessment of the system of rice intensification (SRI). Agricultural Systems 79:261-281.

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

Driessen P., Deckers J., Spaargaren O., Nachtergaele F. (2001) (Eds.) Lecture Notes on the Major Soils of the World, Food and Agriculture Organization, Rome.

Duponnois R., Colombet A., Hien V., Thioulouse J. (2005) The mycorrhizal fungus *Glomus intraradices* and rock phosphate amendment influence plant growth and microbial activity in the rhizosphere of Acacia holosericea. Soil Biology & Biochemistry 37:1460-1468.

Evans C., Justice S., Shrestha S. (2002) Experience with the system of rice intensification in Nepal, in: N. Uphoff, et al. (Eds.), Assessments of the system of rice intesification (SRI) Conference Proceedings, Sanya, China, April 1-4.

Fageria N.K., Santos A.B., Barbosa Filho M.P., Guimaraes C.M. (2008) Iron toxicity in lowland rice. Journal of Plant Nutrition 31:1676-1697.

Feller C., Frossard E., Brossard M. (1994) Phosphatase-activity in low activity tropical clay soils - distribution in the various particle-size fractions Canadian Journal of Soil Science 74:121-129.

Food and Agriculture Organization. (2006) World agriculture: towards 2030/2050. Interim report, Food and Agriculture Organization Rome.

Gani A., Kadir T.S., Jatiharti A., Wardhana I.P., Las I. (2002) The System of Rice Intensification in Indonesia, in: N. Uphoff, et al. (Eds.), Assessments of the System of Rice Intensification (SRI), Conference Proceedings, Sanya, China, April 1-4.

Gehring C., de Moura E.G., Boddey R.M. (2008) System of Rice Intensification (SRI) in southeastern lowlands of Amazonia – a viable alternative for smallholder irrigated rice production?, Maranhão State University and National Agrobiology Research Center.

Government of Panama (2003) Encuesta de Niveles de vida, Ministerio de Economía y Finanzas, Dirección de Políticas Sociales, Panama City.

Gypmantasiri P. (2002) Experience with the System of Rice Intensification in Northern Thailand: N. Uphoff, et al. (Eds.), Assessments of the System of Rice Intensification (SRI) Conference Proceedings, Sanya, China, April 1-4.

Hameed K.A., Jaber F.A. (2007) System of Rice Intensification in Iraq during 2007. Al-Mishkhab Rice Research Station, Najaf, Iraq.

Haynes R.J., Mokolobate M.S. (2001) Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. Nutrient Cycling in Agroecosystems 59:47-63.

Hedges L.V., Gurevitch J., Curtis P.S. (1999) The meta-analysis of response ratios in experimental ecology. Ecology 80:1150-1156.

Hedley M.J., Stewart J.W.B., Chauhan B.S. (1982) Changes in inorganic and organic soil-phosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Science Society of America Journal 46:970-976.

Hengsdijk H., Bindraban P. (2004) Rice: location is vital in crop management. Nature 429:803-803.

Huang S.H., Pant H.K., Lu J. (2007) Effects of water regimes on nitrous oxide emission from soils. Ecological Engineering 31:9-15.

Huguenin-Elie O., Kirk G.J.D., Frossard E. (2003) Phosphorus uptake by rice from soil that is flooded, drained or flooded then drained. European Journal of Soil Science 54:77-90.

IAASTD. (2008) International Assessment of Agricultural Knowledge Science and Technology for Development, Executive Summary of the Synthesis Report, Johannesburg, South Africa.

Ilag L.L., Rosales A.M., Elazegui F.A., Mew T.W. (1987) Changes in the population of infective endomycorrhizal fungi in a rice-based cropping system. Plant and Soil 103:67-73.

Illmer P., Barbato A., Schinner F. (1995) Solubilization of hardly-soluble $AlPO_4$ with P solubilizing microorganims Soil Biology & Biochemistry 27:265-270.

Kabir H. (2006) Adaptation and Adoption of the System of Rice Intensification (SRI) in Myanmar Using the Farmer Field School (FFS) Approach. University of Honolulu. pp. 124 p.

Khalifa S. (2006) Second phase experiments of SRI in loamy sand area Upper Sabangida - Kunduna State of Nigeria. Ahmadu Bello University, Sabon Gari.

Kirk G.J.D. (2004) The biogeochemistry of submerged soils. Wiley, Chichester, England.

Lachat Instruments. QuickChem Methods.

Larijani B.A. (2007) Report on System on Rice Intensification in Iran, Agronomy Group, Haraz Technology Development and Extension Center, Amol, Mazandaran, Iran.

Latif M.A., Islam M.R., Ali M.Y., Saeque M.A. (2005) Validation of the system of rice intensification (SRI) in Bangladesh. Field Crops Research 93:281-292.

Lee S.B., Lee C.H., Jung K.Y., Park K.D., Lee D., Kim P.J. (2009) Changes of soil organic carbon and its fractions in relation to soil physical properties in a long-term fertilized paddy. Soil and Tillage Research 104:227-232.

M S Swaminathan Research Foundation (MSSRF). (2002) SRI experiences during the samba season of 2002 at Pondicherry, Pondicherry, India.

McDonald A.J., Hobbs P.R., Riha S.J. (2006) Does the system of rice intensification outperform conventional best management? A synopsis of the empirical record. Field Crops Research 96:31-36.

Mehlich A. (1984) Mehlich-3 soil test extractant - A modification of Mehlich-2 extractant. Communications in Soil Science and Plant Analysis 15:1409-1416.

Mentzer J.L., Goodman R.M., Balser T.C. (2006) Microbial response over time to hydrologic and fertilization treatments in a simulated wet prairie. Plant and Soil 284:85-100.

MIDA. (2009) El estado del la produccion arrocera Panama, in: MIDA Panama (Ed.), Gobierno Nacional de Panama, Panama.

Namé B., Villarreal J. (2004a) Evaluación agronomica de la roca fosforica de carolina de norte en un ultisol en una rotacion arroz-frijol. , in: B. Namé and J. Villarreal (Eds.), Compendio de resultados de investigación del programa de suelos del IDIAP, Panama.

Namé B., Villarreal J. (2004b) Dinamica de potasio en un Ultisol de Panama repuesta al cultivo de arroz, Compendio de Resultados de Investigacion del Programa de Suelos de IDIAP, Instituto de Investigacion Agropecuaria de Panama, Panama.

Nelson G.C., Rosegrant M.W., Koo J., Robertson R., Sulser T., Zhu T., Ringler C., Msangi S., Palazzo A., Batka M., Magalhaes M., Valmonte-Santos R., Ewing M., Lee D. (2009) Impact on Agriculture and Costs of Adaptation, International Food Policy Research Institute, Washington, D.C.

Nissanka S., Bandara T. (2004) Comparison of productivity of system of rice intensification and conventional rice farming in the dry-zone region of Sri Lanka. Fourth International Crop Science Congress, Brisbane, Australia.

Nziguheba G., Palm C.A., Buresh R.J., Smithson P.C. (1998) Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. Plant and Soil 198:159-168.

Oberson A., Friesen D.K., Tiessen H., Morel C., Stahel W. (1999) Phosphorus status and cycling in native savanna and improved pastures on an acid low-P Colombian Oxisol. Nutrient Cycling in Agroecosystems 55:77-88.

Oberson A., Friesen D.K., Rao I.M., Buhler S., Frossard E. (2001) Phosphorus transformations in an Oxisol under contrasting land-use systems: The role of the soil microbial biomass. Plant and Soil 237:197-210.

Olaleye A.O., Tabi F.O., Ogunkunle A.O., Singh B.N., Sahrawat K.L. (2001) Effect of toxic iron concentrations on the growth of lowland rice. Journal of Plant Nutrition 24:441-457.

Osorio N.W., Habte M. (2001) Synergistic influence of an arbuscular mycorrhizal fungus and a P solubilizing fungus on growth and P uptake of *Leucaena leucocephala* in an oxisol. Arid Land Research and Management 15:263-274.

Parkinson, A. (1975) A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological material. Communication in Soil Science and Plant Analysis. 6:1-11.

Patrick W.H., Delaune R.D. (1972) Characterization of oxidized and reduced zones in flooded soil. Soil Science Society of America Proceedings 36:573.

Patrick W.H., Khalid R.A. (1974) Phosphate release and sorption by soils and sediments - Effect of aerobic and anerobic conditions Science 186:53-55.

Paul E.A. (2007) (Ed.) Soil Microbiology, Ecology and Biochemistry., Elsevier, Oxford. pp. Pages.

Perez R. (2002) Experience in Cuba with the System of Rice Intensification, Assessments of the System of Rice Intensification (SRI), Cornell International Institute for Food, Agriculture and Development, Sanya, China.

Ponnamperuma F.N. (1972) The chemistry of submerged soils. Advances in Agronomy 24:29-96.

Pulford I.D., Tabatabai M.A. (1988) The effect of waterlogging on enzyme-activities in soil. Soil Biology & Biochemistry 20:215-219.

Ramakrishna A., Bailey J.S., Kirchhof G. (2009) A preliminary diagnosis and recommendation integrated system (DRIS) model for diagnosing the nutrient status of sweet potato (*Ipomoea batatas*). Plant and Soil 316:107-116.

Randriamiharisoa R., Uphoff N. (2002) Factorial Trials Evaluating the Separate and Combined Effects of SRI Practices, Cornell International Institute for Food, Agriculture and Development, Ithaca.

Randriamiharisoa R., Barison J., Uphoff N. (2006) Soil Biological Contributions to the System of Rice Intensification, in: N. Uphoff, et al. (Eds.), Biological approaches to sustainable soil systems, CRC Press, Taylor and Francis Group, Boca Raton, FL, pp. 409-424.

Rickman J.F. (2002) Preliminary Results Rice Production and the System of Rice Intensification (SRI), International Rice Reseach Institute, Los Banos.

Sahrawat K. (1982) Nitrification in some tropical soils. Plant and Soil 65:281-286.

Sahrawat K.L. (2003) Organic matter accumulation n submerged soils, in: D. L. Sparks (Ed.), Advances in Agronomy, Academic Press. pp. 169-201.

Sahrawat K.L. (2004) Iron toxicity in wetland rice and the role of other nutrients. Journal of Plant Nutrition 27:1471-1504.

Sahrawat K.L. (2007) Soil fertility advantages of submerged rice cropping systems: A review. Journal of Sustainable Agriculture 31:5-23.

Sanchez P.A. (1976) Properties and Management of Soils in the Tropics John Wiley and Sons, Inc., New York.

SAS Institute. (2002) The SAS system for Windows V. 9.0, Cary, NC, USA.

SAS Institute. (2008) JMP Statistical Discovery 8.0, Cary, NC, USA.

Sato S. (2006) An evaluation of the System of Rice Intensification (SRI) in Eastern Indonesia for its potential to save water while increasing productivity and profitability, International Dialogue on Rice and Water: Exploring Options for Food Security and Sustainable Environments, Los Baños, Phiilippines.

Schiller J.M. (2004) System of rice intesification - SRI - Suitability for lowland rice production in the Lao PDR. National Agricultural Research Center, Laos.

Schoumans O. (2000) Determination of the degree of phosphorus saturation in non-calcareous soils., Methods of Phosphorus Analysis for Soils, Sediments, Residuals and Waters. pp. 31-34.

Seng V., Bell R.W., Willett I.R. (2004) Amelioration of growth reduction of lowland rice caused by a temporary loss of soil-water saturation. Plant and Soil 265:1-16.

Shahandeh H., Hossner L.R., Turner F.T. (1994) Phosphorus relationships in flooded rice soils with low extractable phosphorus. Soil Science Society of America Journal 58:1184-1189.

Shao-hua W., Weixing C., Dong J., Tingboo D., Yan Z. (2002) Physiological characteristics and high yielding techniques with SRI rice, in: N. Uphoff, et al. (Eds.), Assessments of the system of rice intensification (SRI) Conference Proceedings, Sanya, China, April 1-4.

Sharpley A., Tiessen H., Cole C.V. (1987) Soil phosphorus forms extracted by soil tests as a function of pedogenesis. Soil Science Society of America Journal 51:362-365.

Sheehy J.E., Sinclair T.R., Cassman K.G. (2005) Curiosities, nonsense, non-science and SRI. Field Crops Research 91:355-356.

Sheehy J.E., Peng S., Dobermann A., Mitchell P.L., Ferrer A., Yang J.C., Zou Y.B., Zhong X.H., Huang J.L. (2004) Fantastic yields in the system of rice intensification: fact or fallacy? Field Crops Research 88:1-8.

Shengfu A., Xiehu W., Zhongjiong X., Shixiu X., Chanquan L., Yangchang L. (2002) Assesment of SRI with the super hybrid rice variety Liangyoupei 9, in: N. Uphoff, et al. (Eds.), Assesments of the System of Rice Intensification (SRI) Conference Proceedings, Sanya, China, April 1-4.

Singh J.S., Raghubanshi A.S., Singh R.S., Srivastava S.C. (1989) Microbial biomass acts as a source of plant nutrients in dry tropical forest and savana. Nature 338:499-500.

Singh M., Sammi Reddy K., Singh V.P., Rupa T.R. (2007) Phosphorus availability to rice (*Oriza sativa* L.)- wheat (*Triticum estivum* L.) in a

Vertisol after eight years of inorganic and organic fertilizer additions. Bioresource Technology 98:7.

Sinha S.K., Talati J. (2007) Productivity impacts of the system of rice intensification (SRI): A case study in West Bengal, India. Agricultural Water Management 87:55-60.

Song K.Y., Zoh K.D., Kang H. (2007) Release of phosphate in a wetland by changes in hydrological regime. Science of the Total Environment 380:13-18.

Souchie E.L., Azcon R., Barea J.M., Saggin-Junior O.J., da Silva E.M.R. (2006) Phosphate solubilization and synergism between P-solubilizing and arbuscular mycorrhizal fungi. Pesquisa Agropecuaria Brasileira 41:1405-1411.

Stocking M.A. (2003) Tropical Soils and Food Security: The Next 50 Years. Science 302:1356-1359..

Stoop W.A. (2002) The "system of rice intensification" (SRI); results from exploratory field research in the Ivory Coast: further research requirements and prospects for adaptation to divers agroecosystems, West African Rice Development Association, Bouake, Ivory Coast.

Stoop W.A., Kassam A.H. (2005) The SRI controversy: a response. Field Crops Research 91:357-360.

Stoop W.A., Uphoff N., Kassam A. (2002) A review of agricultural research issues raised by the System of Rice Intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. Agricultural Systems 71:249-274.

Surridge C. (2004) Rice cultivation: Feast or famine? Nature 428:360-361.

Takahashi T., Shoji S. (2002) Distribution and Classification of Vocanic Ash Soils. Global Environmental Research 6:83-97.

Tawaraya K., Naito M., Wagatsuma T. (2006) Solubilization of insoluble inorganic phosphate by hyphal exudates of arbuscular mycorrhizal fungi. Journal of Plant Nutrition 29:657-665.

Thakur A.K., Uphoff N., Antony E. (2009) An assessment of physiological effects of system of rice intensfication practices compared with recommended rice cultivation practices in India. Experimental Agriculture 46:77-98.

The Peoples Science Institute (2007) The System of Rice Intensification, Uttarakhand, India.

Tiessen H. (1998) Resilience of phosphorus transformations in tropical forest and derived ecosystems, in: A. Schulte and D. Ruhiyat (Eds.), Soils of Tropical Forest Ecosystems: Characteristics, Ecology and Management. Springer., Berlin. pp. 92-98.

Tiessen H., Cuevas E., Chacon P. (1994) The role of soils organic matter in sustaining soil fertility Nature 371:783-785.

Turmel M.-S., Turner B.L., Whalen J.K. (2011) Soil fertility and the yield response to the System of Rice Intensification. Renewable Agriculture and Food Systems. DOI:10.1017/S174217051100007X.

Turmel M.-S., Espinosa J., Franco L., Perez C., Hernandez H., Gonzalez E., Fernandez G., Rojas C., Sanchez D., Fernandez N., Barrios M., Whalen J.K., L T.B. (2011) On-farm evaluation of a low-input rice production system in Panama. Paddy Water and Environment. Vol.9:1, pg. 155-161.

Turner B.L., Engelbrecht B.M.J. (2010) Soil organic phosphorus in lowland tropical rain forests, Biogeochemistry.

Turner B.L. (2010) Variation in pH optima of hydrolytic enzyme activities in tropical rain forest soils. Applied and Environmental Microbiology Vol. 76:6485-6493.

Turner B.L., Haygarth P.M. (2001) Biogeochemistry - Phosphorus solubilization in rewetted soils. Nature 411:258.

Turner B.L., Romero T.E. (2010) Stability of hydrolytic enzyme activity and microbial phosphorus during storage of tropical rain forest soils. Soil Biology and Biochemistry 42:459-465

Turner B.L., Frossard E., Oberson A. (2006) Enhancing phosphorus availability in low-fertility soils., in: N. Uphoff, et al. (Eds.), Biological Approaches to Sustainable Soil Systems, CRC Press, Boca Raton, Florida, USA. pp. 191-205.

Uphoff N., Kassam A., Stoop W. (2008) A critical assessment of a desk study comparing crop production systems: The example of the system of rice intensification versus best management practice. Field Crops Research 108:109-114.

Van Wambeke A. (1992) Soils of the Tropics: properties and appraisal. McGraw-Hill, Inc., New York.

Vijayakumar M., Sundar Singh S.D., Prabhakaran N.K., Thiyagarajan T.M. (2005) Effect of SRI (System of Rice Intensification) practices on the yield attributes, yield and water productivity of rice (*Oryza sativa* L.). Acta Agronomica Hungarica 52:9.

Walker T.W., Syers J.K. (1976) The fate of phosphorus during pedogensis. Geoderma 15:1-19.

Walworth J., Sumner M. (1988) (Eds.) Foliar diagnosis: a review, Praeger Publishers, NY.

Wang S.-h., Cao W., Jiang D., Dai T., Zhu Y. (2002) Physiological characterisics and high-yield techniques with SRI rice. Assessments of the System of Rice Intensification (SRI). Cornell International Institute for Food, Agriculture and Development, Sanya, China, April 1-4, 2002

Wu J.S., Huang M., Xiao H.A., Su Y.R., Tong C.L., Huang D.Y., Syers J.K. (2007) Dynamics in microbial immobilization and transformations of phosphorus in highly weathered subtropical soil following organic amendments. Plant and Soil 290:333-342.

Yang C.M., Yang L.Z., Lee J.H. (2006) Organic phosphorus fractions in organically amended paddy soils in continuously and intermittently flooded conditions. Journal of Environmental Quality 35:1142-1150.

Yang C.M., Yang L.Z., Yang Y.X., Zhu O.Y. (2004) Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. Agricultural Water Management 70:67-81.

Zhang Y.S., Lin X.Y., Werner W. (2003) The effect of soil flooding on the transformation of Fe oxides and the adsorption/desorption behavior of phosphate. Journal of Plant Nutrition and Soil Science 166:68-75.

Zhao L., Wu L., Li Y., Lu X., Zhu D., Uphoff N. (2009) Influence of the system of rice intensification on the rice yield and nitrogen and water use efficiency with different application rates Experimental Agriculture 45:275-286.