Nitrogen flow analysis in rice agro-ecosystems with different levels of complexity in East Java, Indonesia

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Cover Photo:
Farmers threshing the experimental rice through a mobile threshing machine, Kepanjen, Indonesia.
Photo: Gonzalo Garnacho Alemany.

Preface and acknowledgements

Since the beginning of my MSc, I was thinking about a topic for my thesis. I did not know which crops I wanted to do research about or even in which site of the world I wanted to do my fieldwork. However, I had some ideas in mind. I wanted to do research about mixed farming systems able to feed as many people as possible in an ecologically sound way, which in other words is called "ecological intensification". The first time I heard this term was during a lecture of Prof. Pablo Tittonell about global and historical perspectives of agro-ecosystems. That lecture was of great inspiration and helped me realize about the important role that agro-ecology plays on providing food for the current and future generations.

By that time, I had heard from the Farming Systems Ecology Group about some research carried out in Indonesia regarding complex rice agro-ecosystems. After talking with Jeroen Groot about my ambitions and hearing about the research plans that the PhD student Uma Khumairoh had on that topic, I decided to go to Indonesia.

More specifically, I went to Jenggolo, a village nearby Kepanjen, where I did most of the fieldwork. During my stay there, I could learn about different ways of farming, crops that I had never seen before and different ways to perceive agriculture, as well as different ways to perceive life. I am very grateful to all the people from the village for making my stay so pleasant and rewarding. Moreover, I would like to thank the three farmers that I had the pleasure to interview and learn about their ways of farming: Tamrih, Kaseri and Agus. Those interviews probably would not have taken place without the help of Gaby, Prista and Dwi. I would like to thank them for being such great hosts and teaching me so many things about the Indonesian culture.

During my stay in Indonesia, I had the pleasure to share my experience with two amazing persons: Laia and Paula. Together we had the opportunity to create a farming school for the children of Jenggolo. While they were more focused on the school project, they were always ready to give me a hand with my fieldwork every time I needed it.

I would like to thank my supervisors, Jeroen Groot, Egbert Lantinga and Uma Khumairoh, for their support and guidance from the beginning to the end of my thesis. Moreover, I would like to thank Trini and Stéphanie for their advice and willingness to help me at any time.

Thanks to my parents and family, who have always given me support and encouraged me to do my best.

Last but not least, I would like to thank you Andreu for everything I have lived with you and everything I have learned from you. This thesis is dedicated to you.

Abstract

A yield gap in rice production exists in Indonesia mainly due to insufficient or unbalanced supply of water and nutrients, pest and weed infestation and losses caused by unfavorable weather conditions. Conventional rice production is highly dependent on agrochemicals to face yield-limiting and reducing factors. While external inputs may not be accessible to resource-poor farmers, the use of chemicals represents a threat for biodiversity and human health. Integration of livestock and cover crops may be a way to make a more efficient use of resources and reduce dependency on external inputs while increasing rice yields and total farm productivity. In this study, the performance of seven rice agro-ecosystems with different levels of complexity was analyzed. Only one treatment received chemical fertilizer. The most complex system was composed of rice, azolla, ducks, fish and string beans. Rice yields, total food production and economic performance of each system were compared. Moreover, nitrogen cycling performance was assessed from a field-level perspective through Ecological Network Analysis. Rice yields were generally higher in more complex systems, despite relatively poor performance of fish and azolla. No significant differences in yields were found between the most complex system and the conventional treatment. Complex agro-ecosystems provided larger amounts of food, besides rice also fish and duck products, which resulted in more energy produced per unit of land. Moreover, they were less dependent on nitrogen imports and generally recycled larger amounts of nitrogen. However, those systems were not necessarily more efficient in terms of nitrogen use when considering only one cropping cycle. Better performance of fish and azolla than in the current experiment is required to increase nitrogen use efficiency in complex rice agro-ecosystems.

Keywords: Nitrogen flows; Complex agro-ecosystems; Rice; Ducks; Fish; Azolla; Ecological network analysis; Nitrogen cycling; East Java; Indonesia.

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List of abbreviations

AMI	Average mutual information
ANR	Apparent nitrogen recovery
APL	Average path length
BW	Body weight
C	Carbon
Conv	Conventional treatment
CP	Crude protein
D	Dependency
DAT	Days after transplanting
DM	Dry matter
DP	Digestible protein
EN	Exports of nitrogen
FCI	Finn's cycling index
Fe	Iron
FM	Fresh matter
Hr	Statistical uncertainty
IN	Imports of nitrogen
K	Potassium
L	Number of links
ME	Metabolizable energy
MRp	Million Rupiah
N	Nitrogen
NUE	Nitrogen use efficiency
P	Phosphorus
PD	Plant density
R	Rice only treatment
RDA	Recommended daily allowance
RE_i	Cycling efficiency
RM	Rice-manure treatment
RMA	Rice-manure-azolla treatment
RMAD	Rice-manure-azolla-duck treatment
RMAF	Rice-manure-azolla-fish treatment
RMAFD	Rice-manure-azolla-fish-duck treatment
Rp	Indonesian Rupiah
SGR	Specific growth rate
T	Temperature
TST	Total system throughflow
TSTc	Total cycled system throughflow
Vit A	Vitamin A
WAT	Weeks after transplanting
Zn	Zinc

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1. Introduction

Farming is a very common livelihood in Indonesia, employing more than 40% of the labor force (FAOSTAT 2011). However, 13% of the population is undernourished (FAO 2013), which may be due to micronutrient deficiencies in the diet such as iron, zinc and vitamin A (Jati et al. 2012). Rice is the main staple food in Indonesia, being this country the third largest rice producer in the world. Although Indonesia aims at being self-sufficient in rice production, the country had to import rice during 2013 to meet the demand, mainly due to unfavorable weather conditions. According to IRRI (2014), the average rice yields in Indonesia must increase from 4,6 to 6 tons ha^{-1} cropping $cycle^{-1}$ in order to meet the national demand in the next 25 years. The yield gap between actual and potential yields is often caused by yield limiting factors such as insufficient or unbalanced supply of water and nutrients, reducing factors such as weeds and pests and losses caused by unfavorable weather conditions such as heavy rains and extreme temperatures (Van Ittersum and Rabbinge 1997; Lobell et al. 2009). Moreover, the use of pesticides and chemical fertilizers has increased during the last decades, which has had an impact on increasing production (FAO 2005), but also caused damage to the environment and increased farmers' dependence on external inputs.

Nowadays, rice is commonly grown as a monoculture and pests are usually managed through pesticides. However, the application of pesticides causes a damage to biodiversity including organisms that are beneficial for rice such as natural enemies and soil microorganisms (Matson et al. 1997; Mäder et al. 2002). Furthermore, the high toxicity of those chemicals threatens not only biodiversity, but also human health (Avino et al. 2011). Moreover, nutrients used to fertilize paddy fields are rarely produced on farm and have therefore to be purchased. Although manure is also used as fertilizer in rice production, chemical fertilizer is the most common input to fertilize paddy fields. Since nutrients in chemical fertilizers are in inorganic form, they can rapidly be taken up by the rice plants. However, they are also more prone to losses especially when soil organic matter content is low. Furthermore, the production of mineral fertilizer is highly dependent on non-renewable energies and the prolonged application of chemicals often causes degradation of natural resources (Matson et al. 1997; Steinfeld et al. 2006).

Integrating rice production with livestock may play a key role in reducing the use of external inputs and may contribute to diversify farm households' diets in Southeast Asia (Ahmed and Garnett 2011; Hossain et al. 2005). Despite its high energy content, rice is deficient in important micronutrients especially in iron, zinc and vitamin A, which does not contain at all (Jati et al. 2012). In contrast with that, duck products have a high content of iron and vitamin A (USDA 2011). Although fish may not stand out for a high content of any of those micronutrients, its integration in rice farming can increase the total amount of food produced. Mixing rice and fish or rice and ducks used to be a common practice in Indonesia. However, their integration rarely takes place nowadays. When integrated with rice, fish and ducks can feed on weeds, insects and snails, thus protecting rice yields from reducing factors such as pests and diseases. Moreover, nutrients from the manure excreted by either fish or ducks can be taken up by rice, which may contribute to increase attainable yields (Khumairoh et al. 2012). While fish are sometimes integrated in rice production, full integration of ducks rarely takes place nowadays.

On the one hand, in rice-fish systems, fish usually do not reach the desired weight due to lack of feed sources, which leads to a lower market price (Cagauan et al. 2000). Furthermore, the intensive use of pesticides may increase the mortality of fish when integrated in conventional rice systems (Ahmed and Garnett 2011). On the other hand, rice integration with ducks usually takes place once rice has been harvested. In this case, duck farmers usually release the ducks on the recently harvested fields so birds can feed on remaining grains, insects, worms and other organic material (Picture 1). This way, ducks fertilize the soil with manure while they forage on the recently harvested fields. Ducks are usually housed in sheds near the rice fields. In those systems, ducks have permanent access to the waterways and can access the rice fields after harvesting. However, during the rice-growing period, manure and uneaten feed are accumulated in the sheds under unhygienic conditions and are often not recycled thus causing nutrient losses. In East Java, nomadic duck pastoralism is a very common practice and ducks are herded from a rice field to another in order for them to feed on harvesting leftovers (Picture 2).

Picture 1. Ducks feeding on leftovers from a recently harvested rice field in Kepanjen. *Photo: Gonzalo Garnacho Alemany.*

Picture 2. Nomadic settlement of duck herders on a rice field in Kepanjen. *Photo: Gonzalo Garnacho Alemany.*

All in all, the potential benefits of integrating fish and ducks with rice are not well exploited in the mainstream rice production in Indonesia. In contrast with that, rice is commonly grown as a monoculture and its production is highly dependent on pesticides and chemical fertilizers to achieve higher yields, thus harming the environment and increasing dependency on external inputs.

Therefore, there is a need for finding more integrated and environmental friendly ways of farming, whereby farmers can use resources more efficiently while having higher yields and total farm productivity. Moreover, those practices should reduce the use of chemical inputs not only to be more environmentally sound, but also to increase farmers' self-reliance. Integrated organic rice production, in which neither pesticides nor chemical fertilizers are used, might be a way to achieve such a challenge. Increasing complexity of rice production systems may enhance ecological processes of nutrient cycling and pest control, which may lead to an increase in farm productivity and improve economic performance (Berg et al. 2012; Dwiyana and Mendoza 2008). In wetland rice production, nitrogen supply can be done through azolla, an aquatic fern that forms a symbiotic relationship with the cyanobacterium *Anabaena azollae*, which fixes atmospheric nitrogen that can eventually be taken up by rice. In Indonesia, azolla often grows spontaneously in paddy fields, but its cultivation is not widespread probably due to its susceptibility to pests such as snails and caterpillars, which can also attack rice. Furthermore, in order to reach the optimal density, azolla must be inoculated first in a nursery and then added into the rice fields, which is labor intensive. However, its rapid growth and high nitrogen content make azolla a great organic amendment when used as green manure in paddy fields (Giller 2001). Moreover, field margins are often left bare, thus wasting land that could be used to grow crops other than rice.

Integrating organic rice production with azolla, ducks and fish seems to be a way to increase both rice yields and total farm productivity while restricting the use of agrochemicals and reducing the total inputs (Cagauan et al. 2000; Khumairoh et al. 2012). Moreover, duck and fish production, together with the cultivation of additional crops on the field margins, may also contribute to diversify farm households' diets and provide resource-poor farmers with micronutrients that are often deficient in the average Indonesian diet.

1.1. Objectives

The aim of this study was to analyze the effect of complexity on nitrogen cycling in rice agro-ecosystems in East Java, Indonesia and to determine their relationship with total farm productivity and economic performance. In more detail, the objectives were:

1. Study the effect of complexity on nitrogen cycling.
2. Study the effect of increasing complexity on rice yields.
3. Analyze the relationship of nitrogen cycling with farm productivity and economic performance.

1.2. Research questions

1. How does complexity affect nitrogen use and cycling efficiency?
2. What is the effect of increasing complexity on rice yields?
3. How does complexity affect total farm productivity and economic performance?

1.3. Hypotheses

1. More complex systems recycle larger amounts of nitrogen, which leads to more efficient use of resources.
2. Rice yields are generally higher in complex rice agro-ecosystems compared to rice monocultures.
3. More complex rice agro-ecosystems have a higher total farm productivity and economic performance than less complex rice production systems.

2. Materials and methods

2.1. Site characteristics

The experiment was conducted in Kepanjen, subdistrict of Malang, East Java (Figure 1 and Figure 2). Malang has a relatively cool weather, with a mean yearly temperature of 24,6°C and a relative humidity of 77,2% (Weatherbase 2014).

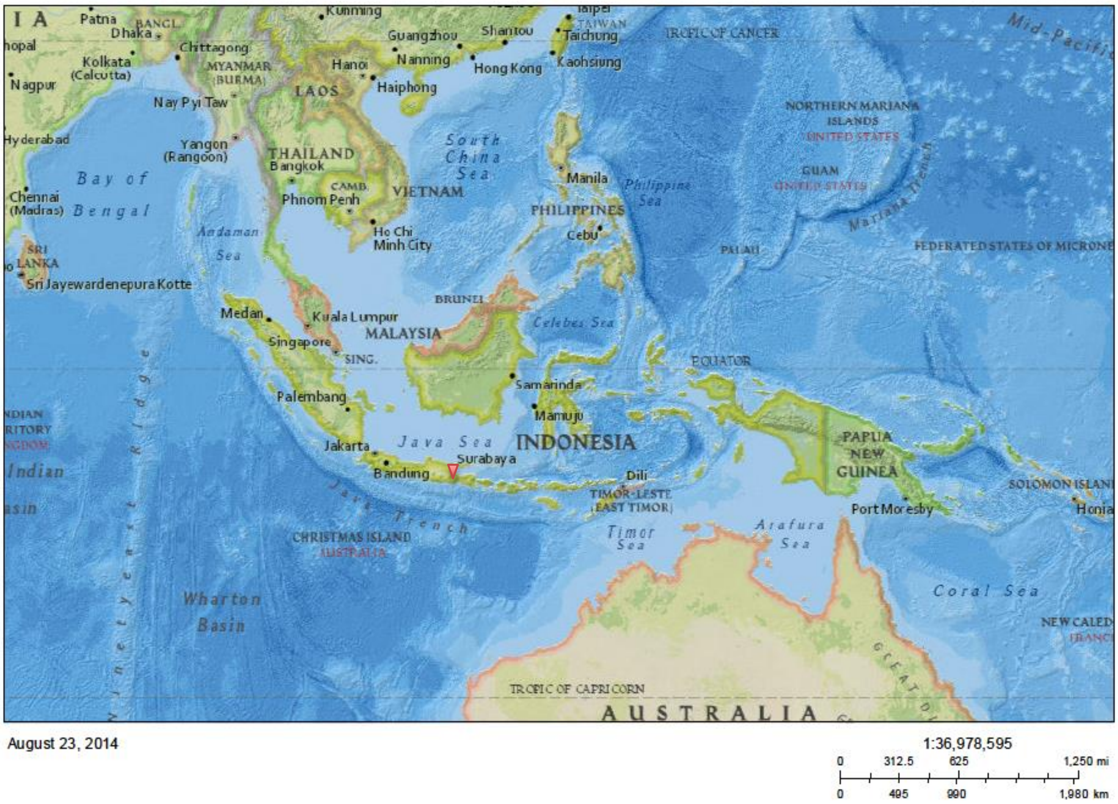

Figure 1. Map of Indonesia. Source: National Geographic (2014).

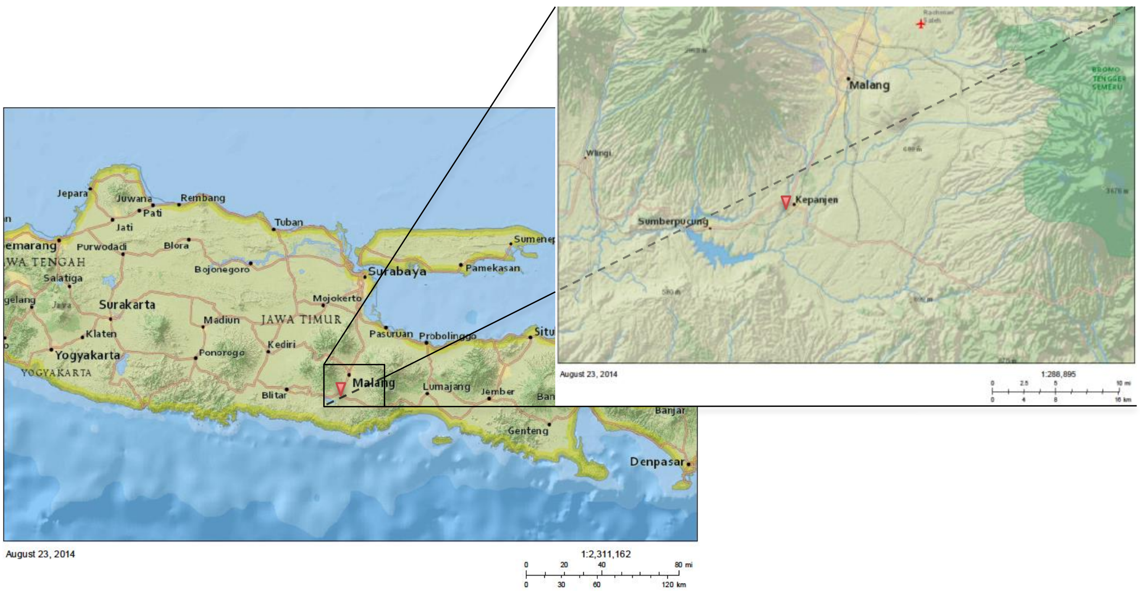

Figure 2. Map of East Java (left) and southern part of Malang district (right). Source: National Geographic (2014).

The experimental fields were located at 320 m.a.s.l. and the total rainfall during the cropping cycle was 735 mm (World Weather Online 2014). Soil texture was clay, with an average N content of 1.897 mg kg^{-1} and a mean C:N ratio of 13 (Del Rio 2014). The plots were surrounded by other rice fields except for the northwestern part, which was bordering trees, a creek and, 10 m further, a road that gave access to the fields (Figure 3). The surrounding fields were managed by the same farmer as in the experiment except for the southern paddies, which were managed by other conventional farmers.

Figure 3. Map of the location of the experimental fields. Source: "Kepanjen." 8° 9'36.38"S and 112°33'12.69"E. (Google Earth). May 10, 2014. August 23, 2014.

In the previous years, the land had been managed by the same farmer of the experiment. While chemical fertilizers were used to fertilize the soil, no pesticides were applied in the previous years. Moreover, rice residues had always been introduced into the soil, therefore preventing soil organic matter depletion.

2.2. Experimental design

The experimental layout was based on a randomized block design of 3 blocks. Each block consisted of 7 rice agro-ecosystems with different levels of complexity: Rice only (R), Conventional (Conv), Rice-Manure (RM), Rice-Manure-Azolla (RMA), Rice-Manure-Azolla-Fish (RMAF), Rice-Manure-Azolla-Duck (RMAD) and Rice-Manure-Azolla-Fish-Ducks (RMAFD) (Figure 4).

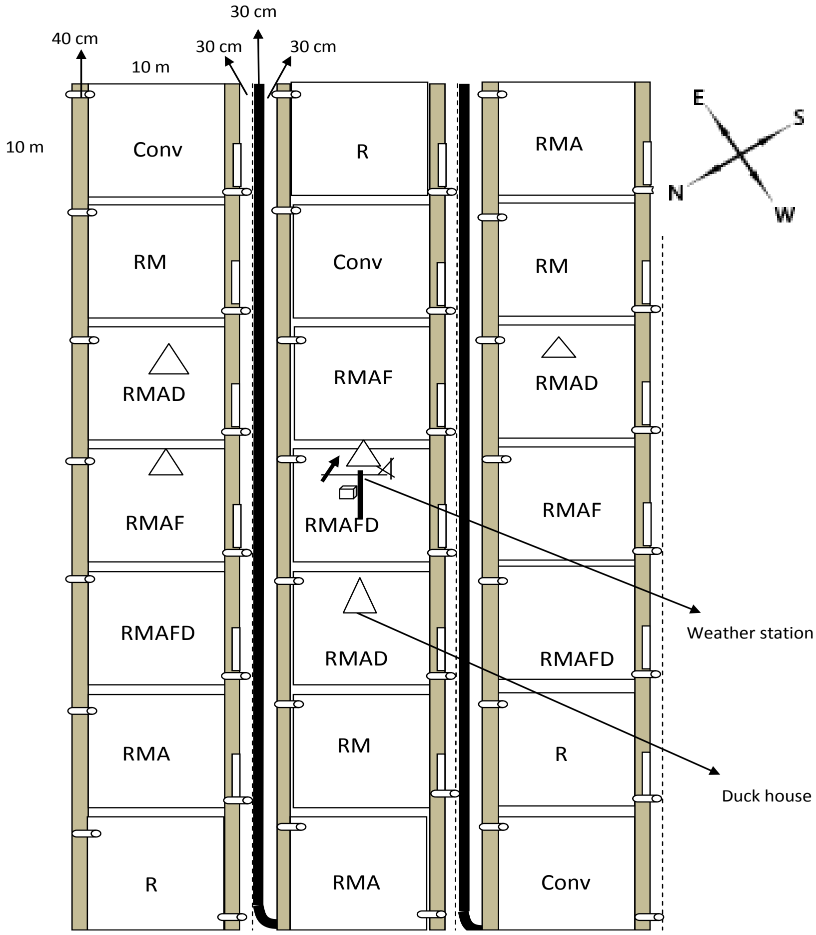

Figure 4. Experimental layout.

Each rice agro-ecosystem was allocated on a 10x10m plot and was fenced with a plastic net (Picture 3). Along with the net, string beans were grown (Picture 4) in those plots with fish (i.e. RMAF and RMAFD) in order to provide them with shade.

Picture 3. Overview of the experimental fields. *Photo: Gonzalo Garnacho Alemany*.

Picture 4. String beans growing along the field margins of an RMAFD plot. *Photo: Gonzalo Garnacho Alemany.*

Waterways were managed so that water from inlet and outlet did not mix in order to prevent contamination. The experiment roughly followed the cultivation methods described on Khumairoh *et al.* (2012), the main difference being the use of duck manure instead of compost.

2.3. Materials

The main farm components that were used in the experiment were rice (*Oryza sativa*) variety Ciherang, azolla fern (*Azolla pinnata*), local Javanese duckling (*Anas* platyrhynchos *javanicus*) and Nile tilapia (*Oreochromis niloticus*).

Ciherang is a rice variety adapted to the local weather conditions, as it is suitable for both dry and wet season (IRRI 2012). Commonly, more than one seedling is planted per hill, leaving a space between plants lower than 30 x 30 cm, and seedlings at the age of 2 weeks or more. Under those conditions, the mean plant height is 105-112 cm and it produces an average of 17 productive tillers per hill (Khumairoh 2011). In the current experiment, only one seedling per hill was planted and larger spacing between hills was left. As a result, 20 kg of seeds per hectare were used to grow the seedlings, which is 87% lower than conventional practices due to the lower planting density (Khumairoh 2011). More information regarding the planting methods is given in section 2.4.

Azolla pinnata was used in the current experiment as an intercrop with rice. This small floating fern can be used as green manure and feed for livestock due to its high nitrogen content. Azolla was first collected from rice fields in which it grows spontaneously and then inoculated in a nursery. Besides supplying rice with N and livestock with feed, azolla can also perform as weed controller due to its rapid growth. However, its susceptibility to pests such as snails and caterpillars, as well as its high P requirements can limit its development.

Anas platyrhynchos *javanicus*, locally known as Mojosari, is a double purpose duck breed commonly raised in East Java. Adult males can reach up to 2,5 kg of weight, while females can weight up to 2 kg. The advantage of this breed is that ducks cannot fly so they should not escape form an open field as long as it is well fenced. In the current experiment, ducks were raised only for meat consumption and were introduced into the fields at the age of 3 weeks, with an average weight of 55 g.

Nile tilapia (*Oreochromis niloticus*) was selected for this experiment because unlike other fish, Nile tilapia is omnivore, aggressive and has a high adaptability to different environmental conditions. Therefore, it may be a feasible way to reduce weed and pest populations as reported in previous research (Khumairoh et al. 2012). Adult Nile tilapia weight 200-250 g and have a length of 20 cm. In the current experiment, fingerlings were introduced into the fields with an average weight of 22,5 g.

String beans were planted along the filed margins of RMAF and RMAFD in order to provide fish with shade. Seeds were planted at the beginning of the cropping cycle and bamboo sticks were used to support plant growth.

All the inputs and the amount used in the experiment are shown in Appendix 2. Besides those inputs, papaya leaves were given to ducks as a way to prevent the from falling sick, given its reported antioxidant and antimicrobial properties (Ifesan et al. 2013; Alabi et al. 2012). Other materials used are 3 duck houses, bambuu sticks to support beans and 3 duck cages that were used for an excreta collection experiment.

2.4. Farming methods

Rice was cultivated following the management practices of System of Rice Intensification (SRI), which are larger planting distances (30 x 30 cm) of individual young (10 days old) seedlings at an early growth stage (2-3 leaf stage). This way, rice plants are able to produce more tillers and consequently more grain. Moreover, the larger spacing distances ease the weeding practices. However, in contrast with SRI recommendations, fields were flooded to allow fish and duck integration. Moreover, duck manure was used instead of compost to fertilize the fields. Weeding was carried out twice: right before transplanting the seedlings and a few days before rice plants started to flower. At the end of the growing season, rice straw and stubble were incorporated into the soil.

No pesticides were applied in any plot during the cropping cycle. Chemical fertilizer was only applied in the conventional treatment (Conv) at a total application rate of 300 kg Urea (46% N), 300 kg ZA (21% N), 100 kg SP-36 (36% P_2O_5) and 75 kg KCl (60% K_2O) ha^{-1}. The other treatments, except for R, were fertilized with duck manure. Both chemical and organic fertilizers were applied 3 times (Table 1).

Azolla was incorporated into RMA, RMAF, RMAD and RMAFD plots 4 days after rice transplanting. Remaining azolla after harvesting was incorporated into the soil.

Integration of ducks was done 22 days after transplanting in RMAD and RMAFD. Density. Ducks fed on weeds and insects from the fields. Moreover, a feed mixture was provided in a daily basis. Papaya leaves were provided roughly once a week, especially after windy days, since strong winds may weaken duck’s immune system and therefore ducks can be more susceptible to falling sick.

Table 1. Timetable of the farming activities.

Activities	Date
Rice transplanting	December 12-13, 2013
Azolla integration	December 17, 2013
First fertilizer and manure application	December 27-28, 2013
Ducks' integration (2 weeks old)	January 4, 2014
Fish's integration	January 21, 2014
Second fertilizer and manure application	January 22, 2014
Third fertilizer and manure application	February 8, 2014
Ducks withdrawal	February 28, 2014
Fish withdrawal	March 22, 2014
Harvesting	March 30, 2014

Fish were added 39 days after rice transplanting. No feed was specially provided for fish as they were expected to feed on plankton, azolla, insects and weeds. At the end of the cropping cycle, string bean residues were incorporated into the soil as green manure.

2.5. Methodology

2.5.1. Yields

Rice was hand harvested and dried under the sun before storing. Yields were quantified by measuring the grain produced in 5 m^2. The selected area was located at the western corner of each plot, 1 m separated from each border site. Samples were measured twice: once right after harvesting and the other one after sun-drying the grain, which was used to determine the rice yields. Moreover, the amount of plant residue was measured. On the one hand, straw that was removed during harvesting was weighted. On the other hand, the remaining crop residues were collected and washed out in order to get rid of soil and dust. Once they were clean, samples were weighted twice: right after cleaning them and the second one after sun-drying them.

String beans were hand harvested periodically and the yields of each block were recorded every time. As in each block there were 2 treatments in which string beans were grown, the recorded yields were for the field margins of 2 plots. Therefore, yields were divided by 2 in order to know the yield of 1 plot.

Ducks were withdrawn from the fields 55 days after their integration, at an age of 11 weeks. Two ducks from each plot were randomly selected and weighted (Picture 5). Therefore, a total of 6 samples per treatment were weighted.

In order to determine carcass distribution, one duck was slaughtered. Carcass was divided into different parts: skin, guts, beak, paws, feathers, giblets, meat and bones (Picture 6) and weighted. Another duck and a duckling were slaughtered to determine the N content.

Picture 5. Measuring the duck weights with the farmers. *Photo: Uma Khumairoh.*

Picture 6. Duck carcass after evisceration. *Photo: Gonzalo Garnacho Alemany.*

Finally, fish were harvested the same day that water from the rice fields was drained away.

2.5.2. Excreta collection experiment

In order to estimate the total amount of excreta produced by ducks, a 24 hours excreta collection experiment was carried out. The experiment was supposed to take place at 3 different duck development stages: duckling, young ducks and adult duck. However, it was eventually carried out only during the adult phase, (more specifically, 1 week before ducks' withdrawal from the fields. In the experiment, 3 ducks were kept simultaneously in 3 different bamboo cages (Picture 7) and replaced every 4 hours by ducks from the field. In order to avoid repetition of duck samples, ducks were taken from a different plot every time (Picture 8).

Picture 7. Bamboo cages built for the excreta collection experiment.
Photo: Gonzalo Garnacho Alemany.

Picture 8. Duck being withdrawn for the excreta collection experiment.
Photo: Gonzalo Garnacho Alemany.

Supplied feed was provided at 8:30 and 16:30 both to the ducks that were in the fields and the ducks that were caged at that moment. Moreover, ducks that were caged were always provided with water.

2.5.3. Nitrogen content

Soil N content was determined through the standard Kjeldahl method. Samples were collected before the field experiment, during the growing period (January 22 and February 8) and right after harvesting (May 31). Random composite sampling was carried out to subtract 7 subsamples form 0 to 15 cm from each plot following the trials showed in Figure 5. Soil samples were analyzed in Wageningen University except for the ones taken at harvesting, which were analyzed in Brawijaya University, Indonesia.

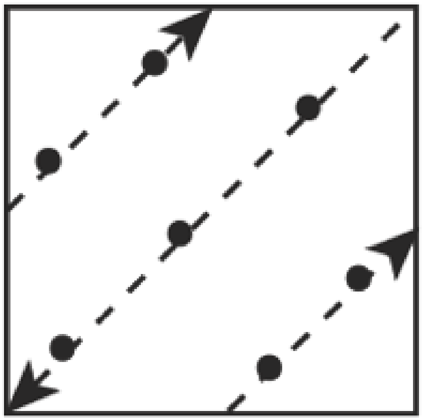

Figure 5. Soil sampling method.

N content of the different inputs and outputs was also determined. The samples collected were: rice seeds, whole rice grain, straw, stubble, bean seeds, bean vegetable, been residues, duck manure, feed, azolla, duckling, rainwater and water from irrigation. All samples except for whole rice grain, straw and stubble were first weighted and then air-dried at 40°C until weight became constant in order to determine dry matter content. Whole rice grain, straw and stubble were sun-dried instead of air-dried at 40°C. Once dried, samples were ground until they passed through a 1 mm sieve (Figure 6).

Figure 6. Ground string beans being sieved through a 1 mm sieve.
Photo: Gonzalo Garnacho Alemany.

2.5.4. N losses: leaching and outflow

N-NO_3 and N-NH_4^+ concentration in outflow water was measured in all plots except RMAD by a fellow MSc student. A detailed description of the methodology can be found in Del Rio, 2014. However, the amount of outflow could not be measured and had therefore to be estimated.

To estimate the amount of water that was lost through outflow and leaching, evapotranspiration (ET) was estimated and then subtracted to total rainfall. The estimation of ET was based on two studies in which ET of flooded rice fields was determined. On the one hand, Alberto et al. (2011) determined an annual ET of 1.440 mm for flooded rice in low-land Philippines. The field was located 25 m adobe see level with a mean air T=27,5ºC. Taking the same annual ET as a reference and supposing the same environmental conditions, the ET for a cropping cycle in the current experiment would be 6 million l ha^{-1} (Eq. 1).

$$ET = \frac{1.440 \text{ mm}}{12 \text{ months}} \cdot 5 \text{ months} = 600 \text{ mm (i.e. 6 million l ha}^{-1}\text{)} \qquad \text{(Eq. 1)}$$

On the other hand, according to Allen et al. (1998), the average daily crop ET in humid and subhumid tropical areas under a moderate temperature (20-30ºC) can range from 3 to 5 mm day^{-1}. Taking the median of those values (4), the ET that would take place during 5 months would be 6 million l ha^{-1} (Eq. 2), which is the same amount as the one determined through Alberto et al. (2011).

$$ET = \frac{4 \text{ mm}}{\text{day}} \cdot \frac{30 \text{ days}}{1 \text{ month}} \cdot 5 \text{ months} = 600 \text{ mm (i.e. 6 million l ha}^{-1}\text{)} \qquad \text{(Eq. 2)}$$

Rainfall in the experimental site during the 5 months of the cropping cycle was 735 mm (7,35 million l ha^{-1}) (World Weather Online 2014). The amount of rainfall that went away through runoff or leaching was the result of subtracting ET to total rainfall, i.e. 1,35 million l ha^{-1}.

In order to estimate the average N concentration of water outflow, the average concentrations of $N\text{-}NO_3$ and $N\text{-}NH_4^+$ were added. The resulting concentration was then multiplied by the previously calculated outflow (i.e. 1,35 million l ha^{-1}) in order to determine the estimated amount of N lost (Appendix 5). Since the amount of water from irrigation was unknown, only rainfall was taken into account.

Due to the lack of equipment to measure N losses through volatilization and denitrification, gaseous losses were neglected in the calculations.

2.5.5. Interviews

In order to compare the productivity and carrying capacities of the experimental rice agro-ecosystems with current rice production systems in Malang district, 3 farms with different income levels were analyzed. The rice 3 farms were located in

Kepanjen, the same location as the experimental fields. Each farm had a different area of land and different level of income.

Data was collected by using a survey and communication during the interview was facilitated by a local translator. The main data collected were yields, economic expenses of all the inputs and sale price of all the outputs. Data regarding total food production and carrying capacities of the 3 farms is showed in Appendix 20 and Appendix 24.

2.5.6. Carrying capacities: energy, Fe, Zn and Vit A

The energy and the nutrient content of all the produced commodities was found in literature, mainly in (USDA 2011). In some products, part of the harvested amount was not edible. Therefore, only the edible portion of all the products was considered to determine the amount of energy and nutrients produced. In most cases, the edible portion was found in literature. In the case of ducks, the edible portion was determined by eviscerating a duck from the experiment.

The standard nutritional requirement of 2100 kcal capita^{-1} day^{-1} (Shapouri et al. 2010) was used to determine the carrying capacity of each farming system. Moreover, the time scale used for the experimental fields was different from the one used for the interviewed farms. On the one hand, a time scale of 160 days was used for the experimental systems, which is the length of a cropping cycle, including the production of seedlings and soil preparation. On the other hand, a time scale of 1 year was used to determine the carrying capacity of the 3 interviewed farms.

Once known the amount of the Fe, Zn and Vit A produced in each system, 3 new carrying capacities were calculated according to the recommended daily allowance of each micronutrient.

2.5.7. Statistical analysis

All statistical tests were conducted with SPSS 22 software package (SPSS Inc., USA). Prior to the analysis, assumptions of normality and homoscedasticity were tested through Shapiro-Wilk and Levene's test respectively. Fisher's least significant difference (LSD) post hoc test was used to determine significant differences on rice yields between treatments. Simple regression analyses were used to determine the association between quantitative variables.

2.5.8. Ecological network analysis

Nitrogen is the most limiting nutrient in low-input agriculture (Rufino et al. 2009b). Ecological network analysis was used to analyze the N flows induced by the different farming activities of the agro-ecosystems. Farming systems were conceptualized as networks with compartments representing the different farming activities (Langeveld et al. 2007). Those compartments and the nutrient flows were limited by a system boundary, which contained the n compartments and their respective interactions (N flows), i.e. a system with two compartments (H_1, H_2), each with a certain storage of N (x_1, x_2), internal flows (f_{21}, f_{12}), external inflows (z_{10}, z_{20}) and external outflows (y_{01}, y_{02}) (Figure 7).

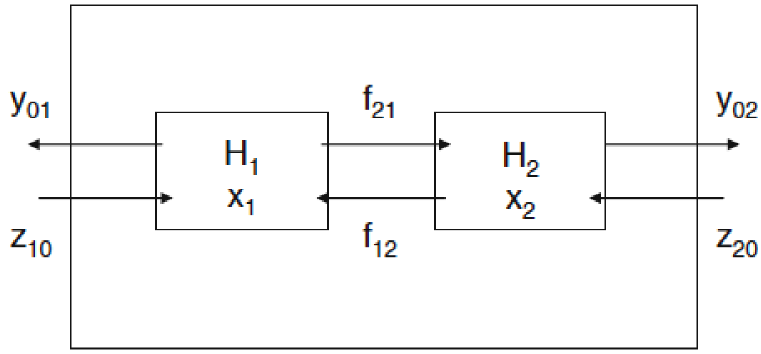

Figure 7. System representing a network with two compartments.
The rectangular box defines the system boundary. Source: Finn (1980).

The system in Figure 7 is characterized by the following elements: H_i is the compartment i, with a certain stored amount of N (x_i). This amount may change due to the different inputs and outputs of the compartment, being $\dot{x}_i$ its variation. On the one hand, y_{oi} represents the outflow from compartment H_i to the external environment, whereas z_{io} is the inflow from the external environment to compartment H_i. On the other hand, f_{ij} represents the internal flow from compartment H_j to compartment H_i.

Therefore, each system had a different number of compartments, being the most complex system (RMAFD) the one with the larger amount of compartments. When they were intercropped, rice and azolla were conceptualized as one compartment only, as they both shared the same N stocks, i.e. soil and water. Ducks, fish and string beans were conceptualized as 3 different compartments. Each compartment had at least one inflow and one outflow, either internal or external.

3. Results and discussion

This section is divided into 3 parts. Firstly, productivity and economic performance of the 7 rice agro-ecosystems is analyzed. Secondly, nitrogen cycling is assessed component by component and from a field-level perspective. In both cases, a best-case scenario is simulated in order to know the potential performance of each agro-ecosystem. Finally, farm productivity and economic performance of 3 rice farms is analyzed and compared with the results of the experimental agro-ecosystems.

3.1. Farm productivity and economic performance

Yields, costs and revenues of the different rice agro-ecosystems are presented first for each component and later for the agro-ecosystem as a whole. The carrying capacities of each treatment are compared in order to show the more productive system in terms of energy, Fe, Zn and Vit A produced.

3.1.1. Rice

Yields were generally lower than the ones achieved in (Khumairoh et al. 2012). However, all the treatments except RM, RMA and the control treatment were significantly higher than the average rice yields in Indonesia (i.e. 4,6 tons ha^{-1}). The overall rice yields ranged from an average of 3,5 tons ha^{-1} for the control treatment to an average of 8,1 tons ha^{-1} for the most complex system (Table 2). Organic rice yields generally increased with complexity while the average yield from conventional production was the second highest yield achieved (Figure 8).

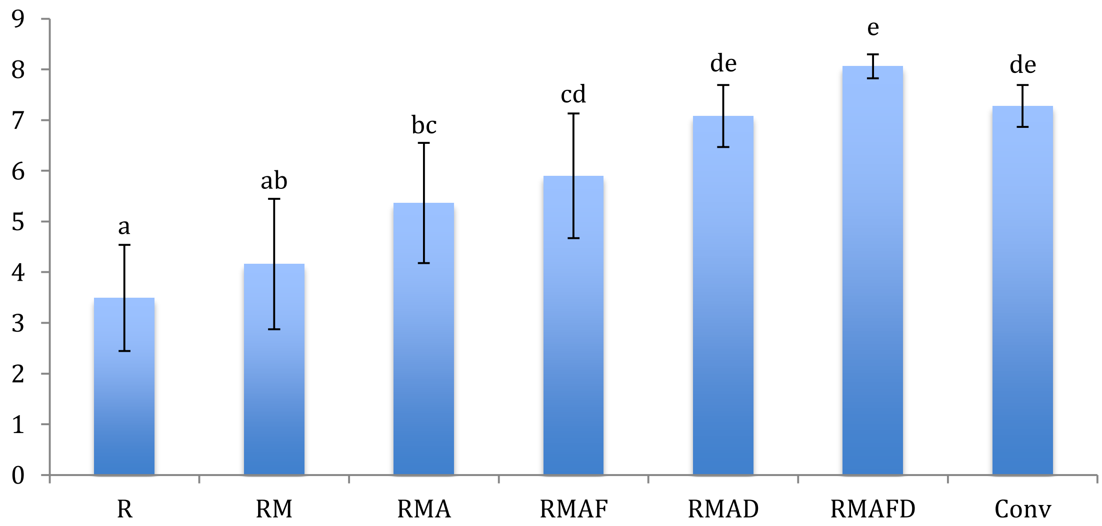

Figure 8. Average rice yields in each treatment (Mg DM ha^{-1}).

Figure 8 shows that there was a treatment effect on rice yields. Addition of manure alone (RM) did not have significant effects on increasing rice yields. However, when manure was combined with azolla (RMA) yields increased significantly compared to the control treatment (R). This may be related with the effect that azolla coverage has on decreasing water pH (Kern and Paul 2003). After the first fertilizer application, water pH was high (pH=8-8,5) (Del Rio 2014), which might have limited nutrient availability. Yet, the coverage of azolla during the first few weeks after transplanting might have lowered water pH, thus increasing nutrient availability, especially of P and N. Anyway, no significant differences were found between rice yields in RM and RMA.

On the one hand, addition of fish alone did not have a significant effect on increasing rice yields compared to RMA, which might be due to high fish mortality. On the other hand, duck integration increased rice yields significantly compared to the organic treatments with no livestock (R, RM, and RMA). This was probably due to the pest and weed suppression carried out by ducks and to a lesser extent to the addition of nutrients through manure, as N recovery from manure was relatively low. Actually, rice plants were generally healthier in those plots in which ducks were integrated and they started to flower later than in the other organic treatments. Therefore, rice plants could develop better during the vegetative phase and produce more panicles during the reproductive stage. As a matter of fact, rice harvest index was generally higher in those treatments with ducks compared to the other organic treatments (Table 2) and significantly higher compared to the control and the RM treatment.

Table 2. Rice yield, harvest index and economic performance of each treatment considering rice as the only agricultural output.

	Yield (Mg DM ha^{-1})	Harvest index (%)	Costs* (MRp ha^{-1})	Revenues** (MRp ha^{-1})	Gross margin (MRp ha^{-1})
R	$3,49 \pm 1,05^{a}$	$25,1 \pm 7,7^{a}$	0,16	13,97±4,18	13,81±4,18
RM	$4,16 \pm 1,29^{ab}$	$24,8 \pm 3,7^{a}$	1,36	16,64±5,15	15,28±5,15
RMA	$5,37 \pm 1,19^{bc}$	$29,9 \pm 4,5^{ab}$	1,36	21,47±4,75	20,11±4,75
RMAF	$5,90 \pm 1,23^{cd}$	$31,3 \pm 1,2^{ab}$	4,29	23,60±4,92	19,31±4,92
RMAD	$7,08 \pm 0,61^{de}$	$34,6 \pm 2,8^{bc}$	15,21	28,32±2,44	13,11±2,44
RMAFD	$8,06 \pm 0,24^{e}$	$35,6 \pm 1,3^{bc}$	18,14	32,24±0,94	14,10±0,94
Conv	$7,28 \pm 0,41^{de}$	$38,6 \pm 2,8^{c}$	2,33	29,12±1,65	26,79±1,65

* All inputs are included. Azolla is assumed to be free of cost.
** Revenues from products other than rice are not included.

The high fish mortality probably limited the potential contribution of fish on increasing rice yields. Although it seems that they might have had an effect on increasing rice yields, no significant differences were found between RMA and RMAF.

Moreover, only when ducks were integrated with fish, rice yields were significantly higher than in RMAF. Integration of ducks and fish seems to play an important role on increasing rice yields as reported by (Khumairoh et al. 2012; Cagauan et al. 2000). However, no significant differences were found between treatments with ducks. Finally, conventional rice yields were higher than R, RM and RMA, but no significant difference was found compared to those treatments with livestock (RMAF, RMAD and RMAFD). In contrast with the researcher's original idea of applying pesticides in the conventional treatment, no pesticides were used at any moment. Despite not using pesticides, no major problems were observed regarding pests and diseases, as rice plants from this treatment generally had a healthy appearance and could develop well. However, most of the farmers from the area apply pesticides in a regular basis, which indicates that pests are a major threat for rice production and can potentially reduce actual yields.

It is important to remark that yields were generally lower in Block 3. This might be due to a border effect. Block 3 was located at the southwestern part of the experiment, bordering conventional rice fields. As samples were taken at the western corner of each plot, the samples of Block 3 were bordering the conventional field. Therefore, pesticides sprayed on that field could have reduced the amount of natural enemies around, leaving rice plants more vulnerable to pests and diseases. Although there were no significant differences on rice yields between blocks when considering all the treatments, there seems to be a block effect when treatments with ducks are excluded from the Post hoc analysis ($p<0,07$). This could be explained by the biological pest control performed by ducks. To mitigate possible border effects, samples should be taken in the middle of each plot. Moreover, only 5% of the plot area was sampled, which probably increased data variability. To reduce the standard deviation of each treatment and therefore increase the reliability of the results, a larger area should be sampled.

Regarding the gross margin from rice, the conventional treatment was the one that resulted in the highest margin (Table 2). However, other commodities such as ducks, fish and beans were produced in the most complex systems, which increase the overall gross margin when considering the system as a whole.

3.1.2. Azolla

Azolla was depleted differently in each treatment. However, azolla was ran off very similarly at the beginning of the cropping cycle, when neither ducks nor fish were integrated yet. Apparently, great part of the azolla introduced was lost through runoff due to heavy rains, especially during the month of December (Appendix 1), and strong winds. This early depletion of azolla hindered its performance regarding N fixation, coverage, and biomass used as feed for ducks and fish. All the implications regarding these issues are detailed in section 3.1.2.

Moreover, when azolla was intercropped with rice, light interception was reduced as rice plants developed their canopy, which could limit azolla growth. According to Lumpkin (1987), shading by rice crop can start affecting azolla performance in 2-3 WAT and usually stops azolla growth in 45 DAT, depending on factors such as maturation period, leaf area index and plant height. Other reasons that could have limited azolla growth are plant damage by insects, lack of P (Giler 2001) or overgrowth of algae or weeds (Watanabe 1982).

In RMA and RMAF treatments, azolla was completely depleted at 67 DAT. However, in the case of RMAF, azolla probably ran off earlier due to intake by fish. Regarding the plots with ducks, azolla ran off 2 weeks after duck integration, i.e. 37 DAT. Therefore, when fish were introduced in RMAFD plots, azolla had already been eaten by ducks or lost through runoff.

As azolla was collected from nearby rice fields and then inoculated, no costs were considered for azolla integration. However, in case of choosing to purchase it, the cost would be 50.000 Rp kg FM^{-1}, which is extremely high given the required amount of input (2.000 kg ha^{-1}). Another possibility would be to collect all the required amount of azolla by hand. However, this would require extra labor and would carry an extra cost. In previous experiences, 2 workers were needed to collect 100 kg of azolla in one day. Each worker earned 70.000 Rp day^{-1} and the required time to collect 2000 kg of azolla was 20 days. Hence, the total cost of labor to collect 2000 kg azolla was 2.800.000 Rp (70.000 x 2 x 20), so the cost per kg of azolla would therefore be 1.400 Rp/kg. Although this would increase the overall cost of production, the option of hiring labor to collect azolla is definitely more feasible than purchasing the whole amount. However, it is important to know whether azolla grows spontaneously at the area where is being searched; otherwise the required time to obtain the desired amount can be longer thus increasing the cost of labor.

3.1.3. Ducks

At the time of withdrawal, ducks weighted an average of 1,2 kg both in RMAD and RMAFD (Appendix 8) with a proportion of meat of 35% (see Appendix 7 for the distribution of duck live weight). Mortality was 0 in all the cases and the selling price was the same for every duck. Therefore, total revenues and gross margin from ducks were the same in both treatments. However, the low yields achieved and the high costs of production resulted in a negative gross margin (Table 3).

Table 3. Economic balance from ducks.

Costs (Rp ha^{-1})		Revenues (Rp ha^{-1})	Gross margin (Rp ha^{-1})
Ducklings	Feed		
5.200.000	8.650.878	10.000.000	- 3.850.878

Feed conversion ratio (FCR) at 10 weeks of age was calculated by dividing the total amount of supplied feed consumed by the weight gained during the whole period (Table 4). Regarding the feed intake, it was assumed that ducks spilled 10% of the feed when eating. Therefore, the supposed feed consumed was 90% of the feed supplied. Azolla and other feed sources were not considered in the calculation of the FCR, which suggests that the actual FCR would be higher.

Table 4. Duck body weight increase and FCR.

Initial weight (g)	Final weight (g)	Weight gained (g)	Feed consumed (g duck^{-1})	FCR
55	1.200	1.145	9.220	8

The resulting FCR seems rather high compared to the results of other studies carried out using Mojosari ducks. Purba and Ketaren (2011) reported a FCR of 5 at 8 weeks of age, whereas the FCR determined by Indarsih and Tamsil (2012) ranged from 5,31 to 7,65 at the same age depending on the feed supplied.

The high FCR is explained by the low nitrogen use efficiency (NUE) (see section 3.2.3 for NUE of ducks), as only a small part of the protein intake could be utilized for growth. The low NUE was probably due to the lack of metabolizable energy (ME) available to digest the consumed digestible protein (DP). In contrast with former studies in which ducks were caged, ducks in the experiment were constantly moving around the field and sometimes coping with strong winds, which increase the energy required for maintenance. A measure that may improve FCR would be to increase the energy content of the feed supplied. Tugiyanti et al. (2013) determined that increasing protein and energy content of feed had a positive impact on duck growth, thus decreasing FCR from 5,26 to 4. The protein and energy content that resulted in the lowest FCR was 21% and 3100 kcal kg $^{-1}$ respectively. In the current experiment, feed supplied had approximately a protein content of 21% and an energy content of 2288 kcal kg^{-1} (Table 5). On the one hand, protein content was estimated by multiplying the N content of feed (3,2% DM) by the protein-to-N conversion factor. On the other hand, feed energy content was calculated by dividing total ME supplied by the total amount of feed supplied. While the protein content was roughly the same as in Tugiyanti et al. (2013), the ME was approximately 26% lower.

Table 5. Energy content of the original feed mixture.

Feed ingredient	%	ME* (kcal kg DM^{-1})	Amount supplied (kg DM duck^{-1})	ME supplied (kcal)
Rice bran	75,0	2.040	7,7	15.675
Dry rice	18,6	2.940	1,9	5.592
Corn	4,6	3.390	0,5	1.612
Ground corn	1,1	3.390	0,1	374
Dried fish	0,7	2.600	0,1	191
Total	*100*	*2.288*	*10,25*	*23.444*

*Source: (Batal and Dale 2010).

Rice bran was the main feed ingredient (75%) due to its low cost and high availability. However it has a low energy content compared to other feed ingredients. Therefore, it would be interesting to investigate how much would the FCR decrease when replacing part of the rice bran supplied for a high-energy feed such as rice or corn.

In order to decrease FCR, two more caloric feed mixture were suggested based on the same ingredients as the original one. By decreasing the proportion of rice bran and increasing the percentage of dry rice and corn, the feed energy content was increased. In both feed mixtures, the ME content was the same or very close to 3100 kcal kg^{-1}, following the recommendations of Tugiyanti et al. (2013) (Appendix 9). On the one hand, feed mixture 1 had corn as the main ingredient so as to provide 3100 kcal kg^{-1}. This however increased a lot the cost of feed as corn is the most expensive ingredient. On the other hand, feed mixture 2 uses dry rice as the main ingredient, so the cost of feed is lower compared to the other mixture. However, more feed was needed to supply the same amount of ME as the feed ME content was lower in the second mixture.

By reducing the amount of rice bran supplied and increasing the proportion of corn and rice, protein content of the feed mixture may decrease. However, this should be compensated by the intake of azolla and insects, which have a high-energy content. However, because ducks in the current experiment consumed more energy than under conventional conditions due to their constant movement, the FCR would still be higher than the achieved in Tugiyanti et al. (2013). Anyway, further research should be carried out in order to determine how much would this variation in the feed mixture affect duck growth.

Taking a FCR of 6, ducks would weight an average of 1,5 kg for the feed mixture 1 and 1,6 for the feed mixture 2, which is respectively 25% and 33% more than average weight in the experiment. Therefore, ducks could be sold at a higher price. However, the higher revenues would not compensate the high cost of feed in any case (see comparison of the 3 feed mixtures in Appendix 10).

In order to increase the gross margin from ducks, part of the feed should be produced on farm. Both rice bran and dry rice could come from own production. Regarding the rice bran however, not all of the required amount for the feed mixture could be produced on farm. As each duck consumes a total of 7,68 kg DM of rice bran from the feed mixture, the total amount of rice bran needed is 3.073 kg DM ha^{-1}. Yet, the amount of rice bran that can be provided from own production will depend on the rice yields achieved. Provided that 20% of the whole grain is husk (Juliano 1993), the amount of rice bran that could be provided from each treatment would be 1.416 kg ha^{-1} for RMAD and 1.612 kg ha^{-1} for RMAFD (Table 6).

Table 6. Amount of rice bran provided from RMAD and RMAFD.

	Rice yield (Mg ha^{-1})	Rice bran produced (kg DM ha^{-1})	Extra rice bran needed (kg DM ha^{-1})
RMAD	7,08	1.416	1.657
RMAFD	8,06	1.612	1.461

The use of on-farm produced rice bran should not affect the revenues from rice production, as rice bran is a byproduct of milling (Picture 9) and the same amount of refined rice grain could still be sold. However, the revenues would still not be high enough to cover the cost of the rest of feed and ducklings. Therefore, using on-farm rice bran would decrease the costs of production, but it would not be enough to achieve a positive gross margin. However, price of feed and ducklings as well as the sale price for adult ducks may fluctuate, which could actually result in a positive gross margin. Regarding dry rice, it is more profitable to purchase it than using rice from own production, as its cost is lower than the sale price from production (3.000 Rp kg^{-1} and 4.000 Rp kg^{-1} respectively).

Picture 9. Harvested rice being milled through a mobile grain miller. Rice bran is collected in a sack (on the left) and grain is collected in a bucket (on the right). *Photo: Gonzalo Garnacho Alemany.*

All in all, the original feed mixture may not be the one that results in the best FCR, but it seems to be the best choice from an economical point of view. Mojosari is a slow-growing breed and it does not seem very profitable under organic conditions due to its high FCR and high cost of production. Therefore, the high cost of duck raising may be a limitation for resource-poor farmers who want to apply the system and do not have enough money to cover the expenses. In order to make it profitable, at least rice bran should be produced on farm. Moreover, breeding could be a way to decrease the high costs of production. However, this would require extra feed and labor to raise adult ducks. Finally, another possibility to make ducks more profitable could be to raise the females for egg production (Cagauan et al. 2000).

However, it is important to bear in mind that although ducks alone may not be profitable when they are integrated in rice production, they make a great contribution on increasing rice yields by performing biological weed and pest control and providing rice plants with a constant supply of nutrients.

3.1.4. Fish

Fish yields were very low in all plots due to high fish mortality (Table 7 and Table 8). Most of the fishes died during the cropping cycle due to low water levels at some points of the season. Although the rice fields were flooded, the water level was sometimes too shallow for the fish to survive, eventually causing a high fish mortality.

Table 7. Yield and amount of fished harvested per plot.

	Block 1		Block 2		Block 3	
	Yield (g 100m^{-2})	Nr. of fishes	Yield (g 100m^{-2})	Nr. of fishes	Yield (g 100m^{-2})	Nr. of fishes
RMAF	540	3	375	2	245	2
RMAFD	430	3	450	2	180	1

Revenues per hectare (Table 8) were lower than the costs of the fingerlings, thus causing a negative economic balance of 1,92 million Rp in the case of RMAF. However, the negative gross margin was compensated by the higher revenues achieved from rice compared to RMA (an average of 2,13 million Rp more).

Table 8. Yield, amount of fishes harvested and revenues per hectare.

	Weight at harvest (g fish^{-1})	Nr. of fishes	Yield (kg ha^{-1})	Costs (Rp ha^{-1})	Revenues (Rp ha^{-1})	Gross margin (Rp ha^{-1})
RMAF	163	233	38	2.500.000	580.000	- 1.920.000
RMAFD	175	200	35	2.500.000	530.000	-1.970.000

More water should have been used to irrigate the plots with fish, especially in periods with low rainfall and high radiation, when evapotranspiration is high. Another possibility to prevent fish mortality could be to construct a pond that fish could use for shelter when water levels are low in the rest of the field. In order to prevent water drainage in the pond area, a plastic layer could be put around 60 cm under the soil. However, no plastic should be allocated in the rice-planted area since it would affect soil functioning, root development and nutrient uptake.

3.1.5. *String beans*

String beans yielded an average of 1.744 kg ha^{-1}. However, since beans were harvested several times during the cropping season and the selling price fluctuated in time, revenues were different depending on the date of harvesting (Appendix 11). In the experiment, the average total revenues were 5.371.833 Rp, which is a remarkable amount given their low cost of production (only 428.400 Rp were spent in seeds). Therefore, the high profit obtained from beans together with the use of the plant residues for green manure, make beans an excellent crop to grow in East Java.

3.1.6. *Comparison of the economic performance*

As well as inputs and yields, total costs and revenues varied from treatment to treatment. Integration of livestock, either fish or ducks, led to an increase on costs. However, duck integration entailed the highest costs by far (Figure 9), which was mainly due to the high cost of feed and, to a lesser extent, to the cost of ducklings.

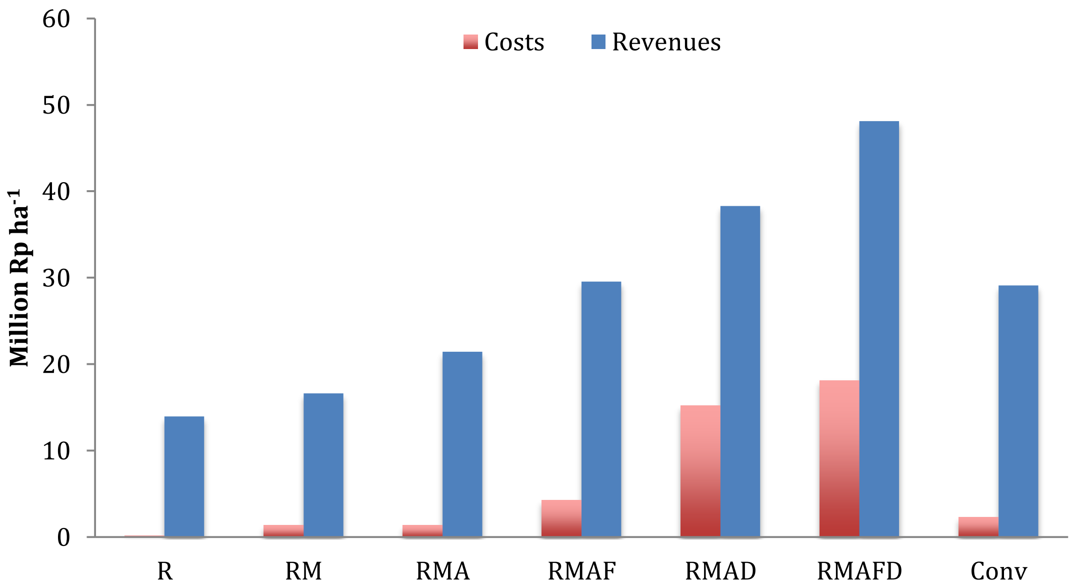

Figure 9. Total costs and revenues of each treatment.

The high costs of raising ducks were compensated by higher revenues. However, RMAF presented a higher gross margin than RMAD (Figure 10), which was due to the high revenues obtained from beans and the lower costs of production. In accordance to the results obtained by Dalsgaard and Oficial (1997), most complex rice agro-ecosystems generally presented a higher gross margin,. Yet, the conventional treatment presented the 2nd highest gross margin, only surpassed by the most complex system (RMAFD).

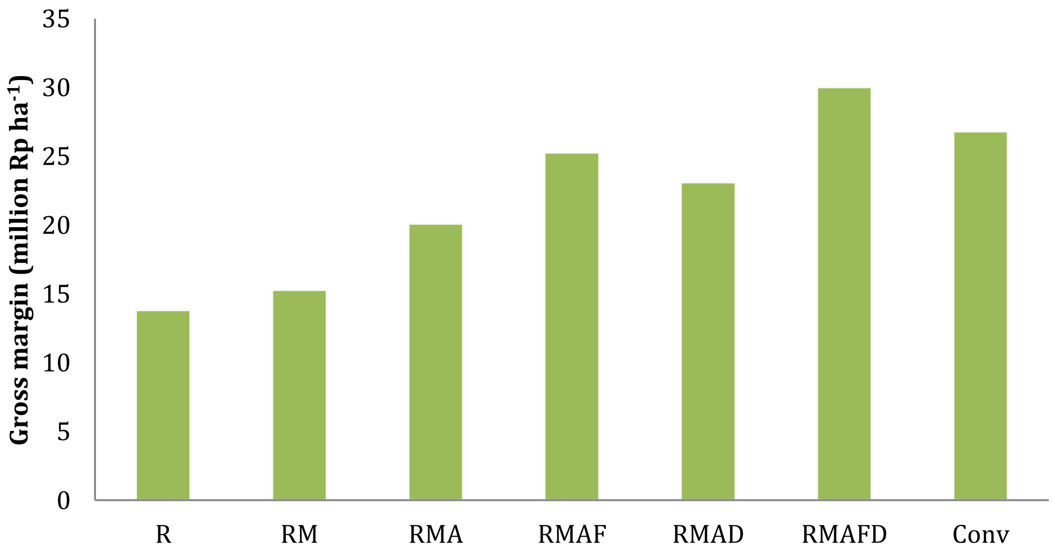

Figure 10. Gross margin of each treatment.

Revenues from ducks and fish did not overcome their cost of production, which decreased the potential gross margin of those treatments with livestock. Although duck integration increased rice yields significantly in both RMAD and RMAFD, the increase was not enough to provide a higher margin than Conv in the case of RMAD. In the case of RMAFD however, the higher rice yields together with the revenues from beans provide a better margin than Conv.

Table 9. Comparison of the economic performance of the 7 treatments.

	Total costs (MRp ha^{-1})	Total revenues (MRp ha^{-1})	Gross margin (MRp ha^{-1})	Revenues:cost ratio
R	0,16	13,97	13,81	87,33
RM	1,36	16,64	15,28	12,24
RMA	1,36	21,47	20,11	15,78
RMAF	4,29	29,55	25,26	6,89
RMAD	15,21	38,32	23,11	2,52
RMAFD	18,14	48,14	30,00	2,65
Conv	2,33	29,12	26,79	12,50

The system that resulted in more revenues per money invested was the control treatment (Table 9). However, rice yields in this treatment would decrease in the following cropping cycles due to mining of nutrients unless amendments were added into the soil, which would decrease the revenues-to-cost ratio. After R, the following treatment that showed the best revenues-to-cost ratio was RMA. Yet, the ratio would have been lower in case azolla had been purchased or collected by laborers. The lowest amount of revenues per money invested occurred in the treatments with ducks. However, this ratio could be enhanced by producing part of the feed on farm and breeding.

3.1.7. Carrying capacities

The amount of people that can be fed per area of land varies a lot depending on the nutrient requirements that are considered. When it comes to energy requirements, the carrying capacity was rather high in all treatments, due to the high-energy content of rice. The most complex system was the one that produced the largest amount of energy per unit of land (27,58 Mcal ha^{-1} cropping $cycle^{-1}$), resulting in a carrying capacity of 73 people ha^{-1} $year^{-1}$ according to energy requirements. Following RMAFD, the treatments that produced the largest amount of energy were RMAD, which provided energy enough to feed 63 people and Conv, which could meet the energy requirements of 62 people. Therefore, the surplus of energy coming from ducks was enough to surpass the energy produced in the conventional treatment (Figure 11), even when rice yields were lower.

Leaving the conventional treatment aside, it seems that energy produced, and thus carrying capacity, increased with system's complexity. In all the cases, the resulting rice consumption would be around 500 g $capita^{-1}$ day^{-1} (Appendix 16), which is slightly higher than the average rice consumption in Indonesia, that is ca. 440 g $capita^{-1}$ day^{-1} (Mohanty 2013).

However, the carrying capacities of all the treatments decreased when considering the recommended daily allowance (RDA) of Fe, Zn and Vit A (Figure 11). The amount of micronutrients produced differed considerably from treatment to treatment (Appendix 17) due to the different nutrient content of each product and the different rice yields achieved. The only treatments that would be able to meet the requirements of Fe, Zn and Vit A for a certain amount of people were those treatments with livestock. However, it is important to note that all the Vit A provided from the RMAF treatment came from string beans, as Nile tilapia does not contain Vit A.

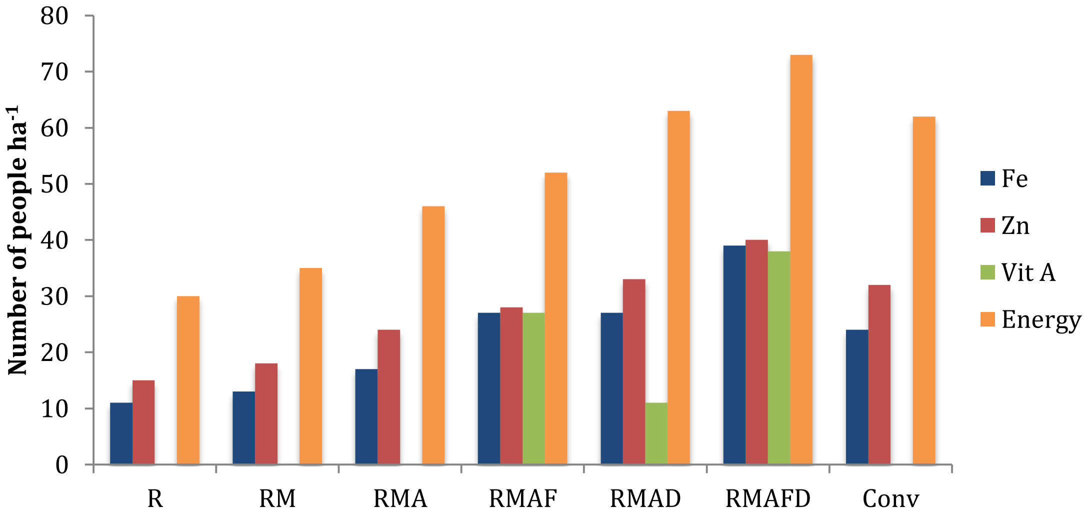

Figure 11. Number of people that can be fed from each system considering the recommended daily allowance of Fe, Zn, Vit A and energy.

The most remarkable difference between treatments was the amount of Vit A produced. While rice does not contain Vit A at all, the content of this micronutrient is high in beans and ducks, especially in giblets. However, animal organs are usually not eaten in Indonesia due to the misconception that they may be unhealthy (Jati et al. 2012). Besides the high content of Vit A, duck meat and giblets are a major source of Fe. However, the contribution of beans to the total amount of Fe produced was greater than of ducks (Figure 12), partly due to the low edible portion of ducks. Despite its low Fe and Zn content, rice was the main source of those nutrients in all the 7 systems. Therefore, it would be interesting to grow other crops that have a higher content of those nutrients.

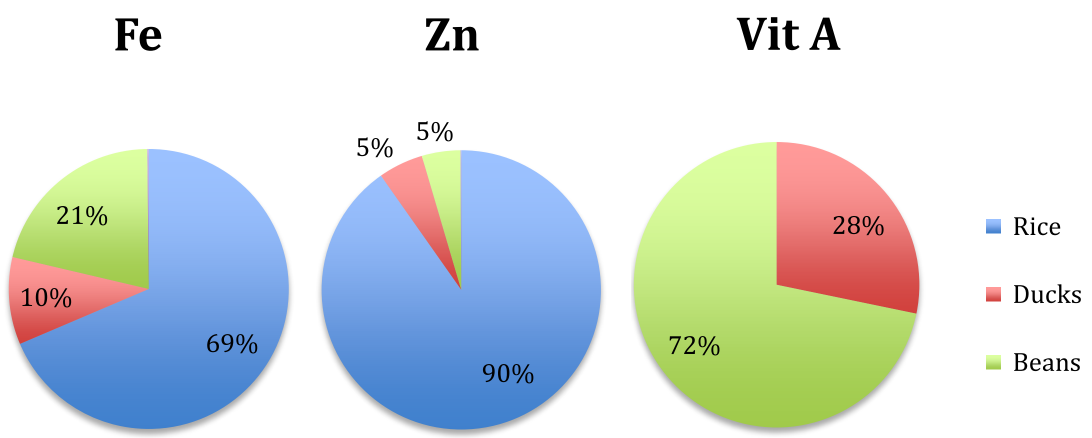

Figure 12. Contribution of each commodity to the total amount of Fe, Zn and Vit A produced in RMAFD. Contribution of fish was lower than 1% in all cases.

All in all, the most complex system was still the one that was able to fulfill the RDA of largest number of people (38) when considering the energy and the 3-micronutrient requirements. To reduce the gap between the different carrying capacities, other food products should be consumed. Intake of meat products (i.e. eggs), vegetables (i.e. cassava) or fruit trees could also be grown to increase the supply of Fe and Zn (Jati et al. 2012). While part of the remaining diet components could be purchased, some crops could be grown on farm, thus making the whole farming system more self-reliant. Groundnut is a good source of Fe (USDA 2011), which could be grown on the field margins (Picture 10). Since it is a leguminous crop, atmospheric N can be fixed through the symbiotic association between Rhizobia and the plant roots. Therefore, part of the groundnut biomass could be used as green manure to fertilize paddy fields (Toomsan et al. 1995). Since coconut has a high content of Fe and Zn, growing coconut trees on the field margins would increase the supply of those micronutrients. Moreover, growing crops such as papaya sweet potato or spinach would increase the supply of Vit A and therefore contribute to provide a more balanced diet (USDA 2011); (Jati et al. 2012). The cultivation of those crops could either take place on the field margins (Picture 10), or on a separated land (Picture 11). However, attention should be paid on the shade provided by those crops on the rice fields, as too much shading would decrease rice yields.

Picture 10. Groundnut growing on a rice field margin near Pasuran, East Java. *Photo: Gonzalo Garnacho Alemany.*

Picture 11. Sweet potato growing next to a rice field near Mojokerto, East Java. *Photo: Gonzalo Garnacho Alemany.*

When comparing the carrying capacities with those from the 3 external farms analyzed (Appendix 20), one can see that the most complex agro-ecosystem (RMAFD) generally performs better than any of the 3 farming systems. While those farms produce a wider variety of products, land use is probably not as intensive as in the most complex system.

Moreover, while most of the energy produced in those systems comes form rice as well, one can see that fruit also contributes significantly to increase the amount of energy produced. The high productivity of fruit trees and the high energy content of fruit, make trees a good alternative to increase the carrying capacity according to the energy requirements. Moreover, fruit generally have a higher Fe, Zn and Vit A content than rice. Growing fruit trees on the field margins such as coconut, banana or papaya could be a way to increase carrying capacity of rice agro-ecosystems. However, attention should be paid on the amount of trees planted and their canopy development in order to avoid too much shade on the rice fields. The high Vit A content of papaya makes it a very interesting crop to grow on the field margins of rice agro-ecosystems. Furthermore, leaves could be easily used to feed the ducks whenever necessary.

Only 1 farm had a higher carrying capacity in terms of energy requirements. On the one hand, the cultivation of sugar cane increased significantly the amount of energy produced. However, most of the production of sugar cane is sold to the sugar industry and cannot be consumed on farm. On the other hand, a fast-growing rice variety was used in this farm, leading to 3 cropping cycles per year. In the case of the complex systems, using such a rice variety would not be feasible because neither fish nor rice would have time to reach the desired weights.

3.1.8. Best-case scenario

In this scenario, the cost of feed was reduced to 2.508 Rp kg^{-1} by using rice bran from own production. Moreover, fish yields were increased by assuming 0 fish mortality and the same average final weight as the achieved in RMAFD (175 g $fish^{-1}$). Rice, duck and string bean yields were the same as the obtained in the experiment.

The use of rice bran from own production reduced the cost of feed by 25% and considerably reduced the total costs of RMAD and RMAFD (Figure 13). Moreover, the higher fish yields caused a remarkable increase on the total revenues of RMAF and RMAFD (Figure 13).

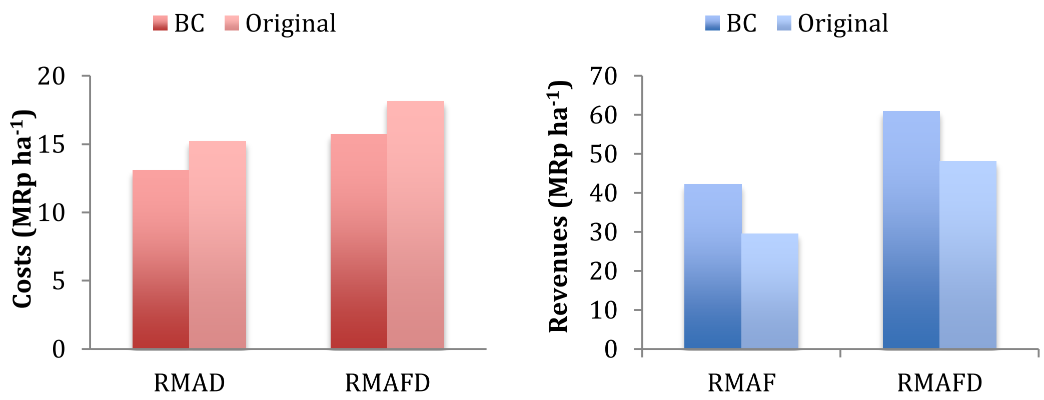

Figure 13. Costs and revenues archived in the best-case scenario (BC) compared to the original results from the experiment.

Consequently, the gross margin of the 3 treatments with livestock increased. The greatest increase was observed in the most complex system, as both costs and revenues of this treatment were adjusted (Figure 14).

Supposing those improvements were carried out in the next following cropping seasons, the treatments with fish (RMAF and RMAFD) would be the most profitable ones.

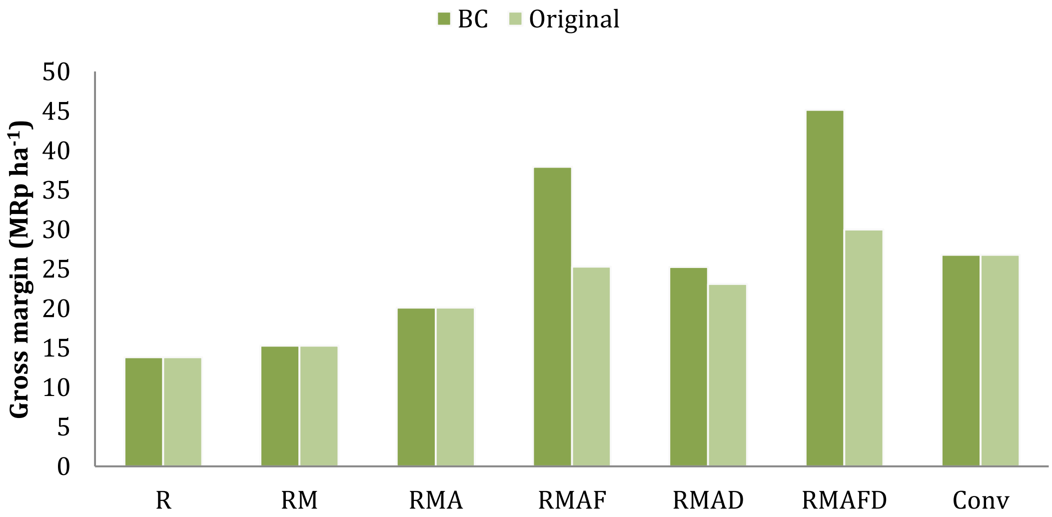

Figure 14. Gross margin achieved in the best-case scenario (BC) compared to the original results from the experiment.

Since fish are not a very caloric aliment, the total energy produced in those treatments with fish would not change very much. However, such an increase would provide enough energy to feed one more person in each treatment, leading to a carrying capacity of 53 people ha^{-1} for RMAF and 74 people ha^{-1} for the RMAFD treatment, when it comes to energy requirements. Moreover, since Nile tilapia is not rich in any of the 3 micronutrients of concern, the increase of total Fe, Zn and Vit A produced would not be enough to change the carrying capacities when it comes to those micronutrients.

3.2. Nitrogen cycling

The results of the N use efficiency and balance of each component (rice, azolla, ducks, fish and string beans) are discussed first and then a field level analysis of the whole N cycling performance is presented.

3.2.1. Rice

As well as yields, N uptake differed from treatment to treatment. As expected, the lowest N uptake took place in the control treatment (R). However, the amount of N taken up by the crop was rather high considering that no input of N was used other than seeds. Therefore, the soil nutrient pool provided enough nutrients for the rice to grow and develop relatively well. While part of the N that was taken up by the rice plants in the control treatment was already inorganic when rice was transplanted, great part of the N taken up was probably mineralized during the cropping cycle. This suggests that the soil was quite rich in organic matter even though this was the first year of transition to organic. However, no pesticides had been applied in the previous years and crop residues had always been added into the soil after harvesting, thus causing a positive effect on the physical and biological soil fertility. Yet, it is important to bear in mind that the yields achieved in the control treatment would very probably become lower in the following cropping cycles due to soil nutrient mining (Table 11).

Taking the control treatment as a reference, apparent N recovery (ANR) from amendments was calculated through the following formula:

$$ANR=\frac{\text{N uptake treatment}-\text{N uptake control (R)}}{\text{N input treatment}}\cdot 100 \qquad \text{(Eq. 3)}$$

N recovery increased with complexity in the organic treatments except for RMAD (Table 10). Treatments with ducks required importing larger amounts of feed, which resulted in a higher N input. Despite the large amount of input, the highest ANR considering rice biomass occurred in the most complex system (RMAFD) due to its high N uptake. The main reason why N uptake was higher in RMAD and RMAFD was the yield protecting measures carried out by ducks (i.e. biological weed and pest control), which enabled the plant to convert more N into biomass. Moreover, the continuous N supply through excreta may have also contributed to increase N uptake. Since a great part of the excreted N was already in inorganic form, more N was available during the cropping season and could therefore be taken up by rice.

Table 10. Apparent N recovery from input.

Treatment	N input* (kg N ha^{-1})	N biomass (kg N ha^{-1})	ANR ** biomass (%)	N output (kg N ha^{-1})	ANR *** grain (%)
R	0	176		58	
Conv	201	253	38	122	31
RM	169	208	19	69	7
RMA	173	229	31	90	18
RMAF	173	241	38	99	23
RMAD	309	269	30	118	19
RMAFD	309	298	39	135	25

* N contained in all the inputs that rice plants could utilize for growth (i.e. fertilizers, imported manure, azolla and feed).

** ANR biomass considers the whole amount of N contained in the rice biomass produced.

*** ANR grain considers the amount of N contained in grain.

Moreover, Conv presented a higher ANR than RM, which means that a greater part of the N applied was taken up by rice. This higher N recovery form chemical fertilizer was due to the form of N applied. On the one hand, N in urea and ZA is already inorganic, so it can immediately be taken up by rice. On the other hand, N in manure is mainly in organic form and needs to be mineralized in order for the plants to absorb it. Once mineralized, the amount of N that eventually is converted into biomass depends on yield-defining factors (e.g. radiation and temperature), yield-reducing factors (e.g. pests and weeds) and the availability of other nutrients. In contrast with the treatments in which ducks were integrated, the presence of pests and weeds probably reduced N uptake in those treatments with no biological control.

N recovery was slightly higher in the most complex system than in the conventional system. However, it is important to bear in mind that no pesticides were applied, which might have negatively affected rice performance in the conventional treatment. While the difference in ANR is rather low, the main advantage of the most complex system over the conventional one is that part of the imported N that did not mineralize will become available in the following cropping cycles (Ventura and Watanabe 1993).

When considering ANR of grain only, the conventional treatment was the one that performed better. This was due to the high N harvest index of conventional rice compared to the other treatments (significantly higher than R, RM and RMA, $p<0,05$).

The N input that could not be taken up by rice would remain in the soil N pool and would become available in the following cropping cycles (Table 11). Therefore, the amount of imported manure could be reduced in the following cropping seasons, especially in those treatments with ducks, in which N balance was higher.

Table 11. Rice N balance (kg N ha^{-1}).

Treatment	N output	N input	Green manure	Azolla lost*	Leaching & outflow**	N added to soil N pool
R	58	0	0	0	4	-62
Conv	122	201	0	0	3	77
RM	69	169	0	0	3	96
RMA	90	173	0	7	3	74
RMAF	99	173	12	4	3	79
RMAD	118	309	0	2	5	183
RMAFD	135	309	12	2	5	179

* Calculations regarding the estimation of azolla losses are detailed in section 3.2.2.
** Calculations regarding the estimation of N losses through leaching and outflow are detailed in section 2.5.4.

However, it is important to remark that N contained in both rice grain and plant residues was overestimated. Since those items were sun-dried instead of air-dried in the oven, some moisture remained, leading to an overestimation of the DM content. Therefore, the actual amount of N output of all treatments should be lower, consequently leading to higher N balances.

3.2.2. Azolla

The biomass of azolla declined after introduction with different patterns in the three treatments with azolla (Figure 15). Those patterns were not directly monitored, but estimated on the basis of various assumptions and observed moment of azolla depletion. In RMA, a linear depletion rate (32,3 kg FM day^{-1}) was assumed for azolla from the day it was introduced (December 17) until it ran out (February 17). In RMAF, the same depletion rate was assumed until fish were introduced (January 21). From then on, azolla was depleted faster, as fish consumed it. The amount of azolla eaten by fish was estimated by assuming that 50% of the protein intake by fish was from azolla (see section 3.2.4 for the estimation of the protein consumed by fish). In RMAD and RMAFD, the initial depletion rate was the same as in the other treatments. However, once ducks were integrated in the system, azolla depletion was accelerated, as they fed on azolla until it ran out 2 weeks later. Therefore, a new linear depletion rate (96,8 kg FM ha^{-1}) was calculated for this period taking the supposed azolla biomass when ducks were integrated and the complete depletion after 2 weeks. In the case of RMAFD, ducks had already consumed all the azolla when fish were integrated, thus leaving no azolla for fish to feed on. Therefore, azolla consumed by ducks was the same both in RMAD and RMAFD.

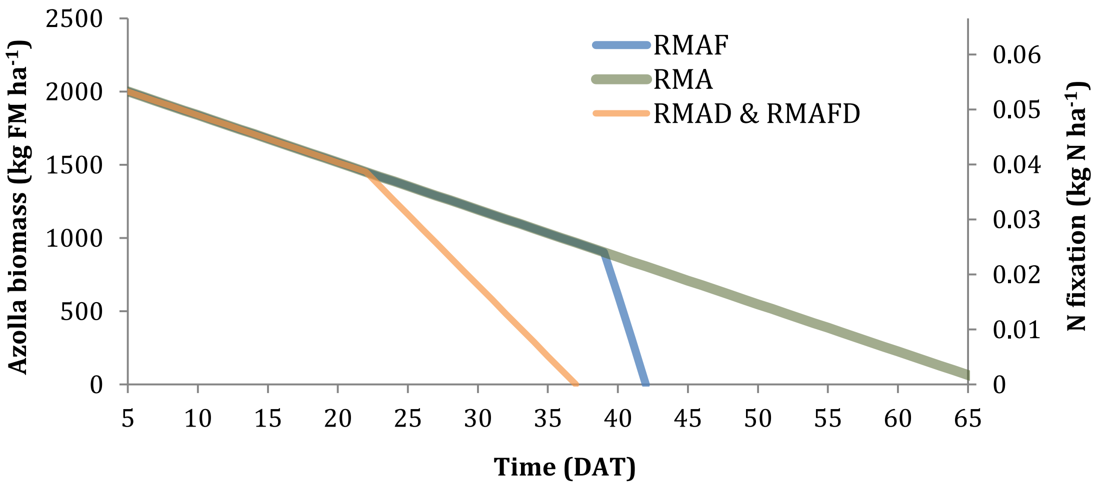

Figure 15. Estimated change in azolla biomass and N fixation in treatments with azolla.

Biological N fixation through azolla was difficult to estimate since there is a lot of variation in literature regarding the amount of N that azolla can fix per unit of land. In an experiment carried out by (Roger, P. A., Kulasooriya 1980), they estimated an average N fixation of 27 kg N ha^{-1} per rice crop, with a maximum fixation of 50-80 kg N ha^{-1}. However, the large variation in the results suggests that those amounts are rather uncertain. A more accurate study determined that azolla intercropped with rice fixes an average of 12 kg N ha^{-1} cropping season^{-1} (Giller 2000). According to Giller (2000), the optimal azolla density is 2-4 tons ha^{-1}. Taking the average fixation (12 kg N ha^{-1}) and the average density (i.e. 3 tons ha^{-1}), the fixation per ton of azolla would be 4 kg N Mg^{-1} azolla ha^{-1} day^{-1}. Assuming the same growing period as in the present experiment (i.e. 150 days), the estimated amount of N fixed would be 0,02 kg N Mg^{-1} azolla ha^{-1}. However, one should note that this is just a rough estimation as weather conditions and azolla density were different in each experiment. Taking the above-calculated fixation rate and the azolla biomass variation in each treatment, the total amount of N fixed per treatment was estimated. Since azolla was depleted in all cases, N fixation was rather low and similar in all treatments (Table 12). The treatment in which azolla fixed the largest amount of N was RMA, due to the lower azolla depletion rate.

Azolla consumption by ducks was therefore the initial amount of azolla when they were introduced at 23 DAT. The N contained in such amount of azolla was 3,5 kg N ha^{-1}. However, azolla kept fixing N while it was being eaten by ducks. The estimated amount of N fixed during that period was only 0,3 kg N ha^{-1}. Therefore, the sum of both amounts resulted in the total amount of N from azolla consumed by ducks, which rounded was 4 kg N ha^{-1}. The calculations for the estimation of the azolla consumption by fish in RMAF are detailed in section 3.2.4.

Table 12. Azolla N balance (kg N ha^{-1}).

	RMA	RMAF	RMAD	RMAFD
Input	5	5	5	5
Ducks' consumption	na	na	4	4
Fish's consumption	na	2	na	na
Lost through runoff	7	4	2	2
N fixation	2	1	1	1

na= not applicable.

Moreover, azolla that was neither eaten by fish nor by ducks was considered lost through runoff. However, azolla also developed growth while being depleted. According to Giller (2001), 80% of the N gained during growth comes from atmospheric N fixation and 20% is taken up from water. Given the low amount of N fixed in all the treatments (≤2 kg N ha^{-1}), the N taken up from water would be lower than 0,50 kg N ha^{-1}. Therefore, only N from fixation was taken into account in the N balance.

3.2.3. Ducks

When ducks were integrated at 23 DAT, azolla had already decreased its coverage. Assuming a linear depletion rate, azolla biomass was 1.355 kg FM ha^{-1} (i.e. 68 kg DM ha^{-1}), when ducks were introduced. Since then, ducks consumed all the azolla in just two weeks. During that period, the estimated azolla consumption by ducks was 4,9 kg DM ha^{-1} day^{-1}. No azolla was considered lost through runoff once ducks were integrated. However, azolla also fixed N and therefore experienced growth during this period. Therefore, the actual consumption of azolla would be slightly higher. To reflect this in the N balance, the N fixed through azolla while ducks were integrated (0,2 kg N ha) was added to the amount of N consumed from azolla (3,5 kg N ha), leaving a rounded amount of 4 kg N ha $^{-1}$ (Table 13).

Since ducks spilled part of the feed while eating, it was assumed that 10% of the feed was not eaten. Actually, the spilled feed fell down on the ground and was mixed with soil and water. Therefore, N contained in the 10% of feed was accounted as an N flow from ducks to the rice-azolla intercrop.

Regarding the outcome from the 24 hours excreta collection experiment, ducks produced an average of 24 g DM duck^{-1} day^{-1}, which is a very low amount considering their feed intake (190 g DM duck^{-1} day^{-1}) and their low FCR (8). The reason for such a low amount may be that ducks were so stressed when they were caged that they could not defecate as usual. Birds were changed every 4 hours, which is a very short time for the ducks to get used to the cages. Consequently, the outcome from this experiment could not be used due to the low reliability of the results. Therefore, N excreted through manure was calculated by making the N balance 0 (Table 13). In reality, ducks also fed on other feed sources besides the supplied feed and azolla. However, those were not considered in the N balance due to the difficulty to estimate those amounts.

Table 13. Duck N balance (kg N ha^{-1}).

	RMAD & RMAFD
Input	1
Azolla intake	4
Feed (90%)	122
Excreta	113
Output	12

The resulting NUE was 10% and was calculated through Eq. 4. However, the actual NUE would be even lower as ducks also consumed N from other feed sources.

$$\text{NUE}=\frac{\text{Output}-\text{Input}}{\text{Feed}+\text{Azolla intake}}\cdot 100 \qquad \text{(Eq. 4)}$$

As explained in section 3.1.3, such a low NUE was due to a low ME intake. Increasing the ME supplied in feed would increase the NUE of ducks, as they would be able to use a larger amount of N for growth. Nevertheless, the N contained in manure is not considered a loss at the field level, as the N from manure can be taken up by rice, consumed by plankton or remain stored in the soil and become available in the following cropping cycles.

3.2.4. Fish

A linear growth rate was assumed, which was estimated by subtracting the average final fish weight to the initial weight and dividing the result by the growth period (i.e. 60 days), resulting in a growth rate of 2,48 g FM day^{-1}.

Two scenarios were developed in order to estimate fish mortality. On the one hand, Scenario 1 assumed a linear mortality rate since fish were integrated until they were caught. This rate was calculated by subtracting the average number of fishes that were harvested to the initial amount of fishes and dividing the result by the growth period, thus resulting on a mortality rate of 79,7 fishes ha^{-1} day^{-1}. On the other hand, Scenario 2 assumed a linear mortality rate since the first dead fish was observed (February 10) until they were harvested, resulting in a rate of 116,7 fishes day^{-1}.

Therefore, fish biomass variation in time was estimated by combining fish weight, growth rate and mortality rate of each scenario (Figure 16 and Figure 17).

In order to calculate the amount of N excreted through fish excreta, daily protein intake was first calculated by using the formulas suggested by Burnell and Allan (2009). In their study, they suggested a series of formulas to calculate protein requirements by Tilapia given a certain body weight, growth rate and water temperature (Eq. 5-8) and (Table 14).

DPmaint = (0,048 · T – 0,65) · BW 0,70 (Eq. 5)

PG = WG · protein content of gain (160 mg g^{-1}) (Eq. 6)

DP_{growth} = expected protein gain · 2,17 (cost in units of DP to deposit one unit of protein as growth) (Eq. 7)

$DP_{maint+growth} = DP_{maint} + DP_{growth}$ (Eq. 8)

Although water temperature varied in time (Del Rio 2014), the low amount of measurements and the low variation observed (30±3°C) made it convenient to use the mean temperature in the calculations.

Table 14. Variables used to calculate fish daily protein intake.

Abbreviation	Variable	Value	Unit
DP_{maint}	Digestible protein required for maintenance	Varies in time	g $fish^{-1}$ day^{-1}
PG	Expected protein gain	0,38 */ 0,41**	g $fish^{-1}$ day^{-1}
DP_{growth}	Digestible protein required for growth	0,83* /0,89**	g $fish^{-1}$ day^{-1}
$DP_{maint+growth}$	Total DP required for maintenance and growth	Varies in time	g $fish^{-1}$ day^{-1}
T	Water temperature	30 (average)	°C
BW	Body weight	Varies in time	kg
WG	Weight gain	$2{,}39 \cdot 10^{-3}$* / $2{,}57 \cdot 10^{-3}$**	kg $fish^{-1}$ day^{-1}

* Values belonging to RMAF.
** Values belonging to RMAFD.

The apparent protein digestibility of azolla by Tilapia (0,55) determined by Leonard et al. (1998) was assumed for all feed sources. Therefore the quotient of the total DP required and the protein digestibility gave the total CP intake (Eq. 9).

Protein intake = (DPmaint+growth) / 0,55 (Eq. 9)

N content was determined by using the protein-to-N conversion factor (Eq. 10).

$$\text{Protein} = 6{,}25\ \text{N} \qquad \text{(Eq. 10)}$$

Once daily N intake was estimated, the amount of N excreted per day was calculated (Figure 16 and Figure 17). On the one hand, N from the CP that was not digested was excreted through feces. This amount was calculated according to the apparent protein digestibility and converted into N through the protein-to-N coefficient (Eq. 11). On the other hand, the N from DP that was eventually excreted was calculated by adding the DP for maintenance to the extra protein required for growth and dividing the result by the protein to-N-coefficient (Eq. 12).

$$\text{Non-digested protein excreted} = (0{,}45 \cdot \text{CP intake}) / 6{,}25 \qquad \text{(Eq. 11)}$$

$$\text{Digestible protein excreted} = (DP_{maint} + (DP_{growth} - PG)) / 6{,}25 \qquad \text{(Eq. 12)}$$

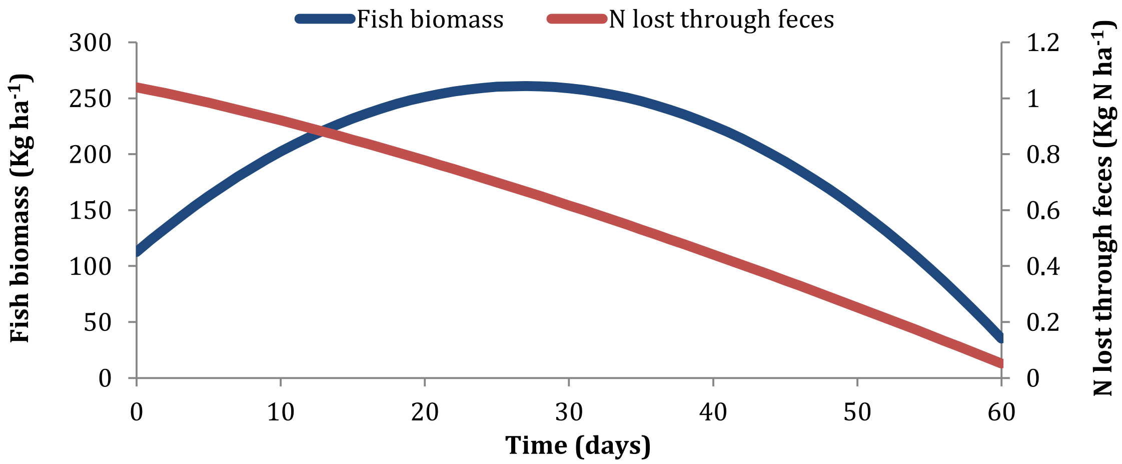

Figure 16. Estimated fish biomass and N lost through excreta in Scenario 1.

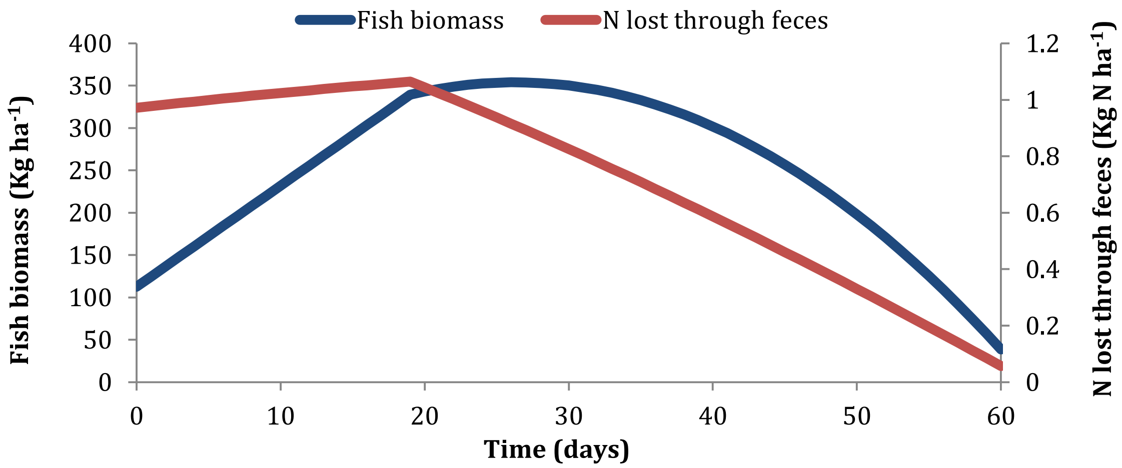

Figure 17. Estimated fish biomass and N lost through excreta in Scenario 2.

Given the two different scenarios of fish mortality, the N flows regarding feed from sources other than azolla, excreta produced and dead fish differ from one scenario to another (Table 15). Although output was slightly different from one treatment to another, the rounded amount of N in output was the same in both cases.

Table 15. Fish N balance (kg N ha^{-1}).

	RMAF (1)	RMAFD (1)	RMAF (2)	RMAFD (2)
Input	3	3	3	3
Azolla intake*	2	0	2	0
Other feed sources	42	47	54	60
Excreta	34	36	44	47
Dead fish	12	12	14	15
Output	1	1	1	1

* Assuming 50% of their daily protein intake came from azolla when this was available.
(1): Scenario 1; (2): Scenario 2.

The resulting NUE was 22%, which means that fish utilized N more efficiently than ducks. However, this efficiency could be lower or higher depending on the actual digestibility of the feed consumed.

3.2.5. String beans

Most of the N contained in the string bean biomass was biologically fixed by Rhizobia. In order to estimate the amount of N that was fixed, N fixation by cowpea was taken as a reference. Senaratne and Ratnasinghe (1995) determined that an average of 83% of the N contained in cowpea was biologically fixed. As no literature was available regarding N fixation of string beans, it was assumed that 83% of the N content of biomass came from fixation (Table 16).

Table 16. String bean N balance (kg N ha^{-1}).

N output	N residues	N fixed
7	12	15

The amount of N in string bean biomass was quite large considering that plants were only growing on the field margins and no fertilizer was applied on the soil. The use of string bean residues as green manure together with its low cost of cultivation make beans a feasible alternative to decrease the amount of N imports used to fertilize paddy fields.

3.2.6. Field level N flow analysis

N flows analysis is divided in 2 sections. On the one hand, the first section shows the N balance of each agro-ecosystem and the efficiency of each system when it comes to N use. On the other hand, ecological network analysis is used in the second section to assess integration, diversity and organization of each network.

N balance and N use efficiency

From a field level perspective, each system used N input (IN) in a more or less efficient way resulting in different amounts of N outputs (EN) (Table 17). The control treatment was the one that performed better in terms of NUE. However, the negative N balance indicated that soil N was depleted, as more N had been exported than imported into the system. In all the other treatments, N balance was positive and relatively high even when considering N losses (full N balance). N that was neither exported nor lost remained stored in the soil N pool and may become available in the following cropping cycles. However, part of the N stored in the soil may also be lost due to gaseous losses, leaching or runoff.

Table 17. N balance and apparent N use efficiency of the rice agro-ecosystems.

	IN	IN*	EN	Partial N balance	NUE	NUE**	N losses	Full N balance
Conv	201	201	122	80	0,60	0,60	3	77
R	0	0	58	-58	187	187	4	-62
RM	169	169	69	100	0,41	0,41	3	96
RMA	175	174	90	86	0,51	0,52	9	76
RMAF	194	177	106	87	0,55	0,60	7	80
RMAD	310	309	131	180	0,42	0,42	8	172
RMAFD	329	312	155	174	0,47	0,50	8	167

All data is expressed in kg N ha^{-1} except for NUE.
* Estimated imported N through fixation is not included.
** Includes azolla lost through runoff.

It is important to bear in mind that including N fixation in the total N input decreased the NUE of those systems in which N fixation took place, either through azolla or string beans. Since N fixation is an ecological service and it does not imply any economic cost for the farmer, this N flow could be neglected when determining systems' NUE. The resulting NUE would therefore represent the use efficiency of the N input that supposed an economic cost for the farmer.

In any case, after the control treatment, Conv was the one that performed better in terms of NUE. This result match with the findings of Ventura and Watanabe (1993), in which NUE in rice production was higher when using Urea than when *Azolla sp.* and *Sesbania sp.* were intercropped with rice and eventually incorporated into the soil. In the current experiment, this was probably due to the high availability of N in Urea and ZA compared to N in manure, which is mainly in organic form. However, N losses are more likely to take place in the conventional treatment, especially through ammonia volatilization (Del Rio 2014), as inorganic N is more prone to losses than organic N. The highest N balances were observed in treatments with ducks, mainly due to the low NUE of ducks themselves. However, most of the N that remained in the soil in the organic treatments was organic, so losses would be prevented. The remaining organic N would mineralize and thus become available in the following cropping cycles, leading to a higher residual effect of amendments on grain yield and N uptake (Ventura and Watanabe 1993). In addition, N input could be reduced in the following cycles, thus improving NUE in the long term.

Since azolla was lost through runoff, N losses were higher in those treatments in which azolla was intercropped with rice. However, total N lost through water outflow and leaching was just a rough estimation as no flow meter could be used in the experiment. Ideally, the amount of outflow should be measured and more measurements should be carried out regarding N concentration in leachates and water outflow.

Ecological network analysis

A schematic representation of the N flows of each treatment is shown in Appendix 22. Moreover, a brief explanation and the calculation of each indicator of network analysis is given in Appendix 21.

Total system throughflow (TST) includes external inflows and internal flows of N. The difference between TST and IN is therefore the amount of N that circulates through internal flows. Since dependency is defined as the quotient between IN and TST, dependency will be lower in those systems with large amounts of N circulating through internal flows and higher in those systems with less or no internal N flows.

Those systems with only one compartment performed equally in terms of network size and integration of the network. Except the control treatment, those systems were highly dependent on external inputs since all the inflows of the network were external. Moreover, as IN>EN (Table 17), it was considered that the entire amount of N output came originally from IN, resulting in the highest dependency possible (D=1) (Table 18). However, this ignored the N that was taken up from the soil N pool. Dependency was lower in those systems that had more than one compartment, due to the internal N flows. The least dependent system was RMAFD due to the large amount of N circulating through internal flows. The low dependency of the control treatment was because no N was imported except for the N contained in the rice seeds.

N was recycled differently in each network and the cycling efficiency depended on the relative cycling efficiency of each compartment (RE_i). RE_i is the fraction of throughflow (T_i) that returns to compartment Hi after flowing through other compartments (Rufino et al. 2009b). The sum of all the RE_i gives the relative cycling efficiency of the network (TSTc). Recycling of N can only take place when compartments are connected in a way that part of the N that goes from one compartment to another can eventually return to the original compartment. In the case of networks with only 1 compartment, no recycling can take place, therefore TSTc=0.

Both ducks and fish were connected to the compartment "Intercrop" in a way that N flows went in both directions: ducks and fish provided the intercrop with manure while they fed on azolla. Therefore, N could be recycled through those compartments. The largest flow of N between those compartments was the amount of manure excreted by ducks that went to the intercrop. Such a large amount increased the probability that N excreted by ducks was recycled and consumed again by ducks when eating azolla. This was the main reason why TSTc was larger in RMAD than in the other systems. In the case of the most complex system, fish could not feed on azolla (Figure 18), which made it impossible to recycle the N excreted by fish (RE_i=0). Furthermore, string beans did not have any internal N inflows. Therefore, N recycling could not take place in this compartment either.

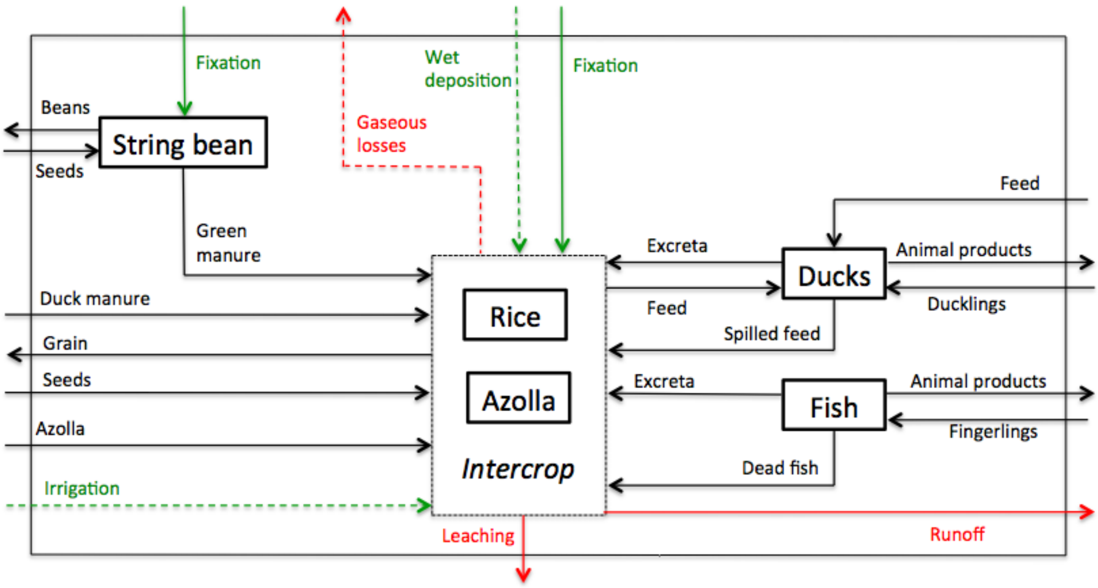

Figure 18. Schematic representation of the N flows of the most complex system (RMAFD).

The Finn's cycling index (FCI) is the proportion of TST that is recycled within the system and may have values between 0 and 1, indicating either no recycling or complete recycling. According to this indicator, the most integrated system was RMAD, as it had the highest relative cycling efficiency (TSTc) (Table 18). Although RMAF had lower TSTc than RMAFD, the smaller network size made FCI be the same as in RMAFD. However, both RMAD and RMAF were more dependent on external inputs than RMAFD as a larger proportion of TST was imported. Moreover, RMAFD was the system with the highest APL, meaning that a unit of flow passed through a larger amount of compartments.

Table 18. Indicators of network size, activity and integration of each system.

	n	T..	IN	TST	L	APL	TSTc	FCI	D
Conv	1	326	201	201	3	1	0	0	1
R	1	62	0	62	3	1	0	0	0,01
RM	1	242	169	169	3	1	0	0	1
RMA	1	274	175	175	3	1	0	0	1
RMAF	3	380	194	323	10	1,3	2,7	0,008	0,60
RMAD	2	580	310	441	7	1,4	5,0	0,011	0,70
RMAFD	4	697	329	597	13	1,5	4,7	0,008	0,55

The diversity and organization of each network depends to a large extent on the network size (i.e. sum of all N flows, number of compartments and links) and both indicators are related. On the one hand, diversity was assessed by the statistical uncertainty (Hr) of N flows. Hr increased when T.. was partitioned among a greater amount of flows, higher values of Hr indicating more diversity. However, flows may be organized in a certain pattern, thus constraining the diversity of the network. The organization of those flows was determined by the average mutual information of the network (AMI), which assesses the probability that a flow entering a compartment comes from a specific compartment. Therefore, AMI depends on how equally the total N flow is divided among compartments, and thereby defines the upper boundary of Hr (Rufino et al. 2009b; Alvarez et al. 2013). Therefore, AMI:Hr is the proportion of diversity that is reduced by the actual pattern of flows (Rufino et al. 2009b).

When comparing the performance of the different systems, RMAFD was the system with the highest Hr and the lowest AMI:Hr ratio, which made it the system with the highest diversity of N flows (Table 19).

Table 19. Indicators of diversity and organization of each treatment.

	Hr	AMI	AMI:Hr
Conv	0,96	0,96	1
R	0,05	0,05	1
RM	0,88	0,88	1
RMA	0,94	0,94	1
RMAF	1,64	0,83	0,51
RMAD	1,46	0,80	0,55
RMAFD	1,90	0,83	0,44

In the analyzed systems, Hr had a positive linear association with rice yields (R^2=0,625, p<0,05) and the amount of energy produced (R^2=0,658, p<0,05) (Figure 19). However, the increase in productivity may also be due to the size of the network, as a positive association exists between Hr and TST (R^2=0,771).

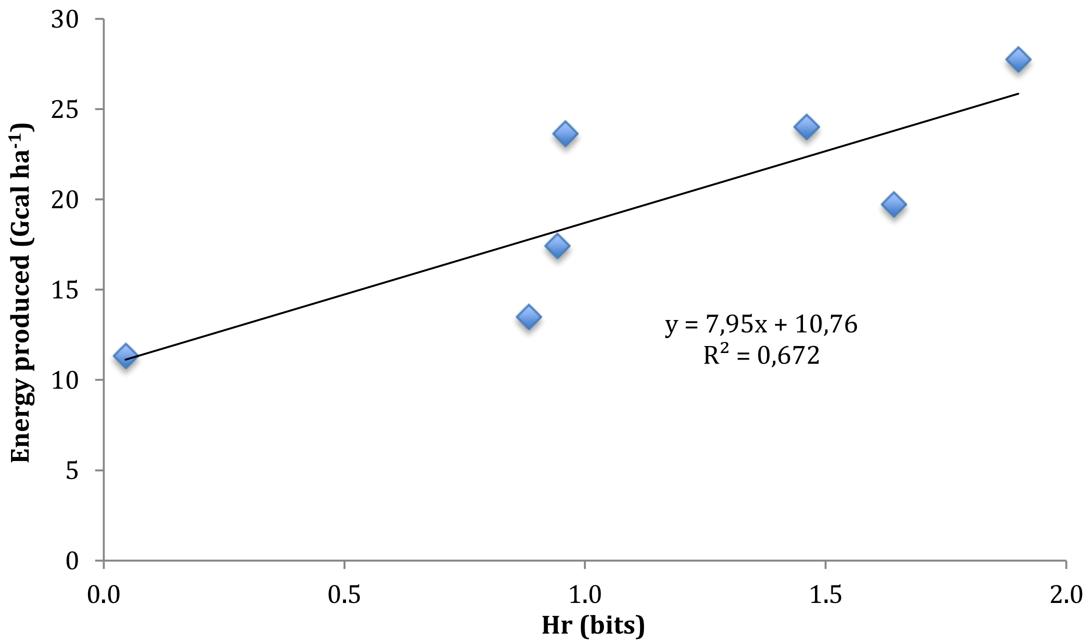

Figure 19. Relation between Hr and the amount of energy produced.

N fixation was considered an external input in the network analysis. However, the dependency of the system on external N input increased when fixation was included, as more N was imported. This could be rather misleading since N fixation is an ecosystem service and not a cause of human action.

N consumed by either ducks or fish coming from sources other than feed or azolla was not considered. On the one hand, ducks' main feed source was the supplied feed and, to a minor extent, azolla. However, they also fed on other feed sources such as weeds, snails and insects. Those flows however, were not included in the network analysis due to the difficulty to estimate the amount of intake and the N content of those sources. Moreover, insects and snails that might have been consumed came from outside the system and are therefore an external input. In the same way as N fixation, attention should be paid to this flow when looking at the dependency of the system, as it is also an input from the environment and not a cause of human action. On the other hand, fish also fed on sources other than azolla. In case of considering the N consumed from other feed sources like plankton, the dependency of the system would decrease and FCI would increase. On the one hand, the decrease of dependency would be owing to the increase of TST caused by the extra flow of N. On the other hand, the increase of FCI would be caused by the increase of the REi of the fish compartment.

It would be interesting to see the outcome of the network analysis from a farm-level perspective. Smallholder farmers in Indonesia normally grow other crops besides rice and usually grow vegetables and fruit trees on their gardens. Moreover, livestock is usually kept in stables and manure is frequently used as fertilizer. While part of the fruit and vegetables produced are sold, a great part is used for self-consumption. Including new compartments such as fruit trees, manure storage or household would increase the network size and would therefore affect the integration, diversity and organization of the networks as well as the nutrient use efficiency (Alvarez et al. 2013). A representation of the N flows of the 3 external farms analyzed in showed in Appendix 24.

3.2.7. Best-case scenario

For the best-case scenario, the performance of azolla and fish was enhanced by assuming no azolla losses and 0 fish mortality. Moreover, it was assumed that part of the rice bran produced during grain milling was used in the feed mixture, thus reducing the external N input. Finally, in this scenario duck houses were placed on the fishpond in a way that fish could consume the feed that was spilled by ducks.

Azolla biomass changes in time were estimated by calculating azolla specific growth rate (SGR), azolla consumption by fish and azolla consumption by ducks (Figure 20).

On the one hand SGR is influenced by azolla plant density (PD) and solar radiation. SGR was calculated by using the formula suggested by (Reddy and De Busk 1985), in which growth is dependent on plant density (Eq. 13).

$$SGR = 0{,}141 - 0{,}00152 \cdot PD \qquad \text{(Eq. 13)}$$

SGR= Specific growth rate (day^{-1}); PD= Plant density (g DM m^{-2} day^{-1})
Initial plant density was 100 kg DM ha^{-1}, i.e. 10 g DM m^{-2}.

Since rice growth was not monitored in the experiment, it was assumed that azolla growth was not influenced by reduced light interception until 45 DAT (Lumpkin 1987). At this point, SGR was set to 0. High densities of azolla can also limit azolla growth due to self-shading and high competition for nutrients (Jackson 1980). Optimal densities for azolla growth are 10-80 g DM m^{-2} (100-800 kg DM ha^{-1}) (Reddy et al. 1983). In the simulations of azolla biomass variation in time, azolla density was within that range except for its peak, which was close to 900 kg DM ha^{-1}.

On the other hand, azolla intake by fish was calculated assuming that fish obtained 50% of their protein requirement from azolla. In order to estimate azolla consumption by ducks, daily intake of azolla was estimated by taking the consumption rate from the experiment as a reference. In the same way as fish, protein intake by ducks may depend on many factors such as body weight, growth and temperature. However, due to lack of information in literature regarding protein intake and growth, it was assumed that consumption of azolla was directly dependent on body weight. To estimate the daily azolla consumption by ducks, the average consumption rate determined from the experiment (4,84 kg DM ha^{-1}) was divided by the average duck biomass during the period in which ducks fed on azolla in the original scenario (149 kg FM ha^{-1}), resulting in a consumption rate of 35,5 g DM kg BW^{-1}. Assuming a linear increase of duck biomass in time, azolla intake per day could be estimated.

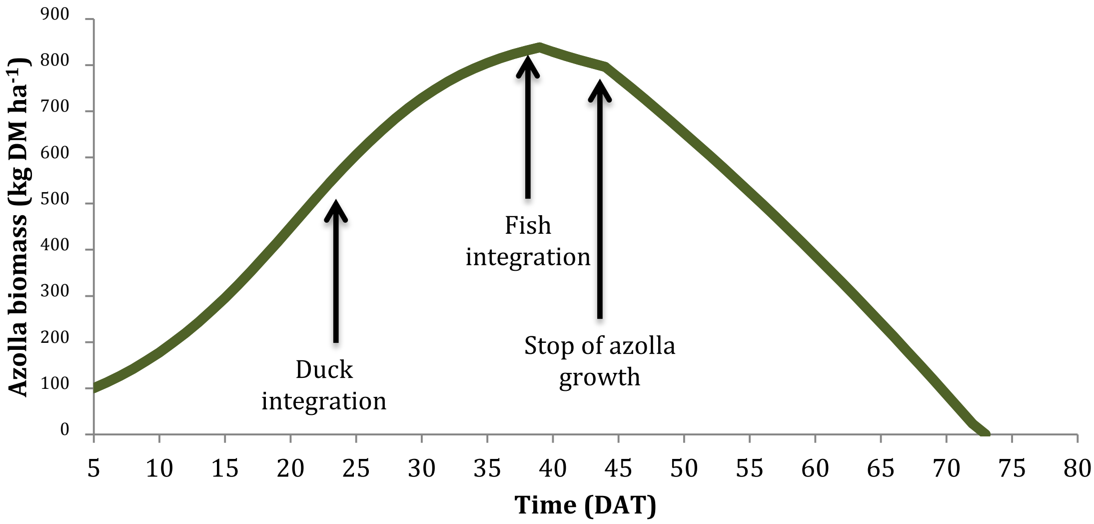

Figure 20. Change in estimated azolla biomass in time in RMAFD (best-case scenario).

Once the total amount of azolla biomass produced was known, the amount of N fixed was estimated by assuming that 80% of the N content in the biomass produced came from fixation (Giller 2001) (Table 20).

Table 20. Azolla N balance in the best-case scenario (kg N ha^{-1}).

	RMA	RMAF	RMAD	RMAFD
Input	5	5	5	5
N fixation	31	31	32	32
Taken up from substrate	7	8	8	8
Ducks' consumption	na	na	24	19
Fish's consumption	na	44	na	26
Incorporated into soil	43	0	21	0

na= not applicable.

Consumption of azolla by fish and ducks caused an increase in azolla biomass production due to a lower PD. Therefore, the reason why more N was fixed or taken up in the most complex systems was because azolla SGR was higher in those treatments.

Since azolla is a low-energy feed, the extra weight that ducks may gain owing to a larger consumption of azolla would be relatively small. Therefore, this weight increase was not considered in the N balance (Table 21). Consequently, duck's NUE in RMAD and RMAFD decreased to 7,5% and 7,8% respectively.

Table 21. Duck N balance in the best-case scenario (kg N ha^{-1}).

	RMAD	RMAFD
Input	1	1
Azolla intake	24	19
Feed (90%)	122	122
Excreta	135	130
Output	12	12

The same final weight as in RMAFD was assumed for all the fishes. Due to no fish mortality, N output increased significantly (Table 22). The same calculations as in section 3.2.4 were used to estimate total feed intake, azolla intake and the excreta produced.

Table 22. Fish N balance in the best-case scenario (kg N ha^{-1}).

	RMAF	RMAFD
Input	3	3
Azolla intake*	44	26
Other feed sources	45	63
Excreta	70	70
Output	22	22

* Assuming 50% of their daily protein intake came from azolla when this was available.

Field level N flow analysis

N input was larger in those treatments with azolla compared to the original scenario due to a higher N fixation. Despite this increase of N input, the higher fish yields improved the NUE of RMAF and RMAFD, as larger amounts of N were exported (Table 23). In the treatments with ducks, the increase in N input from fixation was compensated by the reduction of the imported N through supplied feed. When N from fixation was considered as an external input, the treatment with the highest NUE was still the conventional one, only surpassed by the control treatment. However, when N fixation was not considered, both RMAF and RMAFD presented higher NUE than the conventional treatment.

Table 23. N balance and use efficiency of the agro-ecosystems in the best-case scenario.

	IN	IN*	EN	Partial N balance	NUE	NUE*	N losses	Full N balance
Conv	201	201	122	80	0,60	0,60	3	77
R	0	0	58	-58	187	187	4	-62
RM	169	169	69	100	0,41	0,41	3	96
RMA	204	174	90	115	0,44	0,52	3	112
RMAF	223	177	128	95	0,57	0,72	3	92
RMAD	311	279	131	180	0,42	0,47	5	175
RMAFD	325	278	176	149	0,54	0,64	5	144

* Estimated imported N through fixation is not included.

All in all, better fish yields would make a big improvement in the NUE of RMAF and RMAFD (Figure 21). Moreover, the reduction of imported rice bran would also increase the efficiency of those treatments with ducks. However, the better performance of azolla would lead to larger amounts of N input from fixation, thus decreasing the NUE. Therefore attention should be paid on N fixation when determining NUE of farming systems. When N fixation was not considered an external input, the resulting NUE indicated the amount of N output per unit of N input purchased, which is a more relevant indicator from an economic point of view.

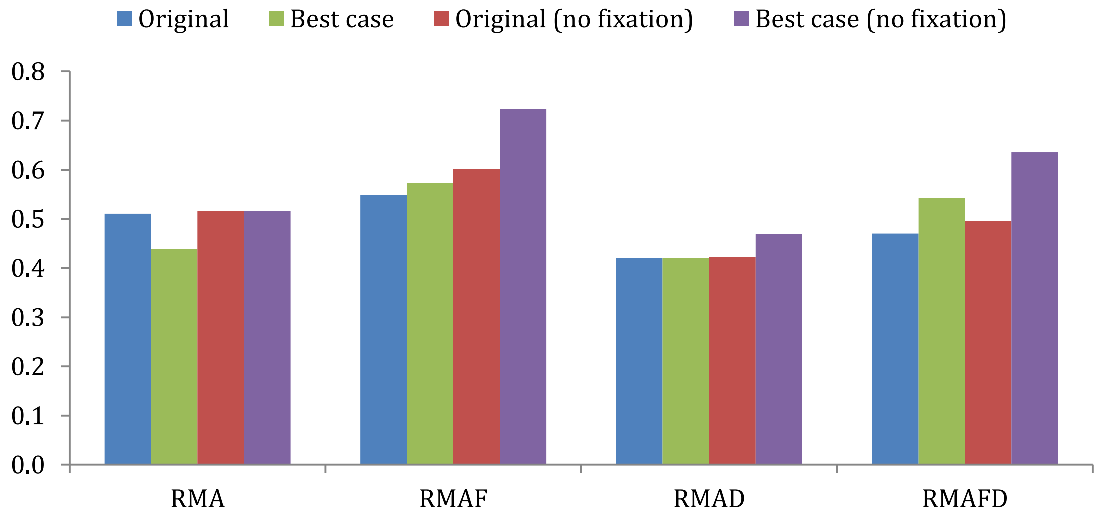

Figure 21. Comparison of the NUE between the original and the best-case scenario of RMA, RMAF, RMAD and RMAFD.

The dependency of the systems with fish and/or ducks was lower than for systems without animals (Table 24), which was mainly due to the good performance of azolla. On the one hand, more azolla was available for fish and ducks to feed on. Therefore, N flow(s) between the intercrop and livestock became larger, thus increasing the TST of those systems and decreasing dependency. On the other hand, the greater N fixation through azolla increased the external imports of N (IN), which limited the decrease of dependency. Therefore, this decrease in dependency would be greater if N fixation was not considered. In the case of those treatments with ducks, the use of on-farm-produced rice bran also reduced the systems' dependency on external N.

Table 24. Indicators of network size, activity and integration of each system in the best-case scenario.

	n	T..	IN	TST	L	APL	TSTc	FCI	D
Conv	1	326	201	201	3	1	0	0	1
R	1	62	0	62	3	1	0	0	0,01
RM	1	242	169	169	3	1	0	0	1
RMA	1	297	204	204	3	1	0	0	1
RMAF	3	479	223	397	10	1,5	43,9	0,111	0,56
RMAD	2	615	311	509	7	1,5	71,5	0,140	0,61
RMAFD	4	773	325	682	15	1,8	92,1	0,135	0,48

In accordance with the findings of Dalsgaard and Oficial (1997), larger amounts of N were recycled in complex rice agro-ecosystems (TSTc). The main reason for such an increase was the greater amount of N flowing between livestock and the intercrop. In the case of RMAFD, the increase of the amount of recycled N was greater also due to 2 new links connecting different compartments. On the one hand, a new link emerged connecting ducks and fish (i.e. spilled feed). On the other hand, unlike in the original scenario, fish could feed on azolla, resulting in a new N flow. Although FCI of those treatments with livestock increased considerably, the larger amounts of N imported through fixation reduced the potential increase of FCI.

In those treatments with livestock, Hr increased and AMI decreased, resulting in a lower AMI:Hr ratio compared to the original scenario (Table 25). While T.. increased considerably in those plots, the greatest part of such increase was due to the larger internal N flows, resulting in a higher Hr. The increase in the internal N flows warded AMI from its upper boundary, resulting in a lower AMI:ratio.

Table 25. Indicators of organization and diversity of each treatment in the best-case scenario

	Hr	AMI	AMI:Hr
Conv	0,96	0,96	1
R	0,05	0,05	1
RM	0,88	0,88	1
RMA	0,89	0,89	1
RMAF	1,67	0,77	0,46
RMAD	1,49	0,61	0,41
RMAFD	1,97	0,63	0,32

A better performance of fish and azolla led to more N recycling and a higher NUE and a higher diversity of N flows. Moreover, producing part of the feed on farm also had a positive effect on N cycling. increased in those systems in which fish and/or azolla compared to the original scenario. All in all, N cycling can be enhanced though a better performance of fish and azolla and producing part of the feed mixture on farm.

4. Conclusions

Both the conventional treatment and the most complex rice agro-ecosystems yielded higher than the average yields achieved in Indonesia. Production costs were significantly higher in the most complex system. However, the higher revenues achieved resulted in a higher gross margin compared to the conventional treatment. Moreover, the production of other food products in the complex systems such as ducks, fish or beans increased the total amount of energy produced per unit of land. Lastly, the most complex systems provided larger amounts of Fe, Zn and Vit A, and could therefore contribute to mitigate the deficiency of those nutrients in the average Indonesian diet.

Ecological network analysis proved to be a useful tool to assess N cycling performance of agro-ecosystems at the field level. However, the outcome of the analysis may vary depending on the definition of the system boundaries and the N flows that are considered. Complex rice agro-ecosystems were less dependent on N imports and generally recycled larger amounts of N. However, those systems were not necessarily more efficient in terms of N use when considering only one cropping cycle. Large amounts of organic N remained in the soil in the complex systems, thus reducing the need to import N in the following cropping cycles and increasing N use efficiency in the long term. Nevertheless, better performance of fish and azolla than in the current experiment is required to optimize N use efficiency in complex rice agro-ecosystems.

5. Recommendations

Management practices

- New management strategies should be carried out in order to improve the performance of azolla and fish. On the one hand, azolla coverage should be monitored frequently, especially after heavy rains and windy days. In case azolla is being depleted too early (i.e. before 45 DAT), more azolla should be added. On the other hand, attention should be paid on the field water levels especially when fish are integrated. Water levels should be high enough for the fish to thrive, but should not be too high in order to prevent runoff. A construction of a fishpond could be the solution for such a challenge.
- In order to improve nutrient recycling, duck houses should be placed on the water in a way that both spilled feed and excreted manure by ducks directly drop into the water and nutrients can eventually be consumed either by fish or plankton.
- Pesticides should be applied in the conventional treatment in order to represent better the conventional practices.

Sampling methods

- When determining dry matter content, all samples must be air-dried in the oven until weight becomes constant.
- Ideally, the sampling area used to determine rice yields should be larger in order to decrease the variability of the results. In addition, samples should be taken in the center of the plots to avoid possible border effects.
- The use of a flow meter to measure the amount of inflow and outflow would be very helpful to estimate the amount of nutrients that enters or exits the system.
- Excreta collection should be carried out in a way that prevents ducks from getting stressed, for instance increasing the time spent on the cage or building bigger cages.

Further research

- It would be interesting to find ways to achieve a higher gross margin from ducks. Costs of production could be reduced by breeding or by producing part of the feed mixture on farm. In order to increase the feed conversion ratio, more energy should be supplied in the feed mixture. It would be interesting to integrate high-energy crops into the system that could be used as feed for ducks so as to decrease the costs of production.

- Further research should be conducted in order to determine whether better performances of azolla and fish would also lead to higher rice yields.
- More cropping cycles should be considered when analyzing N cycling and economic performances, especially in organic agro-ecosystems, in which nutrient mineralization takes place throughout different cropping seasons.
- It would be interesting to investigate the feasibility of integrating other crops with a high content of Fe, Zn and Vit A on the field margins. Ideally residues from those crops should be used as green manure as feed for ducks and/or fish.
- Finally, it would be very interesting to make trials of the complex systems in larger plots, as management may become more challenging in an area larger than 100 m^2.

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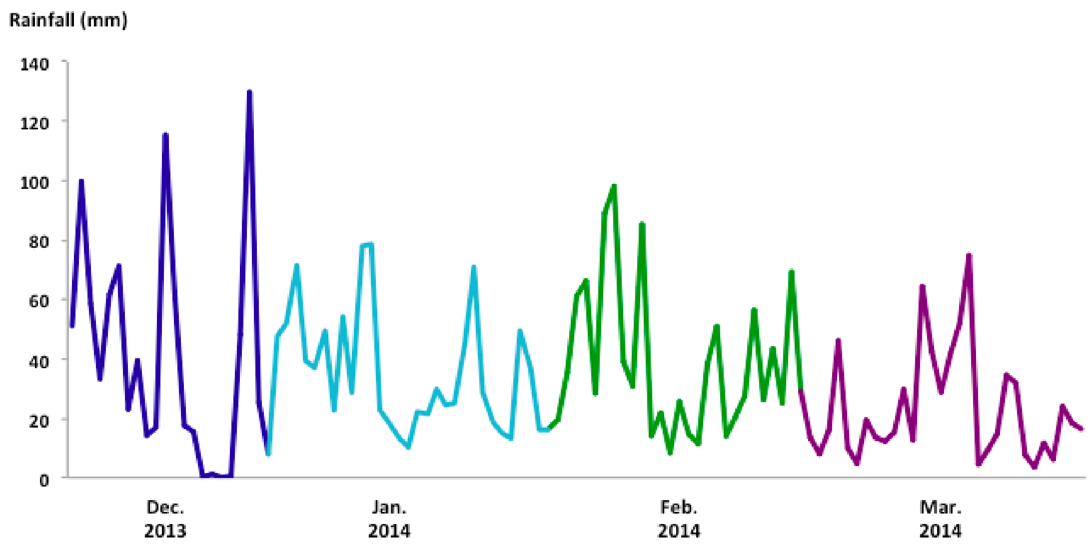
Appendices

Appendix 1. Precipitations during the cropping season



Source: World Weather Online (2014).

Appendix 2. Amount, cost and N content of the different inputs applied

Table 1. Appendix 2. Amounts of the different inputs used.

Material used	Per plot	Total experiment	Per hectare	Units
Rice seeds	0,02	0,39	19	Kg DM
Azolla	0,10	1,20	100,00	Kg DM
Green bean seeds	0,01	0,03	5,42	Kg DM
Feed	40,98	245,88	4.098	Kg DM
- Rice bran	30,74	184,41	3.073,50	Kg DM
- Dry rice	7,61	45,65	760,80	Kg DM
- Corn	1,90	11,41	190,20	Kg DM
- Ground corn	0,44	2,65	44,10	Kg DM
- Dried fish	0,29	1,76	29,40	Kg DM
Duck manure	6	83	5.500	Kg DM
Fertilizer	0,775	2,325	775	Kg DM
- Urea (46% N)	0,30	0,90	300	Kg DM
- ZA (21% N)	0,30	0,90	300	Kg DM
- SP-36 (36% P)	0,10	0,30	100	Kg DM
- KCl (60% K)	0,08	0,23	75	Kg DM
Ducklings	4	24	400	ducks
Nile tilapia	50	300	50.000	fishes

Table 2. Appendix 2. Cost of the inputs used.

Inputs	Price	Units
Rice seed	8.000	Rp kg^{-1}
Bean seed	68.000	Rp kg^{-1}
Fertilizers	2.800	Rp kg^{-1}
Manure	120	Rp kg^{-1}
Feed	2.111	Rp kg^{-1}
Azolla	0	Rp kg^{-1}
Fish	500	Rp $fish^{-1}$
Duckling	13.000	Rp $duckling^{-1}$

Table 3. Appendix x. N content of the inputs used.

	N	Units	Source
Manure	3,07	% DM	Del Rio (2014)
Duck excreta	3,65	% DM	
Feed	3,30	% DM	
Azolla	4,78	% DM	
Fish	2,56	%FM	Burnell and Allan (2009)
Duckling	2,47	%FM	
Duck	2,60	%FM	
Rice seed	1,67	% DM	
Sraw	1,67	% DM	
Stubble	1,06	% DM	
Bean seed	3,11	% DM	
Bean veg	3,44	% DM	
Bean residue	5,04	% DM	

N content of water from irrigation and rainfall was lower than 0,00 and was therefore neglected.

Appendix 3. Amount of manure and spilled feed collected during the 24 hours excreta collection experiment

Time	Sample	1 (g FM)	2 (g FM)	3 (g FM)
07:30	Manure	15,7	9,7	3,7
	Spilled feed	14,6	26,4	21,2
12:00	Manure	1,8	3,9	0,8
16:00	Manure	2,4	19,5	14,8
	Spilled feed	36,8	12,4	5,7
20:00	Manure	25,2	16,9	10,7
24:00	Manure	33,1	33,7	45,2
04:00	Manure	1	2,2	1,9

Appendix 4. Amount of feed supplied and composition

Week	Feed (g $duck^{-1}$ $week^{-1}$)	Composition		
1	172	Rice bran 75%	Ground corn 15%	Dry fish 10%
2	562	Rice bran 75%	Ground corn 15%	Dry fish 10%
3	870	Rice bran 75%	Dry rice 20%	Corn 5%
4	1.005	Rice bran 75%	Dry rice 20%	Corn 5%
5	1.102	Rice bran 75%	Dry rice 20%	Corn 5%
6	1.222	Rice bran 75%	Dry rice 20%	Corn 5%
7	1.327	Rice bran 75%	Dry rice 20%	Corn 5%
8	1.327	Rice bran 75%	Dry rice 20%	Corn 5%
9	1.327	Rice bran 75%	Dry rice 20%	Corn 5%
10	1.327	Rice bran 75%	Dry rice 20%	Corn 5%

Appendix 5. N losses through water outflow

Table 1. Appendix 5. N concentration in water outflow.

Block	Treatment	Date of sampling	N-NO3 (mg/l)	N-NH4 (mg/l)	Sum
1	R	feb-13	1,37	0,02	1,39
2	R	feb-13	4,55	0,00	4,55
3	R	feb-13	0,52	0,00	0,52
1	RM	feb-13	1,32	0,00	1,32
2	RM	feb-13	2,67	0,00	2,67
3	RM	feb-13	1,66	0,00	1,66
1	RMA	feb-13	0,97	0,00	0,97
2	RMA	feb-13	2,46	0,00	2,46
3	RMA	feb-13	1,79	0,00	1,79
1	RMAF	feb-13	3,33	0,00	3,33
2	RMAF	feb-13	1,66	0,00	1,66
3	RMAF	feb-13	2,31	0,00	2,31
1	RMAFD	feb-13	3,39	0,00	3,39
2	RMAFD	feb-13	4,07	0,00	4,07
3	RMAFD	feb-13	5,05	0,00	5,05
1	CONV	feb-13	2,98	0,00	2,98
2	CONV	feb-13	2,75	0,00	2,75
3	CONV	feb-13	2,06	0,00	2,06
1	R	feb-08	5,16	0,00	5,16
2	R	feb-08	2,13	0,48	2,61
3	R	feb-08	1,98	0,00	1,98
1	RM	feb-08	2,11	0,00	2,11
2	RM	feb-08	5,54	0,00	5,54
3	RM	feb-08	1,99	0,00	1,99
1	RMA	feb-08	1,52	0,00	1,52
2	RMA	feb-08	2,61	0,00	2,61
3	RMA	feb-08	2,45	0,00	2,45
1	RMAF	feb-08	1,55	0,00	1,55
2	RMAF	feb-08	3,22	0,00	3,22
3	RMAF	feb-08	0,79	0,00	0,79
1	RMAFD	feb-08	6,67	0,00	6,67
2	RMAFD	feb-08	2,43	0,00	2,43
3	RMAFD	feb-08	2,43	0,00	2,43

1	CONV	feb-08	2,07	0,00	2,07
2	CONV	feb-08	1,79	0,14	1,93
3	CONV	feb-16	0,00	0,00	0,00

These data was measured by Trinidad del Rio.

Table 2. Appendix 5. Average N concentration in water outflow and the amount of N lost during the cropping cycle assuming a water outflow of 1,35 million l ha^{-1}).

	N (mg l^{-1})	N lost (kg N ha^{-1})
R	2,70	3,65
RM	2,55	3,44
RMA	1,96	2,65
RMAF	2,14	2,89
RMAD*	-	5,40
RMAFD	4,00	5,40
CONV	1,96	2,65

*Neither $N\text{-}NO_3$ nor $N\text{-}NH_4^+$ concentrations were measured in this treatment. The same concentration as RMAFD is assumed.

Appendix 6. Rice yields and harvest index of each treatment

Table 1. Appendix 6. Rice yields (Mg ha^{-1}).

	1	2	3	Mean	SD
R	4,42	3,70	2,36	3,49	1,05
RM	5,60	3,76	3,12	4,16	1,29
RMA	6,62	5,22	4,26	5,37	1,19
RMAF	7,24	5,64	4,82	5,90	1,23
RMAD	7,50	6,38	7,36	7,08	0,61
RMAFD	7,80	8,12	8,26	8,06	0,24
Conv	7,34	7,66	6,84	7,28	0,41

Table 2. Appendix 6. Rice harvest index (%).

	1	2	3	Mean	SD
R	29,1	29,9	16,2	25,1	7,7
RM	27,4	26,3	20,6	24,8	3,7
RMA	34,8	25,9	28,9	29,9	4,5
RMAF	32,6	31,0	30,2	31,3	1,2
RMAD	32,1	37,6	34,2	34,6	2,8
RMAFD	35,9	36,8	34,1	35,6	1,3
Conv	37,0	41,8	36,9	38,6	2,8

Appendix 7. Distribution of duck live weight

Body part	Weight (g FM)	%
Meat	561	35
Skin	230	14
Feathers	188	12
Giblets	164	10
Bones	152	9
Blood	139	9
Guts	106	7
Total	*1600*	*100*

Appendix 8. Duck yields and biomass increase in time

Table 1. Appendix 8. Live weight of ducks withdrawn (kg $duck^{-1}$).

Block	I	II	III	Mean
RMAD	1,10	1,40	1,20	1,23
	0,80	1,60	1,25	1,22
RMAFD	1,20	1,45	1,10	1,25
	1,00	1,30	1,10	1,13

Table 2. Appendix 8. Live weight and biomass increase in time assuming a linear growth rate.

Time (weeks)	0	1	2	3	4	5	6	7	8	9	10
Weight (kg $duck^{-1}$)	0,05	0,17	0,28	0,40	0,51	0,63	0,74	0,86	0,97	1,09	1,20
Duck biomass (kg ha^{-1})	22	68	114	159	205	251	297	343	388	434	480

Appendix 9. Characteristics of the two suggested feed mixtures

Table 1. Appendix 9. Energy content of the feed mixture 1.

Feed ingredient	%	ME (kcal kg DM^{-1})	Amount supplied (kg DM $duck^{-1}$)	ME supplied (kcal)
Rice bran	10,0	2.040	1,0	2.091
Dry rice	33,2	2.940	3,4	10.005
Corn	55,0	3.390	5,6	19.111
Ground corn	1,1	3.390	0,1	374
Dried fish	0,7	2.600	0,1	191
Total	*100*	*3.100*	*10,25*	*31.772*

Table 2. Appendix 9. Energy content of the feed mixture 2.

Feed ingredient	%	ME (kcal kg DM^{-1})	Amount supplied (kg DM $duck^{-1}$)	ME supplied (kcal)
Rice bran	9,6	2.040	1,0	2.091
Dry rice	60,5	2.940	6,4	18.946
Corn	28,2	3.390	3,0	10.170
Ground corn	1,0	3.390	0,1	374
Dried fish	0,7	2.600	0,1	191
Total	*100*	*2.982*	*10,7*	*31.772*

Appendix 10. Comparison of the performance of the 3 feed mixtures

Table 1. Appendix 10. Costs of the ingredients of the 3 feed mixtures (Rp kg^{-1}).

		Original		Feed mixture 1		Feed mixture 2	
	Price	%	Cost	%	Cost	%	Cost
Rice bran	1.500	75,0	1.125	10,0	150	9,6	144
Dry rice rice	3.000	18,6	557	33,2	996	60,5	1.815
Corn	6.000	4,6	278	55,0	3.300	28,2	1.690
Ground corn	6.000	1,1	65	1,1	65	1,0	62
Dried fish	12.000	0,7	86	0,7	86	0,7	83
Total			*2.111*		*4.597*		*3.794*

Table 2. Appendix 10. Comparison of the performance of the 3 feed mixtures supposing all the feed is imported

	Original mixture, FCR=8	Feed mixture 1, FCR=6	Feed mixture 2 FCR=6	Units
Feed cost	2.111	4.597	3.794	Rp kg^{-1}
Energy content	2.288	3.100	2.982	kcal kg^{-1}
Amount provided	10,25	10,25	10,65	kg
Total cost feed	8.650.878	18.838.506	16.162.440	Rp ha^{-1}
Final weight	1,2	1,5*	1,6*	kg $duck^{-1}$
Sale price	25.000	31.250**	33.250**	Rp $duck^{-1}$
Revenues	10.000.000	12.500.000	13.300.000	Rp ha^{-1}
Margin***	-3.850.878	-11.538.506	-8.062.440	Rp ha^{-1}

* Final weight was calculated through the FCR assuming that 10% of the feed supplied was spilled.
**Assuming that the sale price would increase in the same proportion as live weight.
***Including cost of ducklings (5.200.000 Rp).

Table 3. Appendix 10. Comparison of the economic performance of the 3 feed mixtures supposing that the rice bran and dry rice supplied was produced on farm (Rp kg^{-1}).

	Original mixture FCR=8	Feed mixture 1 FCR=6	Feed mixture 2 FCR=6	Units
Feed cost	2.508	4.447	3.649	Rp kg^{-1}
Total cost feed	6.232.500	18.232.700	15.617.720	Rp ha^{-1}
Revenues	10.000.000	12.500.000	13.300.000	Rp ha^{-1}
Margin*	-1.432.500	-10.932.700	-7.517.720	Rp ha^{-1}

*Including cost of ducklings (5.200.000 Rp).

Appendix 11. String bean yields, sale price and revenues at different harvesting dates

Date	Amount harvested (Kg FM 100 m^2)			Mean (kg FM m^2)	Mean (kg FM ha^{-1})	Price (Rp kg^{-1})	Revenues (Rp)
	I	II	III				
26-feb	0,45	0,70	0,40	0,52	51,7	7.500	387.500
04-mar	0,70	0,70	0,75	0,72	71,7	3.500	250.833
07-mar	2,11	2,19	2,27	2,19	219,0	3.500	766.500
10-mar	2,30	2,13	2,33	2,25	225,3	3.500	788.667
15-mar	3,73	3,47	3,97	3,72	372,3	2.500	930.833
20-mar	3,50	3,70	3,40	3,53	353,3	2.500	883.333
24-mar	2,30	2,13	2,00	2,14	214,3	2.500	535.833
29-mar	1,50	1,70	1,70	1,63	163,3	3.500	571.667
31-mar	0,7	0,7	0,8	0,73	73,3	3.500	256.667
Total	*17,29*	*17,42*	*17,62*		*1744,3*	*3.611*	*5.371.833*

Appendix 12. Recommended daily allowance of Fe, Zn and Vit A

	Fe (mg $capita^{-1}$ day^{-1})	Zn (mg $capita^{-1}$ day^{-1})	Vit A (mcg RAE $capita^{-1}$ day^{-1})
RDA	12,1[1]	13[1]	800[2]

[1] Source: Jati et al. (2012); [2] Source: HHS (2013)

Appendix 13. Edible portion of the commodities produced in the experiment

Commodity	Edible portion	Source
Rice	0,8	(Juliano 1993)
Duck	0,6*	Experiment
Beans	1	Experiment
Fish	0,72	(Akande et al. 1993)

*0,1 belongs to giblets and 0,5 belongs to meat and skin

Appendix 14. Energy, Fe, Zn and Vit A content of the commodities produced from the experiment

	Energy content (kcal $100g^{-1}$)	Fe (mg $100g^{-1}$)	Zn (mg $100g^{-1}$)	Vit A (IU $100g^{-1}$)	Vit A (RAE $100g^{-1}$)
Rice	360	0,80	1,16	0	0
Duck meat and skin	404	2,40	1,36	168	56
Giblets	124	5,86	3,32	8.847	2.949
Beans	31	1,03	0,24	690	230
Fish	96	0,56	0,33	0	0

Source: USDA (2011).
The values for rice refer to boiled rice, with a water content of 12,9%.
IU was converted into RAE through the conversion factor 1 RAE=3,33 IU (HHS 2013).
The nutrient content of chicken giblets was used since no data was found regarding duck giblets.

Appendix 15. Energy produced per commodity, total energy produced and carrying capacity of each treatment

	Rice (Kcal ha^{-1})	Ducks (Kcal ha^{-1})	Beans (Kcal ha^{-1})	Fish (Kcal ha^{-1})	Total (Kcal ha^{-1})	Carrying capacity
R	11.357.637	0	0	0	11.357.637	30
RM	13.525.125	0	0	0	13.525.125	35
RMA	17.448.278	0	0	0	17.448.278	46
RMAF	19.182.269	0	540.743	26.726	19.749.739	52
RMAD	23.018.723	1.018.908	0	0	24.037.631	63
RMAFD	26.204.930	1.018.908	540.743	24.422	27.789.004	73
Conv	23.668.969	0	0	0	23.668.969	62

Appendix 16. Rice consumption given the carrying capacity of each treatment considering the energy requirements

	Energy from rice (kcal day^{-1} $capita^{-1}$)	Rice consumption (g day^{-1} $capita^{-1}$)
R	2.100	517
RM	2.100	517
RMA	2.100	517
RMAF	2.040	502
RMAD	2.011	495
RMAFD	1.980	487
Conv	2.100	517

Appendix 17. Amount of micronutrient produced per commodity, total amount produced and carrying capacity

Table 1. Appendix 17. Amount of Fe produced per commodity, total Fe produced and carrying capacity of each treatment.

	Rice (mg Fe ha^{-1})	Ducks (mg Fe ha	Beans (mg Fe ha^{-1})	Fish (mg Fe ha^{-1})	Total (mg Fe ha^{-1})	Carrying capacity
R	25.239	0	0	0	25.239	11
RM	30.056	0	0	0	30.056	13
RMA	38.774	0	0	0	38.774	17
RMAF	42.627	0	17.967	156	60.750	27
RMAD	51.153	8.566	0	0	59.719	27
RMAFD	58.233	8.566	17.967	142	84.908	39
Conv	52.598	0	0	0	52.598	24

Table 2. Appendix 17. Amount of Zn produced per commodity, total Zn produced and carrying capacity of each treatment.

	Rice (mg Zn ha^{-1})	Ducks (mg Zn ha^{-1})	Beans (mg Zn ha^{-1})	Fish (mg Zn ha^{-1})	Total (mg Zn ha^{-1})	Carrying capacity
R	36.597	0	0	0	36.597	15
RM	43.581	0	0	0	43.581	13
RMA	56.222	0	0	0	56.222	17
RMAF	61.810	0	4.186	92	66.088	27
RMAD	74.171	4.854	0	0	79.025	27
RMAFD	84.438	4.854	4.186	84	93.562	39
Conv	76.267	0	0	0	76.267	24

Table 3. Appendix 17. Amount of Vit A produced per commodity, total Vit A produced and carrying capacity of each treatment.

	Rice (µg Vit A ha^{-1})	Ducks (µg Vit A ha^{-1})	Beans (µg Vit A ha^{-1})	Fish (µg Vit A ha^{-1})	Total (µg Vit A ha^{-1})	Carrying capacity
R	0	0	0	0	0	0
RM	0	0	0	0	0	0
RMA	0	0	0	0	0	0
RMAF	0	0	4.011.967	0	4.011.967	27
RMAD	0	1.579.289	0	0	1.579.289	11
RMAFD	0	1.579.289	4.011.967	0	5.591.255	38
Conv	0	0	0	0	0	0

Appendix 18. Carrying capacities of RMAF and RMAFD given the total amount of energy, Fe, Zn and Vit A produced per year in the best-case scenario

	Energy prodcued	Carrying capacity	Fe (mg)	Carrying capacity	Zn (mg)	Carrying capacity	Vit A (µg)	Carrying capacity
RMAF	20.333.572	53	64.155	29	68.095	29	4.011.967	28
RMAFD	28.184.081	74	88.327	40	95.577	41	5.591.255	39

Appendix 19. Nutrient value of the food produced in the 3 farms analyzed

	Energy (kcal 100 g^{-1})	Fe (mg 100 g^{-1})	Zn (mg 100 g^{-1})	Vit A, RAE (µg 100 g^{-1})	Source
Rice	406,4	0,8	1,2	0,0	USDA (2011)
Sugar cane	393,1	2,0	0,0	0,0	(Indobase 2014)
Cassava	160,0	0,3	0,3	3,9	USDA (2011)
Coffee	353,0	4,4	0,4	0,0	USDA (2011)
Rambutan	78,0	0,3	0,1	0,0	USDA (2011)
Buffalo	99,0	1,6	1,9	0,0	USDA (2011)
Pepper	40,0	1,2	0,3	354,1	USDA (2011)
Oranges	49,0	0,1	0,1	74,2	USDA (2011)
	Energy (kcal $unit^{-1}$)	Fe (mg $unit^{-1}$)	Zn (mg $unit^{-1}$)	Vit A, RAE (µg $unit^{-1}$)	
Durian	885,0	2,6	1,7	79,6	USDA (2011)
Papaya	336,0	2,0	0,6	2228,2	USDA (2011)
Banana	90,0	0,3	0,2	19,5	USDA (2011)
Coconut	1444,0	9,7	4,6	0,0	USDA (2011)
Dragon fruit	60,0	3,4	13,9	Not found	Khalili et al. (2006)
Chicken	1978,0	8,3	12,1	386,8	USDA (2011)
Eggs	63,0	0,8	0,6	71,5	USDA (2011)
Ducks	5122,0	30,4	17,2	639,6	USDA (2011)

Appendix 20. Food production and carrying capacities of the 3 farms analyzed

Table 1. Appendix 20. Food production, energy, Fe, Zn and Vit A produced in Farm 1.

Crop	Area (ha)	Production (kg $year^{-1}$)	Edible portion	Energy (kcal day^{-1})	Fe (mg day^{-1})	Zn (mg day^{-1})	Vit A, RAE (µg day^{-1})
White rice	0,04	510	0,8	4.543	8,9	13,0	0
Red rice	0,04	540	0,8	4.810	9,5	13,7	0
Black rice	0,04	540	0,8	4.810	9,5	13,7	0
	Units						
Cassava	100	300	na	1.315	2,2	2,8	3,2
Coffee	20	50	na	484	6,0	0,5	0
Rambutan	3	225	na	481	2,0	0,7	0
		Production (units $year^{-1}$)					
Papaya	2	120	na	110	0,6	0,2	732,6
Durian	1	50	na	121	0,4	0,2	10,9
Banana	20	2.400	na	592	1,7	1,0	128,3
Coconut	3	270	na	214	1,4	0,7	0
Livestock							
Chicken	70	66	na	358	1,5	2,2	69,9
Eggs	na	3.000	na	52	0,6	0,5	58,7
Buffalo	4	0,67*	0,5	45	0,7	0,9	0

na: not applicable (nutrient content was found per unit of product).
*1 buffalo is sold every 1,5 years.

Table 2. Appendix 20. Food production, energy, Fe, Zn and Vit A produced in Farm 2.

Crop	Area (ha)	Production (kg year^{-1})	Edible portion	Energy (kcal day^{-1})	Fe (mg day^{-1})	Zn (mg day^{-1})	Vit A, RAE (µg day^{-1})
Rice	2	33.400	0,8	297.510	585,6	849,2	0
	Units						
Rambutan	3	65	na	139	0,6	0,2	0
Dragon fruit	3	45	0,9	67	3,8	15,4	0
		Production (units year^{-1})					
Papaya	2	72	na	66	0,4	0,1	439,5
Livestock							
Eggs		360	na	62	0,8	0,6	70,5
Chicken	36	108	na	585	2,4	3,6	114,4
Ducks	7	21	na	295	1,8	1,0	36,8

na: not applicable.

Table 3. Appendix 20. Food production, energy, Fe, Zn and Vit A produced in Farm 3.

Crop	Area (ha)	Production (kg year^{-1})	Edible portion	Energy (kcal day^{-1})	Fe (mg day^{-1})	Zn (mg day^{-1})	Vit A, RAE (µg day^{-1})
Rice*	2	42.000	0,8	374.114	736,4	1.067,8	0
Sugar cane	1	80.000	0,5**	387.667	1.983	0	0
Pepper	0,13	1.000	1	1.096	32,9	8,2	9.700
Oranges	2	50.000	na	67.123	178,1	109,6	101.608
	Units	Production (units year^{-1})					
Banana	20	2.000	na	493	1,4	0,8	107
Coconut	20	4.800	na	18.990	127,4	60,2	0
Livestock							
Chicken	10	24	na	65	0,3	0,4	13
Sheep**	14	0	0	0	0	0	0

na: not applicable.
*3 cropping cycles per year.
**Source: (Practical Action).
***For the moment they are kept for manure production.

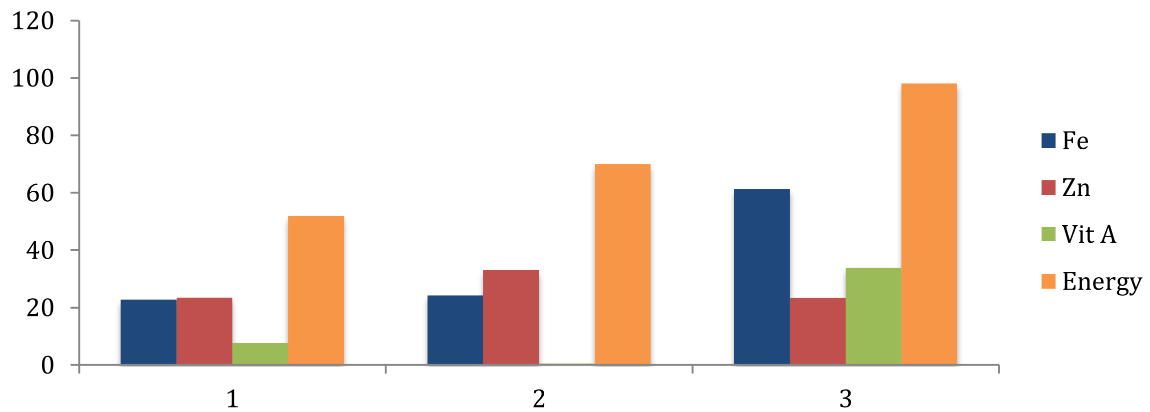


Figure 1. Appendix 20. Carrying capacities of the 3 farms according to the recommended daily allowance of Fe, Zn, Vit A and energy requirement.

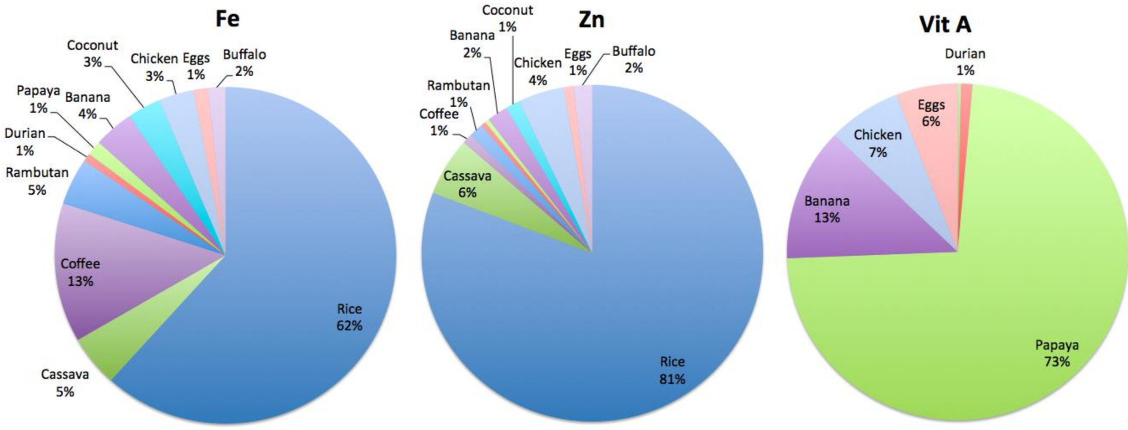


Figure 2. Appendix 20. Contribution of each commodity to the total amount of Fe, Zn and Vit A in Farm 1.

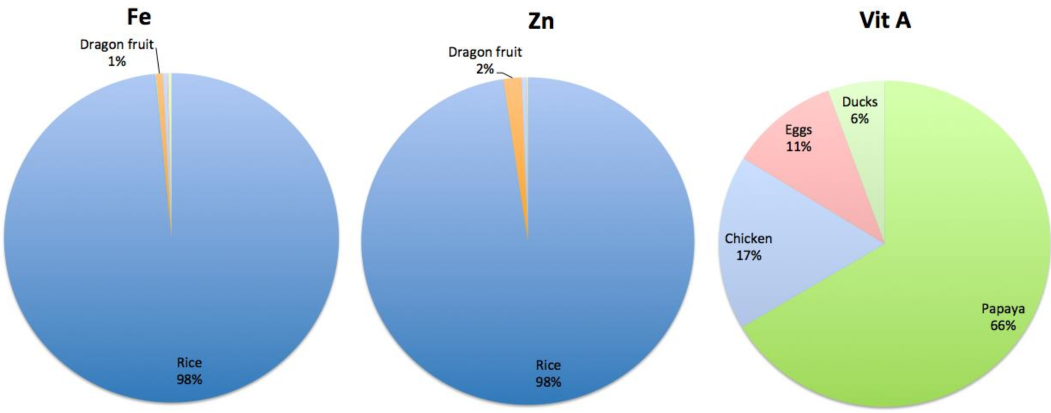


Figure 3. Appendix 20. Contribution of each commodity to the total amount of Fe, Zn and Vit A in Farm 2.

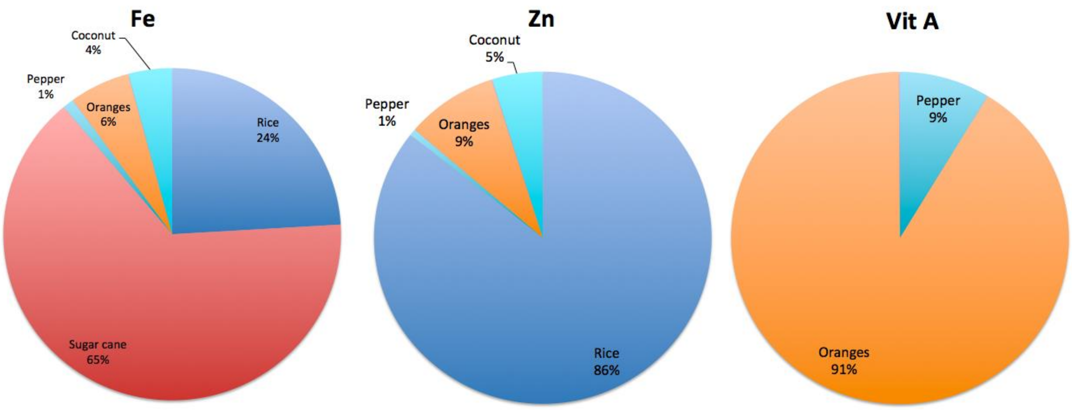


Figure 4. Appendix 20. Contribution of each commodity to the total amount of Fe, Zn and Vit A in Farm 3.

Appendix 21. Indicators of the network analysis

Indicator	Calculation	Explanation
Indicators of network size, activity and integration		
Imports	IN = $\sum_{i=1}^{n} z_{i0}$	N imported from external environment into the system
Total inflow	TIN = $\sum_{i=1}^{n} z_{i0} - \sum_{i=1}^{n} (\dot{x}_i)_{-}$	N imported from external environment plus the N contributed from storage
Compartmental throughflow	$T_i = \sum_{j=1}^{n} f_{ij} + z_{i0} - (\dot{x}_i)_{-}$	Total inflows of compartment *i* plus the N flows contributed by the storage of compartment H_i.
Total system throughflow	TST = $\sum_{i=1}^{n} T_i$	Sum of all the T_i in the system
Total system throughput	$T_{..} = \sum_{i,j=1}^{n} T_{ij}$	Sum of all flows in the system
Dependence on external inputs	D=IN/TST	Ratio between IN and TST
Average path length	APL=TST/TIN	Average number of compartments that a unit of inflow passes through
Relative cycling efficiency	$TST_c = \sum_{i=1}^{n} RE_i T_i$	Ratio between internal inflows and outflows of all compartments
Finn's cycling index	FCI=TST_c/TST	Degree of integration
Indicators to assess organization and diversity		
Average mutual information	AMI= $k \sum_{i=1}^{n+2} \sum_{j=0}^{n} \frac{T_{ij}}{T_{..}} log_2 \frac{T_{ij} T_{..}}{T_i T_j}$	Organization of the network
Statistical uncertainty	Hr= $-\sum_{j=0}^{n} \frac{T_j}{T_{..}} log_2 \frac{T_j}{T_{..}}$	Diversity of the network

Source: Rufino et al. (2009a).

Appendix 22. Summary and schematic representation of the N flows of each system

Table 1. Appendix 22. N flows of Conv.

Flows	N (kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Urea	138
ZA	63
Marketable outputs	
Grain	121,6
Losses	
Runoff and leaching	2,6

Table 2. Appendix 22. N flows of R.

Flows	N (kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Marketable outputs	
Grain	58,3
Losses	
Runoff and leaching	3,6

Table 3. Appendix 22. N flows of RM.

Flows	N (Kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Manure	168,6
Marketable outputs	
Grain	69,4
Losses	
Runoff and leaching	3,4

Table 4. Appendix 22. N flows of RMA.

Flows	N (kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Manure	168,7
Azolla	4,8
Marketable outputs	
Grain	89,6
Biological N fixation	
Azolla N fixation	1,7
Losses	
Runoff and leaching	2,7
Azolla	6,5

Table 5. Appendix 22. N flows of RMAF.

Flows	N (Kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Manure	168,7
Azolla	4,8
Fingerlings	3,6
Bean seeds	0,2
Marketable outputs	
Grain	98,5
Fish	1,0
Beans	6,8
Internal flows	
Azolla intake by fish	2,2
Fish excreta	44,0
Dead fish	14,4
Green manure	11,9
Biological N fixation	
Azolla N fixation	1,4
Bean N fixation	15,4
Losses	
Runoff and leaching	2,9
Azolla	4,0

Table 6. Appendix 22. N flows of RMAD.

Flows	N (kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Manure	168,7
Azolla	4,8
Ducklings	0,5
Feed	135,1
Marketable outputs	
Grain	118,2
Ducks	12,5
Internal flows	
Azolla intake by ducks	3,7
Duck excreta	113,5
Spilled feed	13,5
Biological N fixation	
Azolla N fixation	1,1
Losses	
Runoff and leaching	5,4
Azolla	2,1

Table 7. Appendix 22. N flows of RMAFD.

Flow	N (Kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Manure	168,7
Azolla	4,8
Ducklings	54,3
Fingerlings	3,6
Bean seeds	0,2
Feed	135,1
Marketable outputs	
Grain	134,6
Ducks	12,5
Fish	0,9
Beans	6,8
Internal flows	
Azolla intake by ducks	3,7
Azolla intake by fish	0,0
Duck excreta	113,5
Fish excreta	46,8
Dead fish	15,4
Green manure	11,9
Spilled feed	13,5
Biological N fixation	
Azolla N fixation	1,1
Bean N fixation	15,4
Losses	
Runoff and leaching	5,4
Azolla	2,1

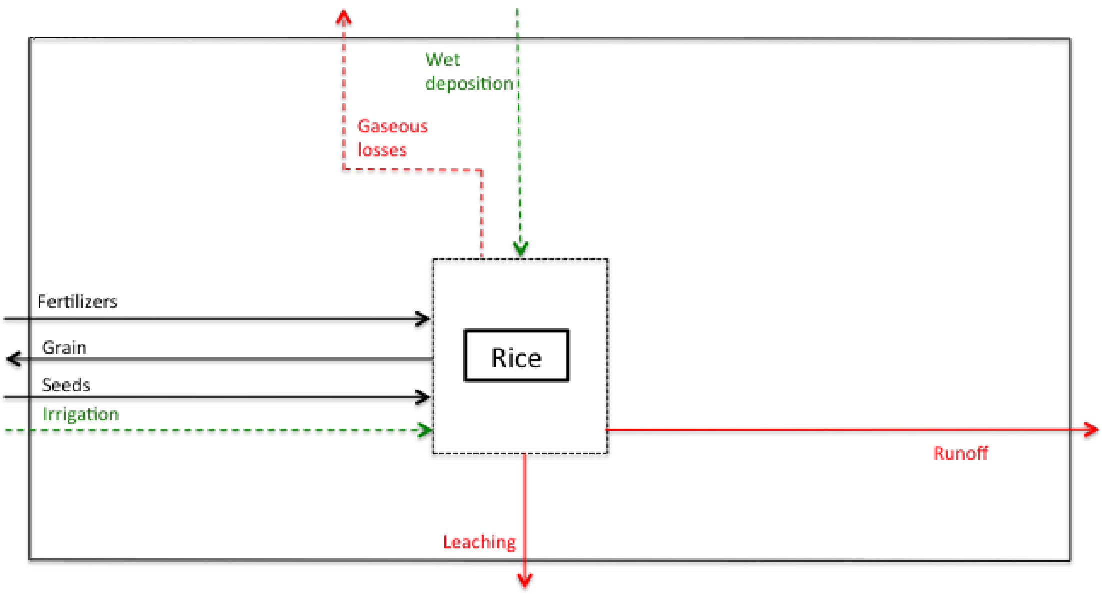


Figure 1. Appendix 22. Schematic representation of the N flows of Conv.

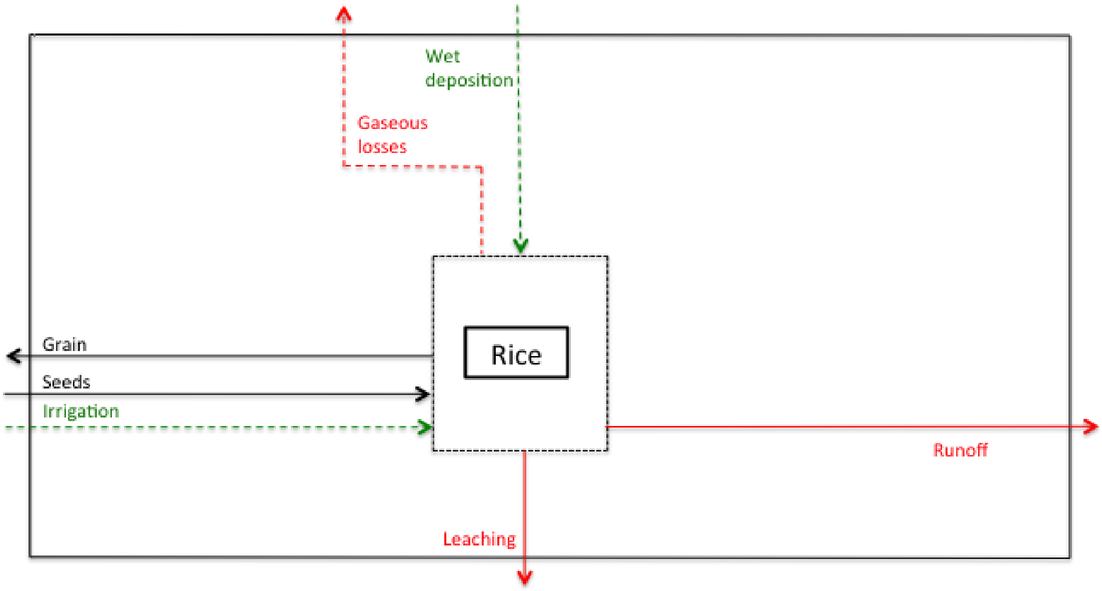


Figure 2. Appendix 22. Schematic representation of the N flows of R.

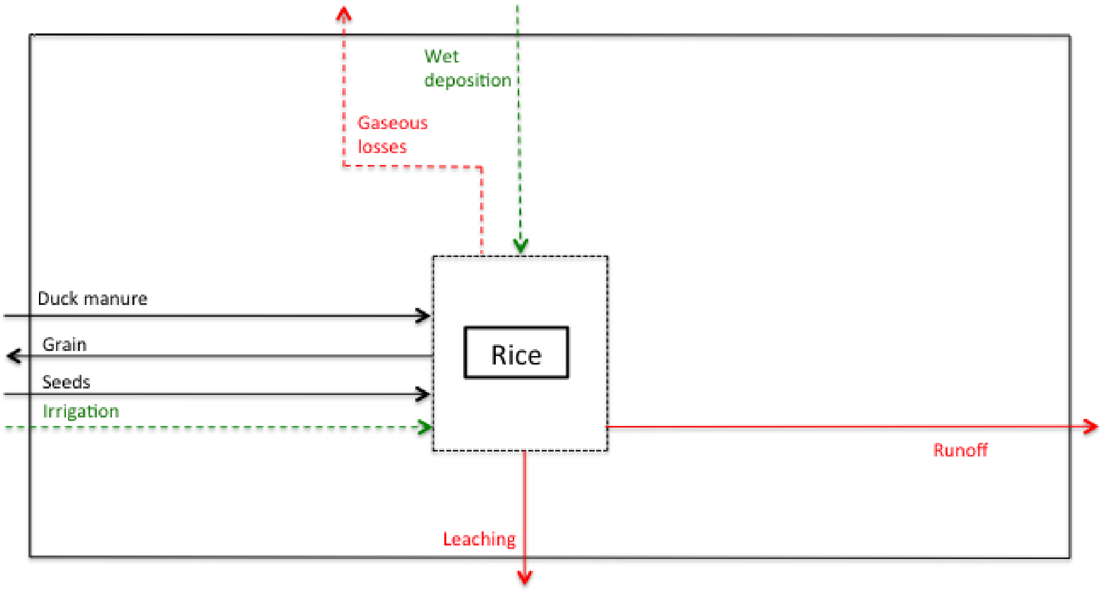


Figure 3. Appendix 22. Schematic representation of the N flows of RM.

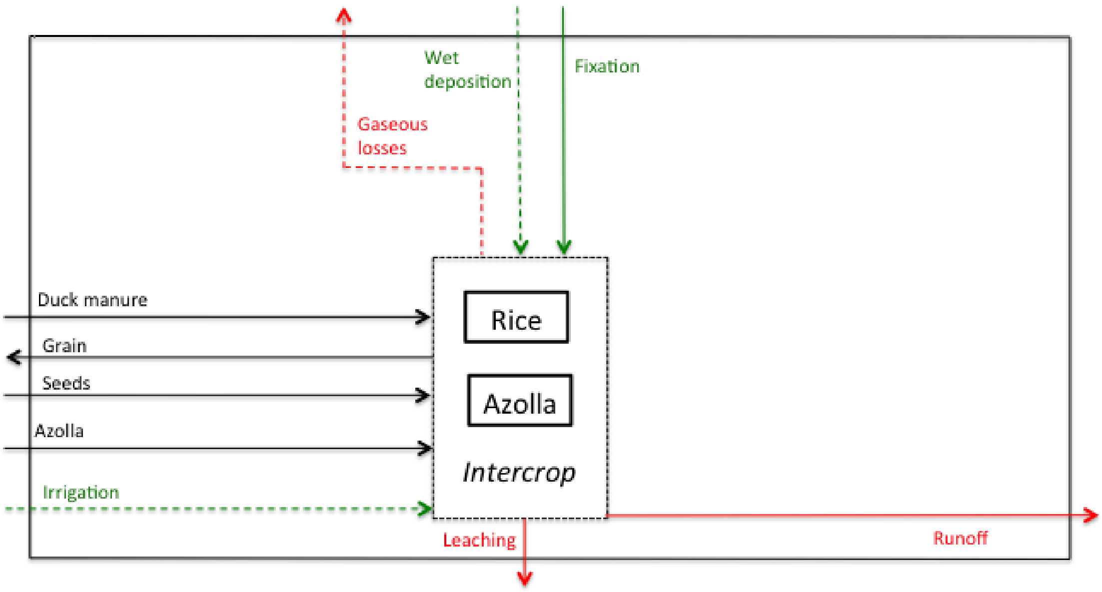


Figure 4. Appendix 22. Schematic representation of the N flows of RMA.

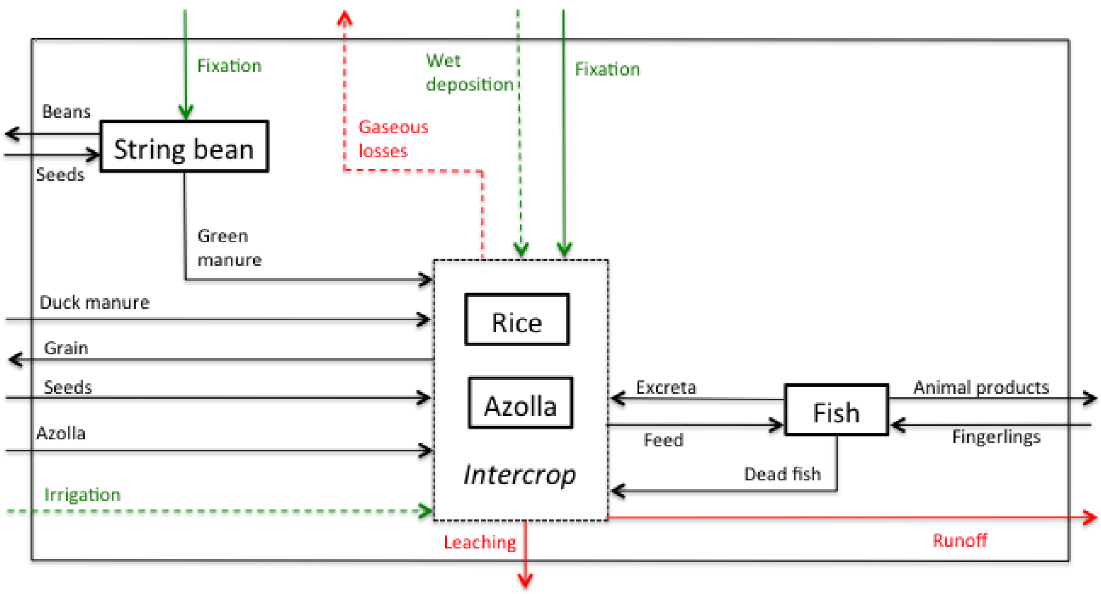


Figure 5. Appendix 22. Schematic representation of the N flows of RMAF.

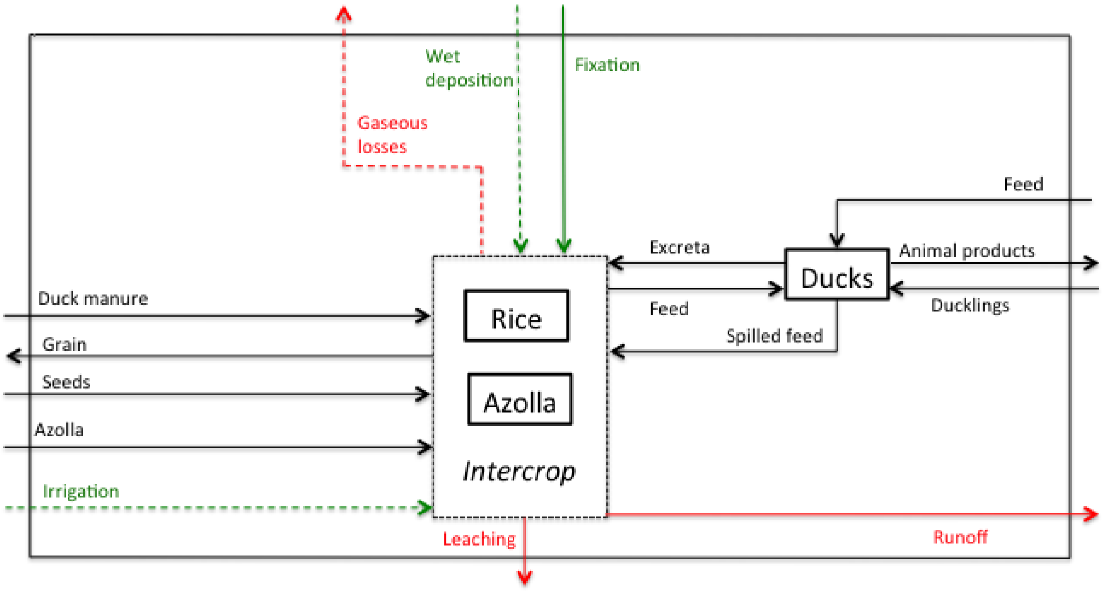


Figure 6. Appendix 22. Schematic representation of the N flows of RMAD.

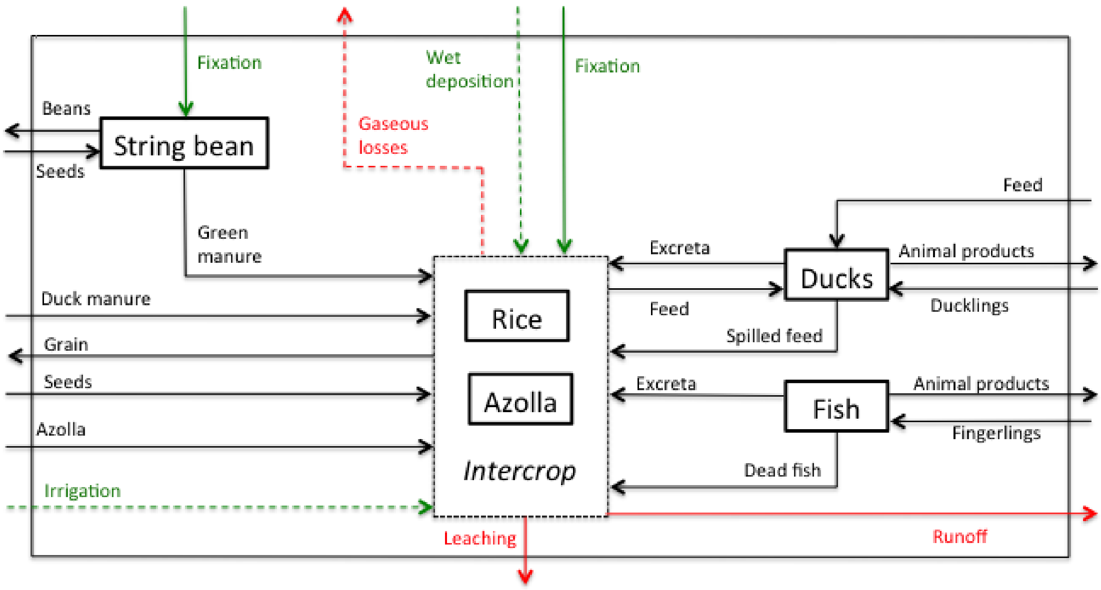


Figure 7. Appendix 22. Schematic representation of the N flows of RMAFD.

Appendix 23. Summary and schematic representation of the N flows in the best-case scenario

Table 1. Appendix 23. N flows of RMA.

Flows	N (Kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Manure	168,7
Azolla	4,8
Marketable outputs	
Grain	89,6
Biological N fixation	
Azolla N fixation	30,6
Losses	
Runoff and leaching	2,7

Table 2. Appendix 23. N flows of RMAF

Flows	N (Kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Manure	168,7
Azolla	4,8
Fingerlings	3,6
Bean seeds	0,2
Marketable outputs	
Grain	98,5
Fish	21,9
Beans	6,8
Internal flows	
Azolla intake by fish	43,7
Fish excreta	69,7
Green manure	11,9
Biological N fixation	
Azolla N fixation	31,1
Bean N fixation	15,4
Losses	
Runoff and leaching	2,9

Table 3. Appendix 23. N flows of RMAD.

Flows	N (Kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Manure	168,7
Azolla	4,8
Ducklings	0,5
Feed	104,5
Marketable outputs	
Grain	87,6
Ducks	12,5
Internal flows	
Azolla intake by ducks	23,8
Duck excreta	133,6
Rice bran	30,6
Biological N fixation	
Azolla N fixation	32,2
Losses	
Runoff and leaching	5,4

Table 4. Appendix 23. N flows of RMAFD.

Flows	N (Kg ha^{-1})
Purchased inputs	
Rice seeds	0,3
Manure	168,7
Azolla	4,8
Ducklings	0,5
Fingerlings	3,6
Bean seeds	0,2
Feed	100,3
Marketable outputs	
Grain	99,8
Ducks	12,5
Fish	21,9
Beans	6,8
Internal flows	
Azolla intake by ducks	19,7
Azolla intake by fish	26,1
Duck excreta	128,9
Fish excreta	69,7
Dead fish	0,0
Green manure	11,9
Rice bran	34,8
Biological N fixation	
Azolla N fixation	32,4
Bean N fixation	15,4
Losses	
Runoff and leaching	5,4

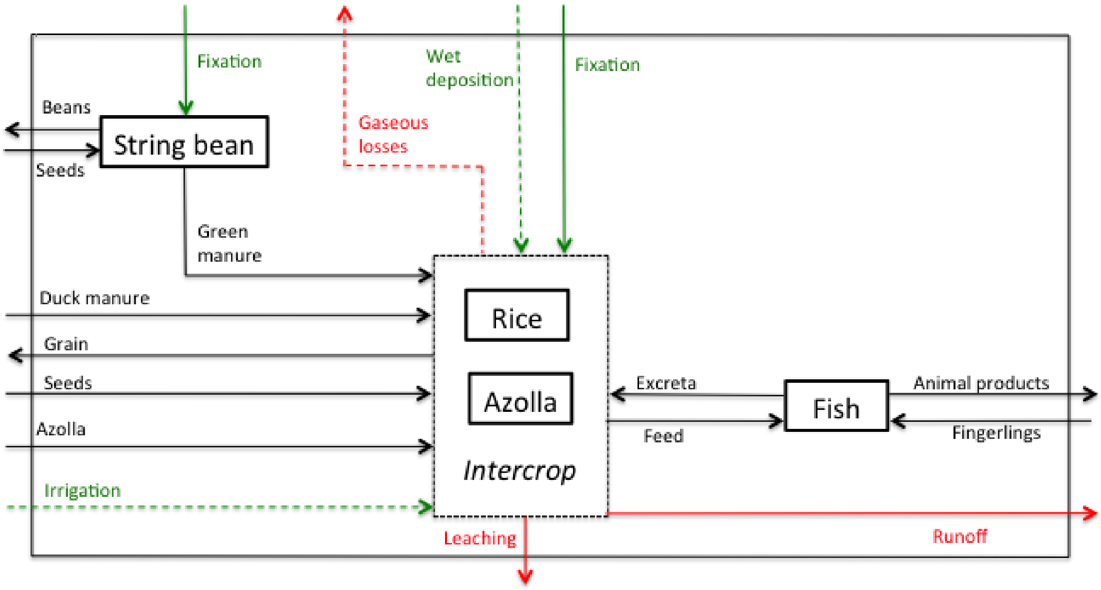


Figure 1. Appendix 23. Schematic representation of N flows of RMAF.

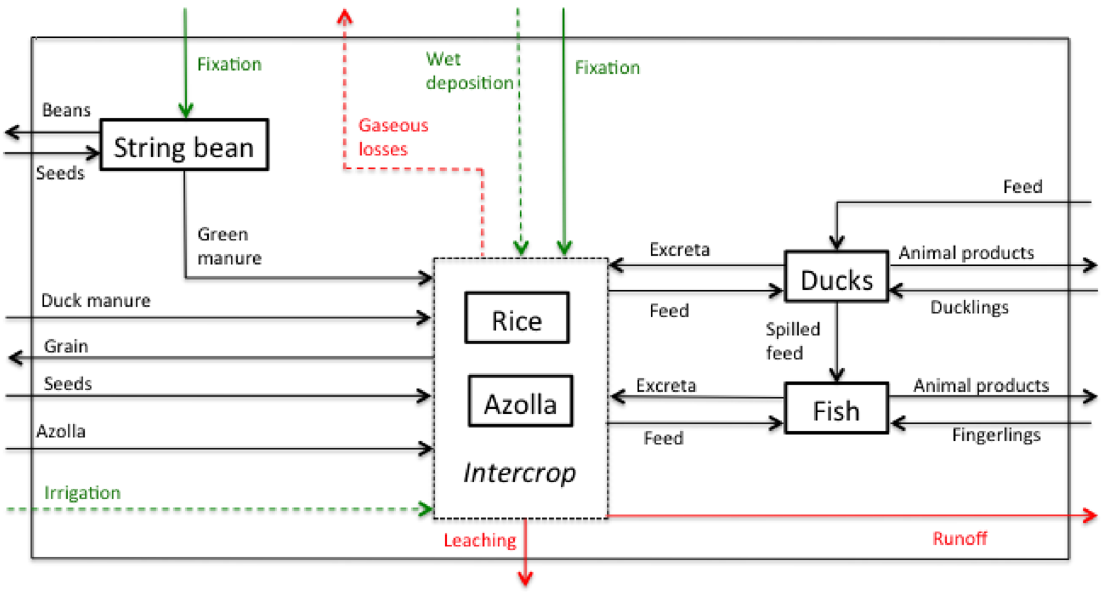


Figure 2. Appendix 23. Schematic representation of N flows of RMAFD.

Appendix 24. Schematic representation of the N flows of the 3 farms

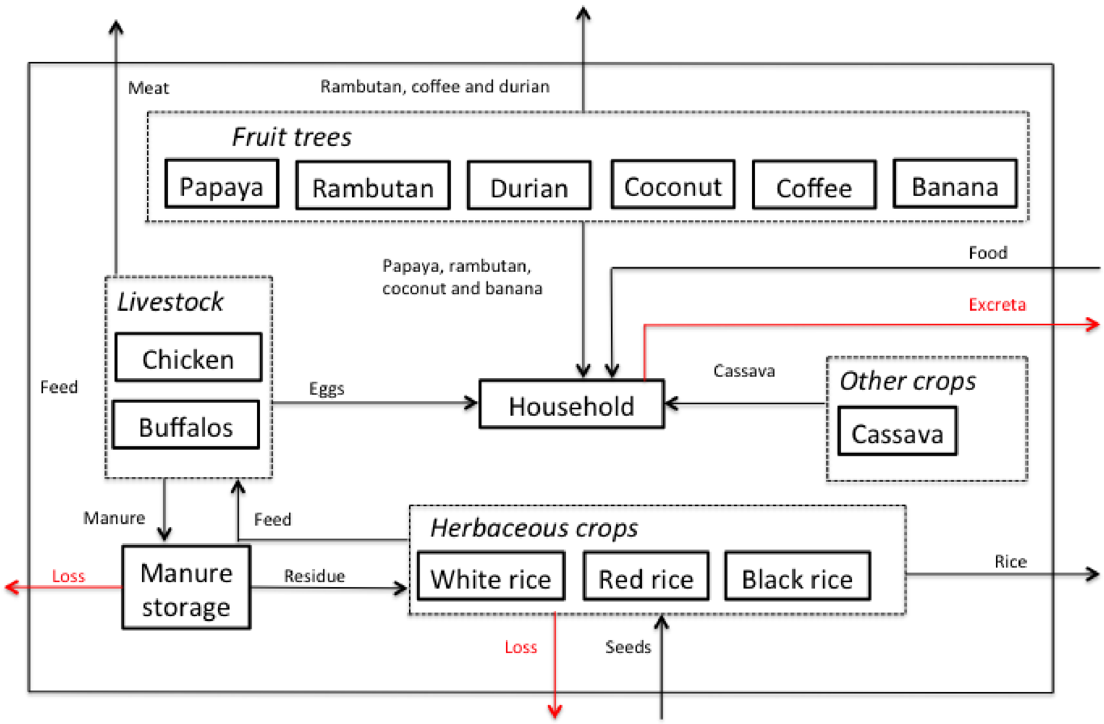


Figure 1. Appendix 24. Schematic representation of the N flows of Farm 1.

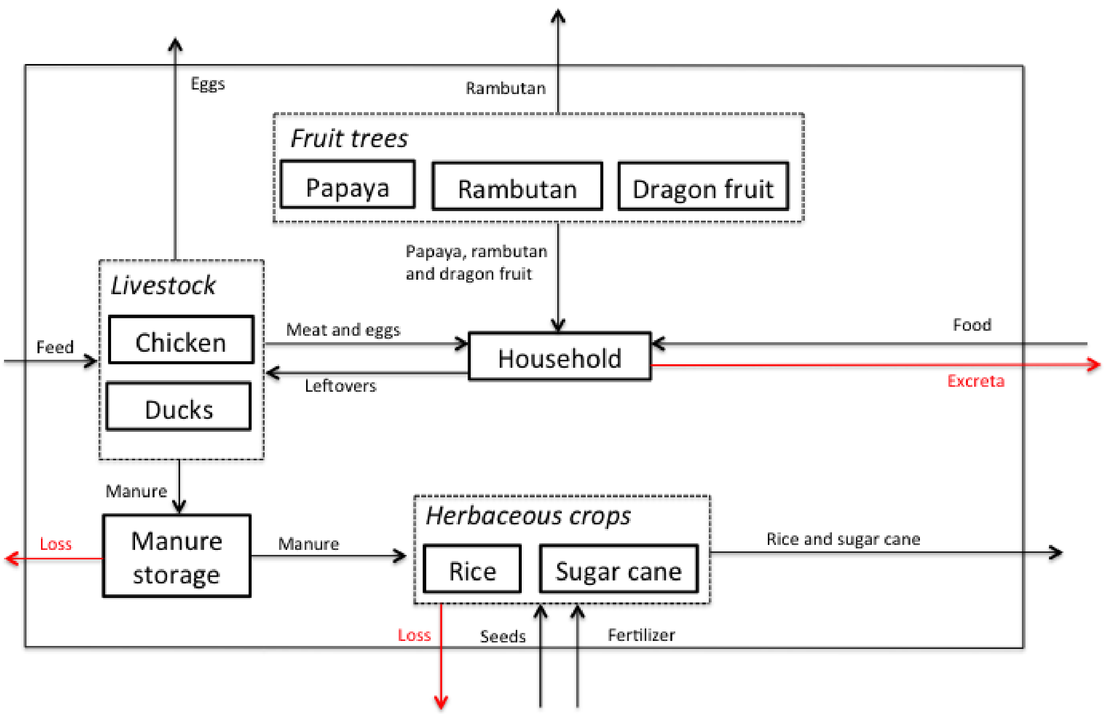


Figure 2. Appendix 24. Schematic representation of the N flows of Farm 2.

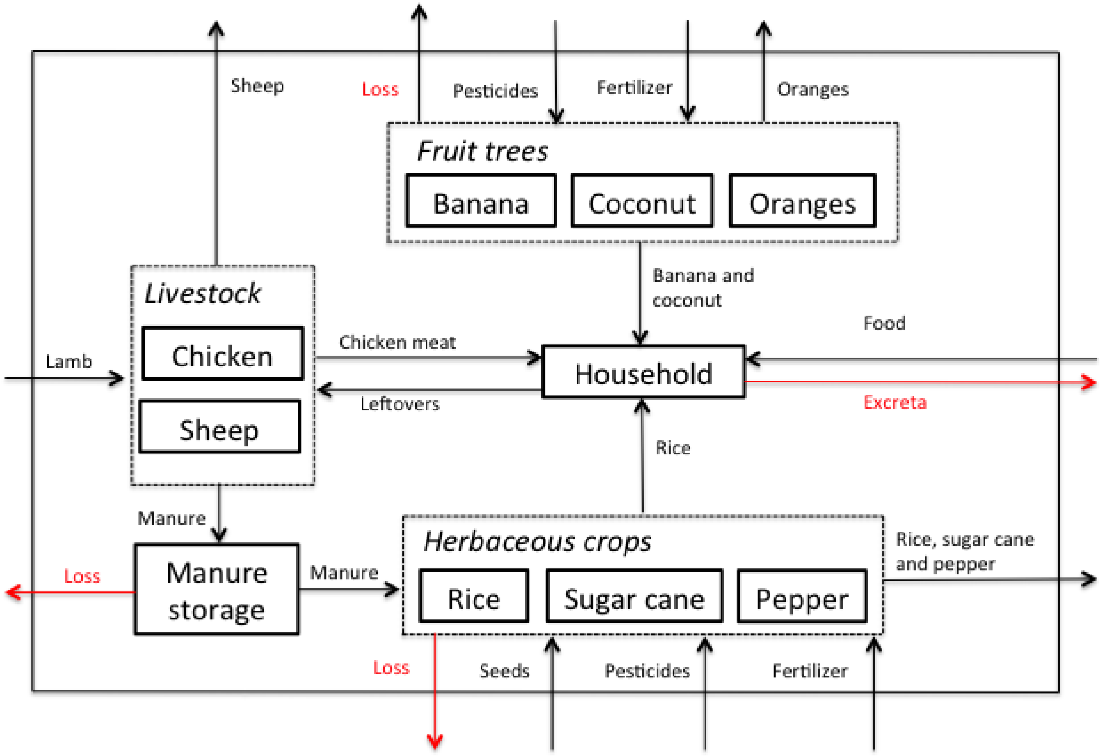


Figure 3. Appendix 24. Schematic representation of the N flows of Farm 3.

Appendix 25. Indicators to assess N balance and N use efficiency

Indicator	Calculation	Explanation
Imports	IN	N imported from external environment into the system
Exports	EN	Sum of N contained in sold items
Partial N balance	IN – EN	Difference between IN and EN
Full N balance	IN – (EN + losses)	Difference between IN and total N output
Whole farm N use efficiency	EN/IN	Ratio between EN and IN

Appendix 26. Fisher's least significant difference

Appendix 26.1. Treatment and rice yields

Multiple Comparisons

Dependent Variable: Yield

	(I) Treatment	(J) Treatment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
LSD	Conv	R	1,89333*	,38646	,000	1,0645	2,7222
		RM	1,56000*	,38646	,001	,7311	2,3889
		RMA	,95667*	,38646	,027	,1278	1,7855
		RMAF	,69000	,38646	,096	-,1389	1,5189
		RMAD	,10000	,38646	,800	-,7289	,9289
		RMAFD	-,39000	,38646	,330	-1,2189	,4389
	R	Conv	-1,89333*	,38646	,000	-2,7222	-1,0645
		RM	-,33333	,38646	,403	-1,1622	,4955
		RMA	-,93667*	,38646	,029	-1,7655	-,1078
		RMAF	-1,20333*	,38646	,008	-2,0322	-,3745
		RMAD	-1,79333*	,38646	,000	-2,6222	-,9645
		RMAFD	-2,28333*	,38646	,000	-3,1122	-1,4545
	RM	Conv	-1,56000*	,38646	,001	-2,3889	-,7311
		R	,33333	,38646	,403	-,4955	1,1622
		RMA	-,60333	,38646	,141	-1,4322	,2255
		RMAF	-,87000*	,38646	,041	-1,6989	-,0411
		RMAD	-1,46000*	,38646	,002	-2,2889	-,6311
		RMAFD	-1,95000*	,38646	,000	-2,7789	-1,1211
	RMA	Conv	-,95667*	,38646	,027	-1,7855	-,1278
		R	,93667*	,38646	,029	,1078	1,7655
		RM	,60333	,38646	,141	-,2255	1,4322
		RMAF	-,26667	,38646	,501	-1,0955	,5622
		RMAD	-,85667*	,38646	,044	-1,6855	-,0278
		RMAFD	-1,34667*	,38646	,004	-2,1755	-,5178
	RMAF	Conv	-,69000	,38646	,096	-1,5189	,1389
		R	1,20333*	,38646	,008	,3745	2,0322
		RM	,87000*	,38646	,041	,0411	1,6989
		RMA	,26667	,38646	,501	-,5622	1,0955
		RMAD	-,59000	,38646	,149	-1,4189	,2389
		RMAFD	-1,08000*	,38646	,014	-1,9089	-,2511
	RMAD	Conv	-,10000	,38646	,800	-,9289	,7289

	R	1,79333*	,38646	,000	,9645	2,6222
	RM	1,46000*	,38646	,002	,6311	2,2889
	RMA	,85667*	,38646	,044	,0278	1,6855
	RMAF	,59000	,38646	,149	-,2389	1,4189
	RMAFD	-,49000	,38646	,226	-1,3189	,3389
RMAFD	Conv	,39000	,38646	,330	-,4389	1,2189
	R	2,28333*	,38646	,000	1,4545	3,1122
	RM	1,95000*	,38646	,000	1,1211	2,7789
	RMA	1,34667*	,38646	,004	,5178	2,1755
	RMAF	1,08000*	,38646	,014	,2511	1,9089
	RMAD	,49000	,38646	,226	-,3389	1,3189

*. The mean difference is significant at the 0.05 level.

Appendix 26.2. Treatment and rice harvest index

Multiple Comparisons

Dependent Variable: Harvest_index

LSD

(I) Treatment	(J) Treatment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Conv	R	13,5000*	3,26424	,001	6,4989	20,5011
	RM	13,8000*	3,26424	,001	6,7989	20,8011
	RMA	8,7000*	3,26424	,018	1,6989	15,7011
	RMAF	7,3000*	3,26424	,042	,2989	14,3011
	RMAD	3,9333	3,26424	,248	-3,0678	10,9344
	RMAFD	2,9667	3,26424	,379	-4,0344	9,9678
R	Conv	-13,5000*	3,26424	,001	-20,5011	-6,4989
	RM	,3000	3,26424	,928	-6,7011	7,3011
	RMA	-4,8000	3,26424	,164	-11,8011	2,2011
	RMAF	-6,2000	3,26424	,078	-13,2011	,8011
	RMAD	-9,5667*	3,26424	,011	-16,5678	-2,5656
	RMAFD	-10,5333*	3,26424	,006	-17,5344	-3,5322
RM	Conv	-13,8000*	3,26424	,001	-20,8011	-6,7989
	R	-,3000	3,26424	,928	-7,3011	6,7011
	RMA	-5,1000	3,26424	,141	-12,1011	1,9011
	RMAF	-6,5000	3,26424	,066	-13,5011	,5011
	RMAD	-9,8667*	3,26424	,009	-16,8678	-2,8656
	RMAFD	-10,8333*	3,26424	,005	-17,8344	-3,8322
RMA	Conv	-8,7000*	3,26424	,018	-15,7011	-1,6989
	R	4,8000	3,26424	,164	-2,2011	11,8011
	RM	5,1000	3,26424	,141	-1,9011	12,1011

	RMAF	-1,4000	3,26424	,675	-8,4011	5,6011
	RMAD	-4,7667	3,26424	,166	-11,7678	2,2344
	RMAFD	-5,7333	3,26424	,101	-12,7344	1,2678
RMAF	Conv	-7,3000*	3,26424	,042	-14,3011	-,2989
	R	6,2000	3,26424	,078	-,8011	13,2011
	RM	6,5000	3,26424	,066	-,5011	13,5011
	RMA	1,4000	3,26424	,675	-5,6011	8,4011
	RMAD	-3,3667	3,26424	,320	-10,3678	3,6344
	RMAFD	-4,3333	3,26424	,206	-11,3344	2,6678
RMAD	Conv	-3,9333	3,26424	,248	-10,9344	3,0678
	R	9,5667*	3,26424	,011	2,5656	16,5678
	RM	9,8667*	3,26424	,009	2,8656	16,8678
	RMA	4,7667	3,26424	,166	-2,2344	11,7678
	RMAF	3,3667	3,26424	,320	-3,6344	10,3678
	RMAFD	-,9667	3,26424	,771	-7,9678	6,0344
RMAFD	Conv	-2,9667	3,26424	,379	-9,9678	4,0344
	R	10,5333*	3,26424	,006	3,5322	17,5344
	RM	10,8333*	3,26424	,005	3,8322	17,8344
	RMA	5,7333	3,26424	,101	-1,2678	12,7344
	RMAF	4,3333	3,26424	,206	-2,6678	11,3344
	RMAD	,9667	3,26424	,771	-6,0344	7,9678

Based on observed means.

The error term is Mean Square(Error) = 15,983.

*. The mean difference is significant at the 0.05 level.

Appendix 26.3. Treatment and rice N harvest index

Multiple Comparisons

Dependent Variable: N_harvest_index

LSD

(I) Treatment	(J) Treatment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Conv	R	15,3333*	4,00397	,002	6,7457	23,9210
	RM	15,3333*	4,00397	,002	6,7457	23,9210
	RMA	9,3333*	4,00397	,035	,7457	17,9210
	RMAF	8,0000	4,00397	,066	-,5877	16,5877
	RMAD	4,0000	4,00397	,335	-4,5877	12,5877
	RMAFD	3,0000	4,00397	,466	-5,5877	11,5877
R	Conv	-15,3333*	4,00397	,002	-23,9210	-6,7457
	RM	,0000	4,00397	1,000	-8,5877	8,5877
	RMA	-6,0000	4,00397	,156	-14,5877	2,5877
	RMAF	-7,3333	4,00397	,088	-15,9210	1,2543
	RMAD	-11,3333*	4,00397	,013	-19,9210	-2,7457
	RMAFD	-12,3333*	4,00397	,008	-20,9210	-3,7457
RM	Conv	-15,3333*	4,00397	,002	-23,9210	-6,7457
	R	,0000	4,00397	1,000	-8,5877	8,5877
	RMA	-6,0000	4,00397	,156	-14,5877	2,5877
	RMAF	-7,3333	4,00397	,088	-15,9210	1,2543
	RMAD	-11,3333*	4,00397	,013	-19,9210	-2,7457
	RMAFD	-12,3333*	4,00397	,008	-20,9210	-3,7457
RMA	Conv	-9,3333*	4,00397	,035	-17,9210	-,7457
	R	6,0000	4,00397	,156	-2,5877	14,5877
	RM	6,0000	4,00397	,156	-2,5877	14,5877
	RMAF	-1,3333	4,00397	,744	-9,9210	7,2543
	RMAD	-5,3333	4,00397	,204	-13,9210	3,2543
	RMAFD	-6,3333	4,00397	,136	-14,9210	2,2543
RMAF	Conv	-8,0000	4,00397	,066	-16,5877	,5877
	R	7,3333	4,00397	,088	-1,2543	15,9210
	RM	7,3333	4,00397	,088	-1,2543	15,9210
	RMA	1,3333	4,00397	,744	-7,2543	9,9210
	RMAD	-4,0000	4,00397	,335	-12,5877	4,5877
	RMAFD	-5,0000	4,00397	,232	-13,5877	3,5877
RMAD	Conv	-4,0000	4,00397	,335	-12,5877	4,5877
	R	11,3333*	4,00397	,013	2,7457	19,9210
	RM	11,3333*	4,00397	,013	2,7457	19,9210
	RMA	5,3333	4,00397	,204	-3,2543	13,9210

	RMAF	4,0000	4,00397	,335	-4,5877	12,5877
	RMAFD	-1,0000	4,00397	,806	-9,5877	7,5877
RMAFD	Conv	-3,0000	4,00397	,466	-11,5877	5,5877
	R	12,3333*	4,00397	,008	3,7457	20,9210
	RM	12,3333*	4,00397	,008	3,7457	20,9210
	RMA	6,3333	4,00397	,136	-2,2543	14,9210
	RMAF	5,0000	4,00397	,232	-3,5877	13,5877
	RMAD	1,0000	4,00397	,806	-7,5877	9,5877

Based on observed means.

The error term is Mean Square(Error) = 24,048.

*. The mean difference is significant at the 0.05 level.

Appendix 26.4. Block and rice yields

Multiple Comparisons

Dependent Variable: Yield

LSD

(I) Block	(J) Block	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	,5240	,48754	,304	-,5383	1,5863
	3	,9820	,48754	,067	-,0803	2,0443
2	1	-,5240	,48754	,304	-1,5863	,5383
	3	,4580	,48754	,366	-,6043	1,5203
3	1	-,9820	,48754	,067	-2,0443	,0803
	2	-,4580	,48754	,366	-1,5203	,6043

Based on observed means.

The error term is Mean Square(Error) = ,594.

Appendix 26.5. Block and rice yields of treatments without ducks

Multiple Comparisons

Dependent Variable: Yield of treatments without ducks

LSD

(I) Block	(J) Block	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	,6950	,39512	,112	-,1988	1,5888
	3	1,1650*	,39512	,016	,2712	2,0588
2	1	-,6950	,39512	,112	-1,5888	,1988
	3	,4700	,39512	,265	-,4238	1,3638
3	1	-1,1650*	,39512	,016	-2,0588	-,2712
	2	-,4700	,39512	,265	-1,3638	,4238

Based on observed means.

The error term is Mean Square(Error) = ,312.

*. The mean difference is significant at the 0.05 level.

Appendix 27. Regression analysis

Appendix 27.1. Hr and rice yields

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Hr[b]	.	Enter

a. Dependent Variable: Grain_Yield

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,798[a]	,636	,563	1,11494

a. Predictors: (Constant), Hr

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	10,863	1	10,863	8,739	,032[b]
	Residual	6,215	5	1,243		
	Total	17,079	6			

a. Dependent Variable: Grain_Yield

b. Predictors: (Constant), Hr

Coefficients[a]

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
1 (Constant)	3,455	,930		3,716	,014	1,065	5,846
Hr	2,190	,741	,798	2,956	,032	,286	4,094

a. Dependent Variable: Grain_Yield

Appendix 27.2. Hr and energy produced

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Hr[b]	.	Enter

a. Dependent Variable: Energy_produced

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,820[a]	,672	,607	3734810,02579

a. Predictors: (Constant), Hr

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	143037564978292,780	1	143037564978292,780	10,254	,024[b]
	Residual	69744029643888,020	5	13948805928777,605		
	Total	212781594622180,800	6			

a. Dependent Variable: Energy_produced

b. Predictors: (Constant), Hr

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	10761635,053	3115040,468		3,455	,018	2754168,610	18769101,496
	Hr	7946993,754	2481683,159	,820	3,202	,024	1567624,104	14326363,404

a. Dependent Variable: Energy_produced

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