On complex rice systems

Uma Khumairoh

Propositions

1. Extreme weather events are often problematic, but provide suitable conditions to test the robustness of agricultural innovations. (this thesis)

2. The knowledge level of farmers after training is not related to their initial knowledge. (this thesis)

3. Targeting self-sufficiency of farms for inputs should be weighed against trade-offs with gross income.

4. Farm typologies are an effective starting point for tailoring agricultural interventions.

5. Equal opportunities accelerate development, discrimination maintains dependence.

6. Naming objects or pets after supervisors helps PhD students working abroad feel guided at all times.

Propositions belonging to the thesis, entitled

'On complex rice systems'

Uma Khumairoh

Wageningen, 5th March 2019

On complex rice systems

Uma Khumairoh

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On complex rice systems

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Abstract

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The escalating global rice consumption has put great pressure on rice production systems which have been challenged by increased variability in weather conditions and concerns about environmental impacts. Meanwhile, current innovations in rice production systems confirm that there are no single solutions that comprehensively address those complex challenges. Therefore, integrated solutions are required to improve and stabilize current rice production levels and their environmental sustainability. To this end, this thesis aimed to develop bio-diversified rice-based farming systems by combining diverse plant and animal species as well as traditional and modern rice cultivation methods. This approach is referred to as complex rice systems (CRS), which have the ultimate goal to improve rice yields and their stability along with the whole farm productivity in an ecological way. This led to the selection of azolla, fish, ducks, and border plants for generating ecosystem services of weed and pest suppression as well as nutrient recycling. These were integrated using three selected cultivation methods: (i) the system of rice intensification (SRI), (ii) '*jajar legowo*' and (iii) organic rice production. *Jajar legowo* is planting rice in straight rows at certain intervals, allowing more rice plants to receive sunlight. We hypothesized that a combination of these cultivation methods and fine-tuning of biodiversity management could lead to high and stable rice yields with additional extra benefits from various secondary products.

To test this hypothesis, we conducted on-farm field experiments and perform action research in four districts of East Java, Indonesia, from 2010 to 2016. In 2010, we conducted an experiment with nine treatment combinations along a gradient of complexity to investigate their effects on attainable rice yields. We found that rice yields improved with increasing level of complexity and that the highest yield was obtained under the most complex system comprising all components (i.e. rice, azolla, ducks and border plants). Consistently, high yields under CRSs across four locations and throughout three rice cropping cycles were observed in an experiment performed between 2014 and 2016. CRSs showed both static and dynamic stability, had the highest reliability index, and were therefore outperforming the conventional and organic monoculture systems.

The mechanisms underlying the established high and stable rice yields of CRSs were elucidated in a multi-year experiment over five rice cropping cycles conducted from 2013 to 2016. The results demonstrated that increasing the level of complexity resulted in lower levels of weed and pest infestation. Analysis of duck behaviour and their gizzard composition showed that ducks foraged intensively on weeds, insects, snails and azolla. Furthermore, nutrient cycling was accelerated by ducks via feeding and excretion as well as by their movement in the field. Altogether, these phenomena explained why the rice yields increased along the gradient of complexity and this was consistent over time.

As the last step, action research was carried out from 2014 to 2016 in four districts of East Java by modifying and simplifying the farmer field school (FFS) approach. Focus point was the selection of adaptation measures for CRS implementation in various socio-biophysical conditions. By modifying the FFS method, feedback from farmers was generated and used for adaptation of CRSs to the contextual conditions. Meanwhile, simplifying the procedures improved the cost-effectiveness of the FFSs.

In summary, this thesis provides insights regarding the essential role of biodiversity as the basis for important agro-ecosystem services such as nutrient cycling and weed and pest suppression. This supports the development of knowledge and innovation of CRSs which result in highly stable rice yields and thus can contribute to safeguarding food security while the additional products potentially improve dietary and income diversity of rice farmer households. The fact that extreme weather conditions occurred during the experiments confirmed the high resilience and adaptive capacity of CRSs. Finally, the case study in this thesis can be used to guide CRS adaptation, but needs to be supported by active communication with stakeholders and appropriate training for farmers which are key drivers for large-scale implementation of these CRSs.

Key words: Adaptation measures, bio-diversified rice-based farming, ecological processes, food security and diversity, *Oryza sativa*, nutrient cycling, pest and weed suppression, participatory experiment and learning, resilience, rice yields and yield stability, weather variability.

Contents

Chapter I

General Introduction

Picture by Andi Bachtiar

1.1. Introduction

1.1.1. Background

Increasing agricultural production is needed to meet the global demands of the still growing population for food, fibre, wood and bioenergy production in conjunction with dietary changes. In response to these demands, agriculture has evolved drastically in many aspects with the overall aim of improving its efficiency (Thrall *et al.,* 2010; Wieczorek and Wright, 2012). Rice is a staple food for more than half of the world population, of which 60% is now living in Asia (UN, 2017). The green revolution in the 1960s was accompanied with improved rice varieties. This was associated with an increased use of inorganic fertilisers, pesticides, and herbicides, as well as improved irrigation infrastructures. In Indonesia, this has led to a steady increase of the rice yields from the late 1970s until the mid 1990s (Panuju *et al.,* 2013; Statistics Indonesia, 2016; Satu Data Indonesia, 2016).

The green revolution development model has raised a concept of agricultural intensification that is conventionally defined as the increase of yield per unit land area through an increase in cultivation frequencies (reduced fallow periods; Carswell, 1997), livestock density and external input levels (Pretty and Bharucha, 2014). Struik and Kuiper (2017) reported that this type of intensification is associated with the current industrialized agriculture that favors economic resource use efficiency over the other dimensions, seen as an essential pathway to feed the world. Nevertheless, a decline of rice yields took place during the Indonesian monetary crisis from 1997 to 2003 (Satu Data Indonesia, 2016; Statistics Indonesia; 2016), which reduced the Indonesian purchasing power such as for agrochemicals. This can be considered as an example that conventional agricultural intensification is less resilient to an economic shock. Another example is the second significant decline of rice yields under conventional systems that occurred due to extreme weather events between 2010 and 2014 (Statistics Indonesia 2016; FAO 2016). Moreover, an increased yield under conventional agricultural intensification has also been attained at the expense of environmental degradation, e.g. the adverse effects to non-target species including animals and humans (Giglio *et al.,* 2017). A wide range of risks can be imposed by the use of chemicals like pest resistance, pest resurgences, and pest outbreaks (Rostant, 2012; Royauté, 2015). The adverse effects from this conventional agricultural intensification have an impact on biosphere integrity (biodiversity loss) and biogeochemical cycles (nitrogen and phosphorous) that now have completely transgressed planetary boundaries (Foley et al. 2005; Rockström, 2009a; Rockström, 2009b; Campbell *et al.,* 2017). For example, the excessive use of nitrogen leads to pollution, drives biodiversity loss and pollutes the soil, air, coastal marine waters and watersheds (Howarth et al. 2011, Swaney *et al.,* 2012) and results in increased levels of N_2O emissions (Zhu *et al.,* 2013; Budria, 2017). Exceeding these planetary boundaries increases the risk of crossing thresholds that will trigger abrupt and irreversible environmental changes within continental to planetary-scale systems (Campbell *et al.,* 2017). Therefore, transformations of the food and agricultural systems are urgently needed.

1.1.2. Alternative rice production practices

Indeed, intensification is important for more productive agricultural land which is required to feed the growing and increasingly demanding human population. However, according to Pretty and Bharucha (2014) only sustainable intensification of agriculture can satisfy the nutritional needs whilst limiting environmental consequences. In a broader sustainable intensification concept, agro-ecology is part of the approach that attempts to reconcile environmental sustainability and production goals using principles and applications of ecological processes throughout the design and management phases of ssustainable agro-ecosystems (Lampkin *et al.,* 2015).

In search of this environmentally-friendly and self-reliant production systems, organic production systems have been developed. The elimination of chemicals has made organic farming systems less polluting and farmers are less dependent on artificial inputs (Reganold and Wachter, 2016). However, other aspects such as decreased productivity and increased labour inputs have led to questions about the sustainability of organic farming. Some people perceived organic farming as an inefficient food production system (Reganold and Wachter, 2016; Meemken and Qaim, 2018) based on several outcomes that manifest low average yields (De Ponti *et al.,* 2012; Seufert *et al.,* 2012; Ponisio, *et al.,* 2015; Van de Ven *et al.,* 2018). Therefore, scaling-out this type of organic production systems could reduce the quantity of food production, resulting in the need of larger areas for crop and animal production and consequently a reduction in the area of natural systems (Meemken and Qaim, 2018).

Alternatively, the system of rice intensification (SRI) can be associated with sustainable intensification as it has been claimed to produce higher rice yields along with reductions in water and fossil energy use as well as greenhouse gas (GHG) emissions (Gathorne-Hardy *et al.,* 2016; Thakura *et al.,* 2016). Higher rice yields under SRI principles are established through the basic principles of the cultivation methods which include the use of: (i) single young rice seedlings per hill in order to promote healthy and vigorous root growth, (ii) wider spacing to reduce competition and allowing optimal development of each individual plant, and (iii) intermitted irrigation events to increase oxygen levels in the soil, which boost root and consequently aboveground plant growth (Uphoff, 2010; Kassam *et al.,* 2011; Stoop, 2011). However, some have also argued that this system bears extra costs, especially those associated with labour inputs. Higher labour inputs reported in SRI investigations were due to the precise application of transplanting and water management (Krupnik *et al.,* 2012; Ndiiria *et al.,* 2013). Intermitted irrigation in SRI increases weed infestation, resulting in higher labour requirement for weeding. Moreover, during its implementation, the application of compost in SRI increases labour inputs and fertiliser use (Berkhout *et al.,* 2015). Therefore, the net income may not be different from that of conventional production systems, despite higher rice yields (Ly *et al.,* 2012).

As another option, a traditional adjustment to rice planting systems practised in Indonesia is *jajar legowo* (Suciandari, 2012; Hamdani and Murtiani, 2014), which literally translates from Javanese as ‘spacious straight rows’. This is a rice-planting method where one out of 3-6 plant rows remains empty, allowing more rice plants to receive sunlight and enabling easier plant monitoring and management (weeding, fertilising, and spraying). However, similar to common conventional production systems, *jajar legowo* is also dependent on chemical inputs that are detrimental to the environment.

Finally, an ‘integrative solution’ (Scheffer *et al.,* 2000) within the sustainable intensification concept is agro-ecological intensification (Struik and Kuiper, 2017; Petersen and Snapp, 2017) which may improve the sustainability of rice production. This can be done for example by combining SRI and *jajar legowo*, including diverse plant and animal species. These production systems are referred to as complex rice systems (CRSs). The selection of integrated species which are suitable for flooded rice ecosystems, e.g. azolla, fishes, ducks and border plants, is key to building successful CRSs.

Azolla, a floating fern that lives in symbiosis with the blue-green algae *Anabaena azollae* fixes atmospheric nitrogen which enriches rice ecosystems. Ducks and fish which are commonly found in the flooded rice production systems in Asia (Jana and Jana, 2003; Lu and Li, 2006; Cheng-fang *et al.,* 2008) can enhance ecological processes of weed and pest suppression, as well as nutrient cycling. This can replace human labour especially for hand weeding and spraying herbicides and pesticides. In addition, border plants can facilitate the development of natural enemies for pest control in CRSs (Zeng *et al.,* 2017). This integrative approach may make an important contribution to sustainable rice production and may be more resilient compared to chemicals which are not very effective during extreme weather events.

However, to date, no studies have been reported which comprehensively examined this integrative approach of CRSs with respect to their social, economic and cultural perspectives to ensure their feasible implementation.

1.2. Objectives and research questions

The main aim of this PhD study was to develop a blueprint for bio-diverse complex rice systems (CRSs) that combine rice cultivation methods with diverse plant and animal species, including rice, azolla, fishes, ducks and border plants. The ultimate goal of developing this system was to improve rice yields along with their stability in an ecological way whilst exploring other possible opportunities. To achieve these objectives, four research questions have been formulated:

1. What are the effects of the combined elements in a gradient of complexity on rice yields?
2. How do rice yields and their stability in CRSs compare to those in monoculture conventional and organic production systems across a variety of environments and weather conditions?
3. Through which mechanisms do the combined elements in CRSs suppress weeds and pests and regulate nutrient recycling that determines rice yields and their stability?
4. How can complex rice systems be adapted to various socio-biophysical conditions without compromising rice yields?

1.3. Approaches and structures of this thesis

In light of the social, cultural and economic aspects of rice production systems, this thesis takes an interdisciplinary approach to agro-eco-technology. A wide range of rice cultivation methods were applied, such as SRI, *jajar legowo*, and organic rice production. The effects of the integrated elements of azolla, fish, ducks and border plants to deal with weeds, pests and required nutrients were investigated by means of various experimental settings. The rice yields were measured across spatial and temporal scales to evaluate the resilience of CRSs under variable weather conditions. Moreover, the link of CRS adaptation to the local conditions is innovative and timely, since the demand for scalable measures of sustainable rice production in smallholder farming systems is large. Thus, transferring knowledge to farmers and adapting measures that consider socio-biophysical conditions are prerequisites for CRS implementation which are also discussed in this thesis. Finally, the importance of the social, biophysical, cultural, and economic aspects that present trade-offs is also analysed in the context of the contribution of CRSs to improving smallholder livelihoods (profit, household nutrition, food diversity and security, resilience, knowledge sharing and labour shortage).

Overall, this study integrated methodological approaches of experimental and action research, while stakeholder participation in the learning process was emphasized. Figure 1 depicts the approach used to achieve the range of objectives which were transformed into the research questions (RQ) examined in this study and links them to each relevant chapter.

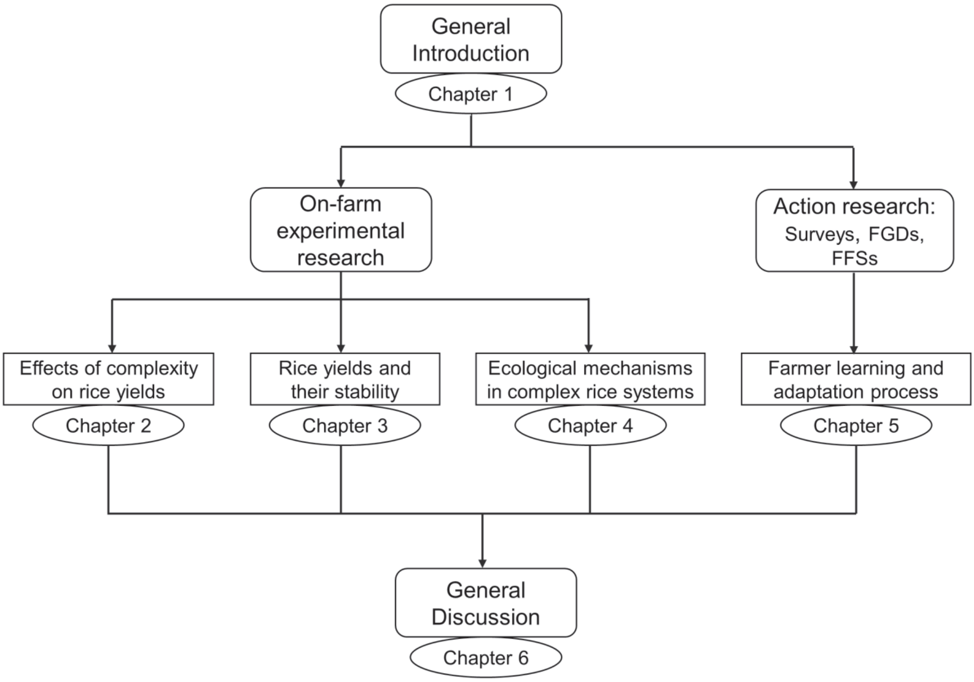

Figure 1. Outline of the methodical approaches in this thesis

The first experiment in **Chapter 2** was set to address RQ 1. Previous studies have shown that integrating animal and plant species into rice systems could reduce the use of fertilisers, pesticides and herbicides while simultaneously producing equivalent rice yields compared to those in conventional systems (Xie *et al.,* 2011). Contrary to previous research projects, agrochemicals were fully eliminated in all treatments in the experiments of Chapter 2 as well as the CRS treatments in Chapters 3 and 4. Chapter 2 and Chapter 4 demonstrate the effects of the combined elements on nutrient use and pest suppression regulation. Besides, the attainable yields and the whole farm productivity affecting the economics of CRSs are discussed here.

This led to the next research question which was to verify whether the established yields of CRSs are stable across spatial and temporal scales. Thus, in **Chapter 3** a further experiment was carried out across four districts of East Java over three cropping cycles. Coincidentally, some cropping cycles in this experiment experienced extreme weather conditions, which supported an assessment of the resilience of CRSs in comparison with conventional and organic monoculture rice systems.

A series of experiments is discussed in **Chapter 4** to explain the mechanisms underlying the established experimental yields and how their stability was affected by nutrients, weeds and pests at differing levels of complexity. The role of ducks and their behaviour in recycling nutrients, as well as suppressing weeds and pests was analysed. Furthermore, this chapter also explains how each integrated element interacts with each other and fills niches above and below the water surface and on rice bunds.

The development of a methodological framework to support the transfer of knowledge and adaptation processes of CRSs is highlighted and described in **Chapter 5**. The approach presented here employed the farmer field school (FFS) method (Anderson and Feder, 2004; Larsen and Lilleør, 2014) which was modified and simplified. The modifications and simplifications were made in order to comply with the objective of knowledge sharing to make adaptation measures of CRSs inexpensive and more effective. Integrating repetitive cycles in analytical learning steps of FFS are underlined to collect pertinent farmers' feedback to make CRSs more adaptive to the local conditions. Furthermore, we provide the results of the participatory evaluation of the adaptation and learning processes in this chapter.

Finally, **Chapter 6** discusses the reflections and implications of the findings in this thesis directed towards the development of CRSs. This highlights the potential contribution of CRSs to improving smallholder livelihoods, nutrition, food security, income diversification and the overall environmental quality as well as to solving labour shortage problems. Additionally, insights into the trade-offs of CRS implementation are identified along with the potential strategies for alleviating these trade-offs for mainstreaming CRS implementation. Accordingly, a number of ideas for future research needs are also presented in Chapter 6.

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Chapter 2

Complex agro-ecosystems for food security in a changing climate

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Picture by Rohmatin Agustina

Abstract

Attempts to increase food crop yields by intensifying agricultural systems using high inputs of non-renewable resources and chemicals frequently lead to degradation of natural resources, whereas most technological innovations are not accessible for smallholders that represent the majority of farmers world-wide. Alternatively, cocultures consisting of assemblages of plant and animal species can support ecological processes of nutrient cycling and pest control, which may lead to increasing yields and declining susceptibility to extreme weather conditions with increasing complexity of the systems. Here we show that enhancing the complexity of a rice production system by adding combinations of compost, azolla, ducks and fish resulted in strongly increased grain yields and revenues in a season with extremely adverse weather conditions on East Java, Indonesia. We found that azolla, duck and fish increased plant nutrient content, tillering and leaf area expansion, and strongly reduced the density of six different pests. In the most complex system comprising all components the highest grain yield was obtained. The net revenues of this system from sales of rice grain, fish and ducks, after correction for extra costs, were 114% higher than rice cultivation with only compost as fertiliser. These results provide more insight in the agro-ecological processes and demonstrate how complex agricultural systems can contribute to food security in a changing climate. If smallholders can be trained to manage these systems and are supported for initial investments by credits, their livelihoods can be improved while producing in an ecologically benign way.

Keywords: Agro-ecology, pest suppression, nutrient cycling, rice, smallholders

2.1. Introduction

Narrowing existing gaps between actual and potential crop yields has been identified as one of the priorities to secure food availability for the increasing global human population (Tilman *et al.,* 2002; IAASTD, 2009; Graham-Rowe, 2011). Currently, the actual yields obtained by farmers are ca. 50% of the potential yields, and in exceptional cases in irrigated crops up to 80% is reached (Lobell *et al.,* 2009). These yield gaps are caused by insufficient or unbalanced supply of water and nutrients, damage due to weeds, pest and diseases, and losses caused by weather-related events such as extreme temperatures, severe rainfall events and prolonged periods of drought (Van Ittersum & Rabbinge, 1997; Lobell *et al.,* 2009). In the near future, farmers and their agricultural systems should be able to deal with even stronger fluctuations in environmental and weather conditions, since climate change is expected to increase the incidence of weather anomalies (Naylor *et al.,* 2007; Lobell *et al.,* 2009; Meinke *et al.,* 2009; Gornall *et al.,* 2010).

Increasing both productivity and robustness of agricultural systems will require concerted developments in technological innovation and improved crop cultivation techniques (Uphoff, 2010; Graham-Rowe, 2011). However, attempts to increase food crop yields by intensifying agricultural systems using high inputs of non-renewable resources and chemicals frequently lead to degradation of soils and other natural resources (Matson *et al.,* 1997; Steinfeld *et al.,* 2006; IAASTD, 2009), whereas most technological innovations are not accessible for smallholders that represent the majority of farmers world-wide (Kiers *et al.,* 2008; Herrero *et al.,* 2010). Thus, in many cases, increasing and stabilizing the productivity of food crops will primarily depend on better management of crops, ecological processes and organic resources to increase soil structure and fertility, and to protect crops against weed competition and damage by pests and diseases.

Complex agricultural systems consisting of assemblages of plant and animal species can support ecological processes of nutrient cycling and pest control, which may lead to higher yields and reduced susceptibility to extreme weather conditions when the complexity of the systems increases (Van Noordwijk & Swift, 1999; Altieri, 2002; Shennan, 2008). However, there is a lack of scientific knowledge concerning agro-ecological processes of plant growth and development, effectiveness of pest suppression, nutrient cycling, and the productive performance of agricultural systems on gradients of complexity and under extreme conditions. Integrated rice cultivation can be considered as a pertinent model system for the analysis of ecological processes in complex agro-ecosystems, due to its importance as a food crop and the inherent complexity of cultivation practices involving soil, water and plant resources.

We conducted a field trial to investigate the attainable yields in complex agro-ecosystems by studying the combined effects of integration of compost application, ducks, fish and azolla in a flooded rice system in a season with extremely adverse weather conditions of high rainfall on East Java, Indonesia. Rice was cultivated using selected practices from the System of Rice Intensification (SRI), i.e. larger planting distances (30 x 30 cm) of individual young (10-days old in the 2-3 leaf stage) seedlings and using compost as organic fertiliser (Kassam *et al.,* 2011), but in contrast to SRI recommendations the fields were flooded to allow fish and duck integration. Ducks and fish are widely used in flooded rice production systems in Asia (Lu & Li, 2006; Jana & Jana, 2003; Cheng-fang *et al.,* 2008), but less frequently applied jointly. More complex combinations involving also compost and azolla are scarce in practice and in scientific research, as only one production dataset (Cagauan *et al.,* 2000) without further information on nutrient and pest dynamics is available. In these systems, compost can serve as a source of organic matter and nutrients to improve soil structure and crop nutrient status. This includes a sufficient provision of micronutrients that are frequently deficient when inorganic fertilisers are used (Kassam *et al.,* 2011). Azolla is a floating fern that lives in symbiosis with the blue green algae *Anabaena azollae*, which can fix atmospheric nitrogen. Ducks and fish can feed on azolla, weeds and pest organisms, thus improving nutrient cycling within the system and suppressing weed and pest populations (Cagauan *et al.,* 2000; Jana & Jana, 2003). The results obtained in the experiment reported here, with systems in a gradient of complexity, provide more insight in the agro-ecological processes and demonstrate how complex agricultural systems can contribute to food security in a changing climate.

2.2. Methods

2.2.1. General

The on-farm field experiment was conducted between September 1 and December 12, 2010, in Pagelaran, Malang district, East Java, Indonesia (8°10'27"S, 112°35'58"E), at an altitude of 335 m.a.s.l. on a clay-loam soil. The experimental layout was a randomized block design with two replicate blocks. The control treatment consisted of rice only (R), the other eight treatments consisted of combinations of nutrient management (compost (+C) and compost and azolla (+C+A)) and pest management (ducks (+D) and ducks and fish (+D+F)). This resulted in nine treatment combinations with a gradient in complexity. Experimental plots of 200 m^2 were surrounded by dikes to prevent flows of nutrients, fish and azolla between plots. Plots with ducks were fenced to prevent movement of ducks between plots and contained a duck house (1.5 m x 1.5 m x 1.0 m) constructed of bamboo and rice straw. Compost was produced of straw, duckweed, water hyacinth and duck manure, heaped for a month and turned once. The compost was spread manually using a hoe.

Rice (*Oryza sativa*, Var. Ciherang) suitable for both wet and dry seasons was cultivated. The rice cultivar used is tolerant to brown plant hopper biotypes 2 and 3, as well as rice blast diseases strain III and IV. Plants were seeded at a rate of 20 kg per ha. In agreement with the recommendations of Kassam *et al.* (2011) to enhance the development of the root system, seedlings were transplanted 10 days after germination in the 2-3-leaf stage, and planted on hills with a planting distance of 30 x 30 cm, resulting in a plant density of ca. 11 plants m^{-2} (August 22-25, 2010). Plots with azolla treatment were inoculated with a mixture of *Azolla pinnata* and *A. microphylla* at a rate of 2000 kg per ha. The azolla growth was stimulated by 28 kg per ha of SP-36 phosphorous fertiliser ($Ca(H_2PO_4)_2$, with 5% of sulphur, and total P_2O_5 of 36%). Local ducks (*Anas platyrhynchos Javanicus*; local name: Mojosari) were introduced in the plots with duck treatment at a rate of 400 per ha. Annex feed was supplied to the ducks at a rate of 75-150 g per animal per day, depending on the body weight. Nile tilapia (*Oreochromis niloticus*) of 10 cm length (ca. 30 g) were used in the fish treatments at a rate of 5000 per ha. Azolla, ducks and fish were released into plots two weeks after transplanting (September 8, 2010). A second inoculation of azolla was performed on September 15, 2010 at the same rate as for the initial inoculation. Plots were weeded manually three times in plots without ducks and two times in plots with ducks.

2.2.2. Measurements

Five plants per plot were harvested diagonally at early tillering (28 days after transplanting, DAT), maximum tillering (49 DAT), flowering (70 DAT) and grain filling (84 DAT). The final harvest was conducted at 112 days after transplanting. The leaves were dissected of the plant and leaf area was measured using a Leaf Area Meter (Li310, LICOR Inc., USA). Leaves, stems, grains and roots were oven-dried at 70 °C for 72 hours and subsequently weighed to determine the dry matter (DM) content. Samples were ground to pass a 1mm screen in a hammer mill and analysed for nutrient contents. Ducks and fish were removed at flowering (70 days after transplanting) and weighed.

Snails (*Bellamya javanica*) were counted in an area of 30 cm^2 around a rice plant for 5 plants per plot on a diagonal. Mature snails could be collected manually whereas smaller snails were recovered from soil. A square wooden box was used to mark the area, and then soil and snails were taken out by a shovel. The sample was sieved to collect the snails. Dead snails and eggs were not counted.

Yellow traps were used to measure insect populations of rice whorl maggots (*Nephotettix virescens*), leaf hoppers (*Nephotettix virescens*), plant hoppers (*Nilaparvata lugens*) and stem borers (*Scirpophaga incertulas* and *S. innotata*). Five yellow traps per plot located on a diagonal within the plot were tied on a bamboo stick, and then the bamboo stick was plugged onto a single rice hill in the morning. The population of rice bugs (*Leptocorisa oratorius*) was estimated by trapping in dead crabs attached to a bamboo stick (five traps per plot on a diagonal). The traps remained in the field for 24 hours.

Total inputs and outputs of nitrogen, phosphorus and potassium were calculated to discern the effects of nutrient additions to the system from effects of improved nutrient cycling within the system. The inputs included rice seeds, compost (consisting of duckweed, straw and duck manure), duck feed (consisting of rice bran, corn and dried fish), ducklings, juvenile fish and phosphorus fertiliser; the composition of these inputs is presented in Annex Table A2.1. In addition, for nitrogen we estimated atmospheric deposition of 0.4 g N m^{-2} and symbiotic fixation by azolla of 1.8 g N m^{-2}. The outputs of nutrients were in rice grain, duck and fish. Nutrient losses by leaching, volatilization or denitrification were not included in the balance calculations, since we aimed to assess the contribution of improved nutrient cycling to the productive potential of the systems along the complexity gradient.

Costs for all inputs (seed, duck feed, manure, fish and ducklings) and labour (for rice management, keeping ducks and fish), equipment and water management were recorded. Revenues were calculated from all sold products: rice grain, ducks and fish.

2.2.3. Statistical analysis

The normal distribution of data was tested using skewness and kurtosis tests, where necessary log-transformation was performed. Trends in annual average temperature and cumulative precipitation were tested with linear regression. Experimental treatment effects were tested by analysis of variance, and Tukey's post hoc test was used to establish significant differences between treatments. All statistical tests were conducted with SPSS 18 software package (SPSS Inc., USA).

2.3. Results

Throughout the last 20 years the mean temperatures have significantly increased in the Malang district ($F_{(1,19)} = 6.6848$, $P = 0.01814$), but during the experiment the temperatures were not higher than the long-term average (Figures 1a and b). In contrast, although annual precipitation rates have not shown an increasing trend in the period 1990-2010 ($F_{(1,19)} = 1.8686$, $P = 0.1876$; Figure 1c), the total rainfall amounts in the years 1998 and 2010 have been extremes in terms of total rainfall and amounts per event (Figures 1d and e), which resulted in undesired natural flooding and conditions that were very conducive for growth of pest populations in the trial presented here.

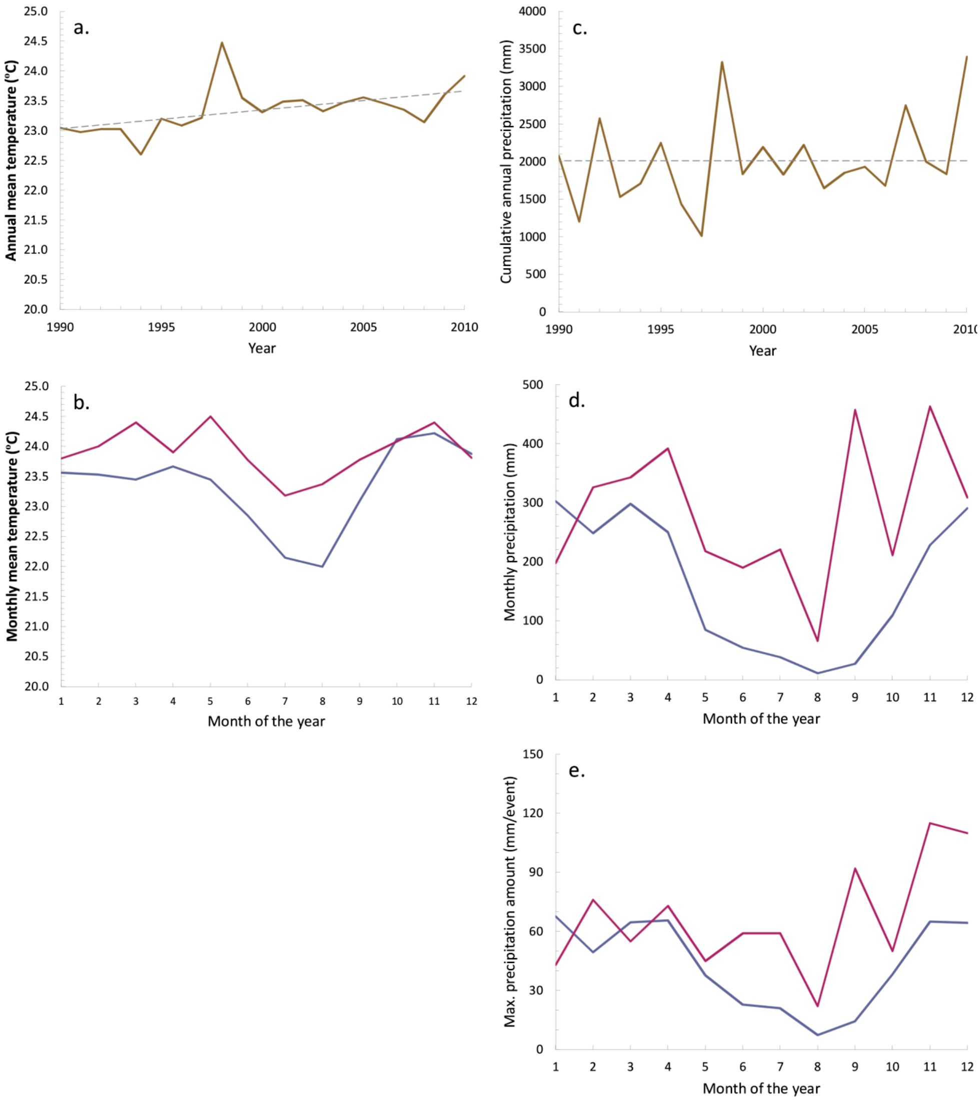

Figure 1. Trends in climatic conditions in the Malang region, Indonesia. (a) Average annual temperature. (b) Monthly mean temperature. (c) Cumulative annual precipitation. (d) Monthly amount of precipitation. (e) Maximum amount of precipitation in one event per month. Blue lines denote 20-years average (1990-2010), red lines represent the observations for the year of the experiment (2010), results of linear regressions are indicated with dashed lines.

The populations of six pest species were monitored (Figure. 2). Snails (*Bellamya javanica*) and rice whorl maggots (*Nephotettix virescens*) were abundant directly after transplanting the seedlings but their populations declined throughout the experiment. Populations of leaf and plant hoppers (*Nephotettix virescens* and *Nilaparvata lugens*) and stem borers (*Scirpophaga incertulas* and *S. innotata*) were initially small but increased until flowering (ca. 60 days after transplanting) and declined thereafter, whereas the number of rice bugs (*Leptocorisa oratorius*) increased only from 70 days after transplanting onwards, during grain filling. For all pests the size of the population was largest for the rice-only treatment, and lower for the more complex combinations of system production factors. In particular the presence of ducks reduced the pest abundance. The rice plants in the more complex treatment combinations had higher leaf expansion rates and reduced plant stress as indicated by the lower values for biomass dry matter content and specific leaf area (Rubia-Sanchez *et al.,* 1999; Quentin *et al.,* 2010) (Annex Figure A2.1).

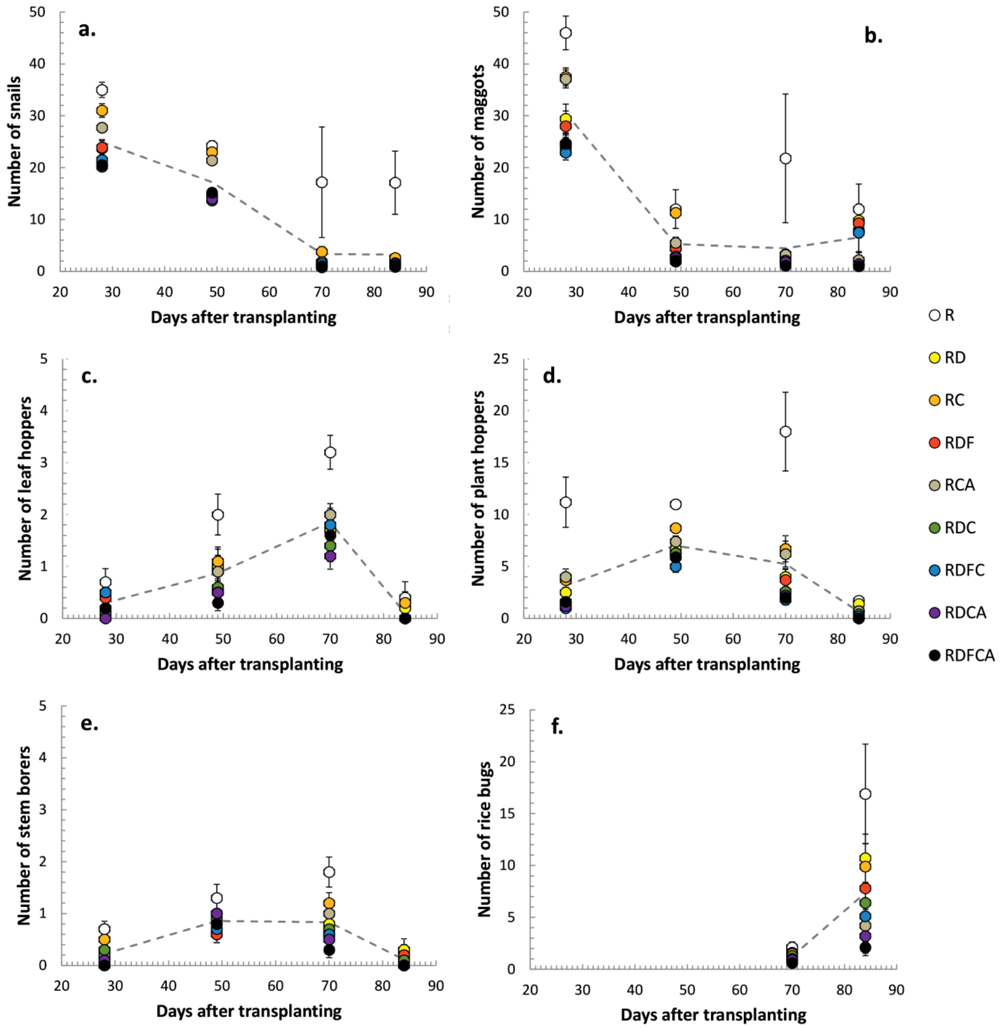

Figure 2. Abundance of plant pests per hill (± standard error of mean), (a) snails (*Bellamya javanica*), (b) rice whorl maggots (*Nephotettix virescens*), (c) leaf hoppers (*Nephotettix virescens*), (d) plant hoppers (*Nilaparvata lugens*), (e) stem borers (*Scirpophaga incertulas* and *S. innotata*), (f) rice bugs (*Leptocorisa oratorius*). R = rice, D = with ducks, C = with compost, F = with fish, A = with azolla. The dashed line indicates the trend in the overall average. Error bars represent standard error of the mean (n = 10).

The total biomass and grain yield increased with larger system complexity ($F_{(8,81)} = 31.645$, $P < 0.001$) and hence the highest grain yield of 1.06 kg dry matter m^{-2} was obtained in the most complex system comprising compost, azolla, ducks and fish (Figure 3; Annex Figure A2.2). The higher grain yields for more complex combinations of production factors could be attributed to higher number of tillers per plant and larger seed weight due to application of compost and introduction of ducks, whereas the presence of azolla resulted in an increase of the number of grains per panicle (Annex Table A2.2). The contribution of fish to grain yield was not significant (interaction between nutrient and pest protection treatments, $F_{(4,81)} = 3.003$, $P = 0.023$), but it resulted in significantly higher nitrogen and potassium accumulation in the rice crop (Annex Table A2.3).

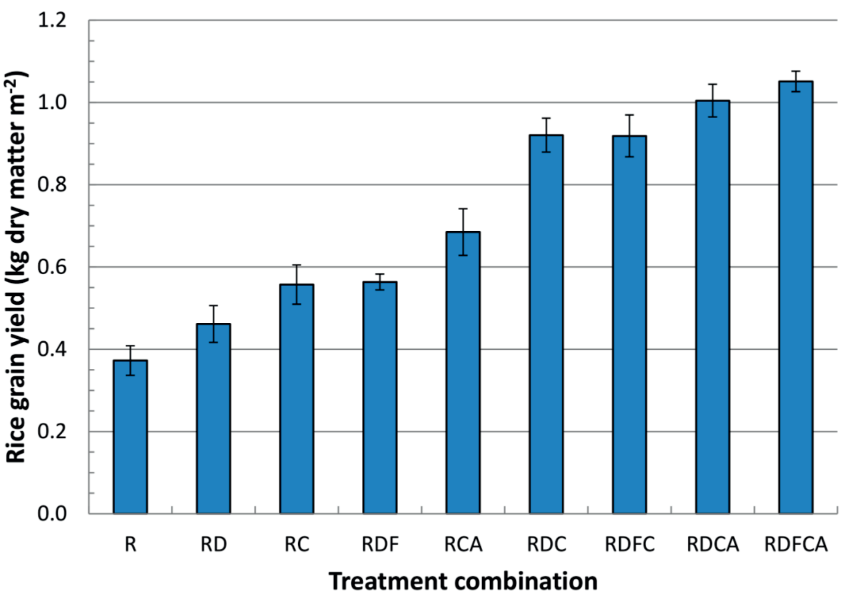

Figure 3. Yield of rice grain for increasingly complex rice cultivation systems (± standard error of mean). R = rice, D = with ducks, C = with compost, F = with fish, A = with azolla. Error bars represent standard error of the mean (n=10).

Analysis of the relation between total nutrient inputs and total nutrient outputs allowed to discriminate the effects of adding nutrients with increasing complexity (for instance in compost and duck feed) from impacts of ducks and fish on nutrient cycling processes. This analysis revealed that both ducks and fish improved nitrogen cycling, only ducks contributed to potassium cycling and that ducks and fish did not affect the phosphorus cycling in the various rice cultivation systems (Annex Figure A2.3).

When compared to the generally applied organic rice cultivation practices where compost is applied, the more complex systems required extra investments to purchase the applied production factors of young ducks and fish (Annex Table A2.4). However, these investments were more than compensated by the additional revenues from the sales of the better yielding rice grain and the mature ducks and fish, as demonstrated from the comparison between the rice with compost (RC) treatment and the most complex treatment combination (Figure. 4).

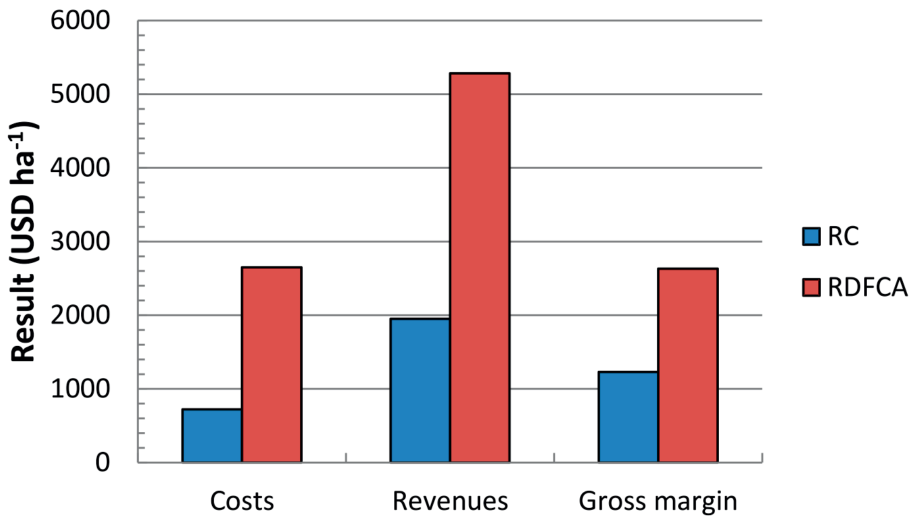

Figure 4. Economic results of rice cultivation in terms of costs, revenues and gross margin for rice with compost (RC) and a complex system involving ducks, fish, compost and azolla (RDFCA), expressed in USD per ha.

2.4. Discussion

Increasing potential and actual cereal yields has been identified as one of the main challenges to secure food supply to a large part of the global population (Cassman *et al.,* 2003; Normile, 2008; Godfray *et al.,* 2010). Compared to other food crops, for rice there is less pressure on developments in plant breeding and genetic engineering to improve productivity, because the seed market is limited as most of the seed is derived from own cultivation. A major part of the gap between potential and actual yields is caused by biotic stresses such as pests and diseases (Lobell *et al.,* 2009), which are expected to put an even larger pressure on yields with the predicted changes in climatic conditions (Chakrabortya & Newton, 2011). The impact of breeding for resistance and developing pesticides to protect crops against these stresses is often limited and temporary, since pests and diseases evolve to break plant resistance or become resistant against pesticides (Normile, 2008). Moreover, the use of fertilisers and pesticides needs to be reduced to safeguard the environment (Matson *et al.,* 1997; Lansing & Kremer, 2011). Therefore, improved farming practices and the utilization of ecological processes are crucial to improve rice yields. In the experiment reported here, selected methods from integrated pest management (Glen *et al.,* 1995; Gurr *et al.,* 2004) (IPM) and system of rice intensification (Uphoff, 1999) (SRI) were combined with integration of organic fertiliser application and incorporation of ducks and fish as productive components. It clearly demonstrated the potential of farming based on ecological processes in systems with increasing complexity for improvement of yields.

The selected SRI practices have a clear plant physiological basis. The larger spacing between plants allows for better development of individual plants and rooting systems due to reduced competition above and below ground (Kassam *et al.,* 2011). Seeding in a nursery and transplanting 8-12 days after emergence results in more vigorous plant development in the field (Stoop, 2011). Although synthetic fertilisers supply more nutrients to the crop that are often directly available, organic fertilisers such as compost can contribute to soil improvement and lift constraints on crop production related to the supply of micronutrients, in many cases more effectively than synthetic fertilisers (Kassam *et al.,* 2011).

The experiment was conducted in a season with high cumulative precipitation amounts and large amounts per event when compared to the 20-year average. Although these conditions were very conducive for pest development, a provisional estimate of the total grain dry matter yield was high (10.6 Mg ha^{-1}) in the most complex treatment. Despite the fact that this amount was derived from up-scaling of yields from individual plant level and considerable caution is warranted, it indicates that the yields measured in this experiment were at least comparable to those of successful irrigated rice crops in field and on-farm experiments. In such trials, yields usually range between 5 and 7 Mg ha^{-1} for organic systems (Hariyoto, 2011) and between 8 and 12 Mg ha^{-1} for conventional systems (Cassman & Pingali, 1995). However, in the season of our experiment in the Pagelaran sub-district the average conventional rice yields were 7.9 Mg ha^{-1} (CASM, 2011).

The increase in yield along the complexity gradient indicated that the productivity in the more complex systems were robust to the high rainfall conditions probably due to beneficial effects of the synergies between system components. The effect of increasing system complexity on reducing the abundance of pest organisms and weeds (less frequent weeding in plots with ducks) was evident. In particular the presence of ducks reduced the pest abundance (Figure 2). Ducks eat insects and weeds. Fish can eat and uproot weeds, and can contribute to fungus suppression by feeding on mycelia (Xie *et al.,* 2011). Moreover, the moving ducks and fish can hit rice stems resulting in an increased removal of dewdrops (and consequently less risk of spore generation and mycelium penetration) and in more insects falling into the water (Xie *et al.,* 2011).

Nutrient cycling was probably enhanced by various processes, including the feeding and manure production by ducks and fish (Cagauan *et al.,* 2000), the improved degradation of organic wastes due to improved aeration of the water by the animal movement (Bird *et al.,* 2000), and the nitrogen fixation by the algae associated with the azolla fern. The activities of duck and fish such as trampling and stirring in the rice field also increase dissolved oxygen in the water. Higher dissolved oxygen lead methanogenic bacteria changes organic acid in the rice field to CO_2 instead of CH_4. Therefore, CH_4 transfer from rice field to the air will be reduced (Zhiqiang *et al.,* 2008). However, under aerobic conditions the nitrification process is also enhanced and as a consequence the production of N_2O could be increased (Li *et al.,* 2009).

Both the reduced pest and disease pressure and the improved nutrient status had a positive effect on yield, probably related to a more vigorous plant growth and better plant resistance. This was also reflected in morphological plant characteristics (higher leaf expansion rates) and improved plant physiological status (lower biomass dry matter content and specific leaf area). Here we have focused primarily on the beneficial effects on rice crop performance, but these effects are mutual, indicating true synergies. Both ducks and fish benefit from the presence of the rice plants that attract the insects that serve as feed. Also the azolla serves as a feed and fixes atmospheric nitrogen, and on the other hand benefits from the non-nitrogenous nutrients that are dissolved in the water and that originate from decomposition of compost and decayed plant material and from the excreta of ducks and fish (Cagauan *et al.,* 2000). Moreover, the rice plants provide shade due to leaf expansion, a low-ammonia aquatic environment due to nutrient uptake, which are factors that positively influence fish (Xie *et al.,* 2011).

The resulting gross margin was sufficient for smallholders to acquire the necessary inputs for the next season and to refund more than 70% of the initial credit. Alternatively, cooperation of rice producers with duck farmers can substantially reduce the required investments since ducklings and feed represent 74% of the extra costs and would also alleviate labour constraints, but this cooperation would depend on mutual commitment, social organization and trust (Pretty & Smith, 2004; Simmons & Birchall, 2008). Similar positive economic benefits of ecologically based practices by smallholders have been observed for rice cultivation using IPM principles in Bangladesh (Dasgupta *et al.,* 2007). Also integration of cocultures at field level into complex whole-farm systems could be feasible and profitable (e.g., Behera *et al.,* 2008).

The successfulness of complex agro-ecosystems relying on ecological processes will depend on the system at hand and local conditions, but the approach to rice cultivation presented in this paper can serve as a suitable model system (cf., Lansing & Kremer, 2011), since it consists of a diverse assemblage of water, plants, animals and organic residues and because the influences of the various production factors could be clearly distinguished in our experiment. Although the revenues from the complex agro-ecosystems will be variable due to the strong dependence on ecological processes that are susceptible for environmental fluctuations (Morton, 2007; Gregory *et al.,* 2009), the improved nutrient status and biological weed and pest control enhance the robustness of the systems (Shennan, 2008; Altieri, 1999), as demonstrated in the extremely unfavourable conditions as experienced in the trial presented here. Farmers will require training to manage the timing and application rates of the various production factors. The initial investments that are required to add an increasing number of components in order to constitute complex agro-ecosystems that support ecological processes without relying on artificial inputs can contribute considerably to increasing rice grain yields and thus food security, and to improving the livelihood of resource-poor smallholders.

Annex 2

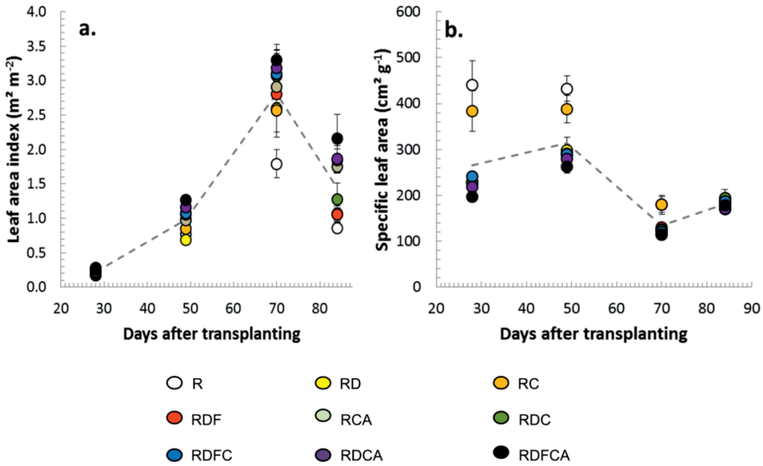

Figure A2.1. Changes in leaf and biomass characteristics at different days after transplanting of the rice plants. (a) Leaf area index (m^2 leaf/ m^2 soil). (b) Specific leaf area (cm^2 leaf/g leaf). (c) Plant biomass dry matter content (g/kg). R = rice, D = with ducks, C = with compost, F = with fish, A = with azolla. The dashed line indicates the trend in the overall average. Error bars represent standard error of the mean (n = 10).

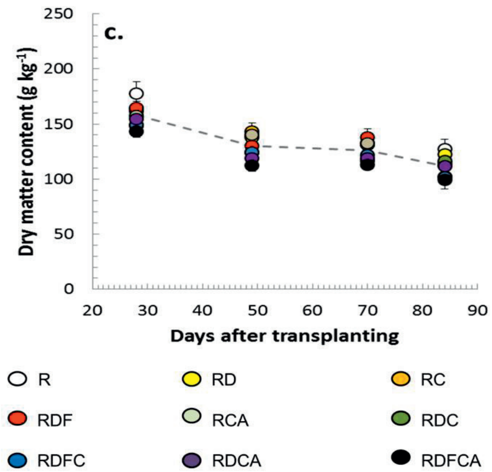

Figure A2.2. Dry matter accumulation at different days after transplanting of the rice crop. R = rice, D = with ducks, C = with compost, F = with fish, A = with azolla. The dashed line indicates the trend in the overall average. Error bars represent standard error of the mean (n=10).

Table A2.1. Nutrient contents of inputs.

Name of input	Nitrogen (N)	Phosphorus (P)	Potassium (K)
Rice seed (DW)	15.3 g kg^{-1}	3.1 g kg^{-1}	11.4 g kg^{-1}
Ducklings (30 g/duckling) (FW)	33 g kg^{-1}	1.6 g kg^{-1}	2.0 g kg^{-1}
Juvenile fish (20 g/fish) (FW)	32.5 g kg^{-1}	1.7 g kg^{-1}	3.2 g kg^{-1}
Azolla (FW)	1.8 g kg^{-1}	0.6 g kg^{-1}	1.8 g kg^{-1}
Compost			
Straw (DW)	10.0 g kg^{-1}	5.4 g kg^{-1}	10.0 g kg^{-1}
Duck manure (DW)	13.9 g kg^{-1}	13.6 g kg^{-1}	6.5 g kg^{-1}
Duckweed (FW)	2.9 g kg^{-1}	1.6 g kg^{-1}	2.1 g kg^{-1}
Duck feed			
Rice bran (DW)	15.3 g kg^{-1}	5.4 g kg^{-1}	11.4 g kg^{-1}
Corn (DW)	13.0 g kg^{-1}	4.0 g kg^{-1}	4.8 g kg^{-1}
Dried fish (DW)	46.0 g kg^{-1}	3.0 g kg^{-1}	5.0 g kg^{-1}

Table A2.2. Yield components of rice as affected by increasing complexity of the production systems due to adding ducks (D), compost (C), fish (F) and azolla (A). Means with different letters are significantly different, following the Tukey's post hoc test. n=10 per treatment.

Variable	Pest Management	Nutrient management			Mean
		R	+C	+C+A	
Number of panicles per hill	R	13	16	17	15a
	+D	17	23	22	20b
	+D+F	18	23	23	21b
	Mean	16a	20b	21b	
Number of grains per panicle	R	108	123	141	124a
	+D	101	142	159	134b
	+D+F	114	139	158	137b
	Mean	108a	135b	153c	
1000-grain weight (g)	R	26	26	27	26a
	+D	25	27	27	27b
	+D+F	26	27	28	27b
	Mean	26a	27b	27b	

Table A2.3. Uptake of nutrients (g m^{-2}) by rice as affected by increasing complexity of the production systems due to adding ducks (D), compost (C), fish (F) and azolla (A). Means with different letters are significantly different, following the Tukey's post hoc test. n=10 per treatment.

Variable	Pest management	Nutrient management			Mean
		R	+C	+C+A	
Nitrogen (N)	R	9.4	14.5	17.5	13.7a
	+D	15.5	22.3	25.1	20.9b
	+D+F	18.6	24.2	30.0	24.2c
	Mean	14.5a	20.3b	24.1c	
Phosphorus (P)	R	2.9	4.5	6.1	4.5a
	+D	3.9	6.2	9.7	6.6b
	+D+F	5.1	5.7	10.2	6.9b
	Mean	3.9a	5.5b	8.7c	
Potassium (K)	R	5.4	9.0	12.6	9.0a
	+D	10.9	16.5	18.0	15.1b
	+D+F	12.3	17.0	21.9	17.0c
	Mean	9.5a	14.1b	17.5c	

Table A2.4. Details of financial calculations for treatments with rice with compost (RC) and including ducks, fish, compost and azolla (RDFCA).

Attribute	**Units (per ha)**	**Unit price**	**R**	**RDFCA**
<u>COSTS</u>				
Duck manure (sacks)	300	0.46	139.37	139.37
Rice seeds (kg)	20	0.87	17.42	17.42
Ducklings	400	1.16		464.58
Nile tilapia, 10 cm	5000	0.03		174.22
Duck feed (kg)	4111	0.23		954.94
Azolla	1	30.20		30.20
Bio-pesticides	1	1.16	1.16	1.16
Renting tools				
- Plow	1	174.22	174.22	174.22
- Harvest equipment	1	27.87	27.87	27.87
Labor (hours)				
- Composting	20	4.07	81.30	81.30
- Soil preparation	4	4.07	16.26	16.26
- Seeding and transplanting	22	4.07	89.43	89.43
- Pest management	1	4.07	4.07	4.07
- Weed management	24	4.07	97.56	
	18	4.07		73.17
- Water management	1	17.42	17.42	17.42
- Duck management	6	52.26		313.59
- Fish management	15	4.07		60.98
Total costs			**666.09**	**2640.19**
<u>REVENUES</u>				
Rice (kg)	5600	0.35	1951.22	
Rice (kg)	10500	0.35		3658.54
Fish (kg)	625	0.81		508.13
Ducks	320	3.48		1114.98
Total revenues			**1951.22**	**5281.65**
Gross margin			**1285.13**	**2641.46**

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Chapter 3

Complex rice systems to improve rice yield and yield stability in the face of variable weather conditions

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Abstract

Extreme weather events and pest outbreaks decrease rice yields and increase their variability, presenting challenges for the agricultural agenda to increase rice productivity and yield stability in Asia. The integration of azolla, fish and ducks has been shown to create robust systems that maintain high yields under heavy rainfall, but no clear evidence exists that rice yields in these systems are stable across locations and throughout time under divergent weather conditions. We show that the introduction of additional elements into the rice cropping system enhanced the adaptive capacity to extreme weather events across four locations and three cropping cycles. The complex system showed both static and dynamic stability, and had the highest reliability index, thereby outperforming the conventional and organic monoculture systems. The complex rice system design provides a promising example for resilience towards the impacts of climate change on rice production and for safeguarding food security in Asia and beyond.

Key words: Dynamic yield stability, rice, rice production systems, static stability, yield reliability, weather variability.

3.1. Introduction

Climate change is expected to increase the variability in weather conditions and the frequency of extreme weaather events such as floods and droughts (Iizumi *et al.,* 2014; Brönnimann, 2015), which will have direct effects on agricultural production worldwide (Challinor, 2014). For example, in Asian rice systems, the anticipated changes in weather patterns could lead to faster development, growth, and spread of weeds and of important crop pests and diseases, presenting a major challenge to food stocks (Lamichhane *et al.,* 2015; Lesk *et al.,* 2016; Shrestha *et al.,* 2016; Xu, 2017). This is of great relevance to Indonesia; although it is the third largest rice producer in the world, demand for rice exceed production (ACAPS, 2016; FAO a, 2016), resulting in an insecure national stockpile that remains dependent on imports.

Domestic rice production and food security in Indonesia have recently been affected by extreme weather events that include heavy rainfall in 2013 and in 2016 caused by la Nina, which were interrupted by an el Nino event that prolonged the dry season during 2015. Water logging may decrease rice yields through hypoxia, while heavy rains disturb pollination, fertilization, and grain-filling processes. A longer duration of rainfall reduces light intensity, affecting the drying of grains at the ripening stage. Heavy rainfall may also affect grain quality resulting from shattered, lightweight, blackened or chalky grains (Choi *et al.,* 2013; Yang *et al.,* 2015; Sarangia *et al.,* 2016; FAO b, 2016). In addition, extreme weather events may trigger pest and weed outbreaks. To compensate the resulting decline in production, Indonesian rice imports increased by 44%, from 1.25 million tonnes in 2015 to 1.80 million tonnes in 2016 (FAO b, 2016).

Increased use of agro-chemicals aimed at addressing this challenge is not only potentially harmful to the environment and human health, but also increases the dependency of farmers on external inputs (Tilman *et al.,* 2002). Organic agriculture has been proposed as an option to reduce the negative impacts on the environment and human health, but it is often associated with lower crop yields and more labour intensive crop management practices, although this is dependent on the type of organic system (Seufert *et al.,* 2012; Ponisio *et al.,* 2015; Gurr *et al.,* 2016). For example, complex rice systems (CRSs) can be more productive than monoculture systems (Khumairoh *et al.,* 2012).

CRSs integrate the cultivation of azolla, fish and ducks into the rice system, and have previously been shown to be a promising approach to ecologically address pest problems and increase rice yields in organic rice production systems (Khumairoh *et al.,* 2012). However, to date no clear evidence was available on the stability and applicability of CRSs across locations and throughout time under divergent weather conditions.

In this paper, we measured the yields and assessed yield stability of conventional, organic and complex rice production systems across temporal and spatial scales. Conventional treatments were characterised by the use of artificial fertilisers, pesticides and herbicides, while organic treatments received organic fertilisers and bio-pesticide applications. CRS treatments integrated azolla, fish and ducks into organic rice systems, coupled with growing border plants on 50-100 cm wide ridges surrounding CRS plots. Border plants consisted of green manures and vegetables, which can supply food and feed, and refugia to attract natural enemies. Hence, no pesticides were applied in the CRS treatments. Finally, the potential for the scalability and replicability of the proposed CRSs' design was discussed in this paper.

3.2. Methods

3.2.1. Study sites

The experimental sites were in the Lamongan sub-district of Lamongan (7°08′27.10″S − 112°23′46.79″E), Kepanjen sub-district of Malang (8°09′11.82″S − 112°34′33.32″E), Gandusari sub-district of Blitar (7°59′34.14″S − 112°18′21.79″E) and the Prigen sub-district of Pasuruan (7°41′49.82″S − 112°37′40.44″E). The sub-districts are distributed over a range of altitudes: Lamongan (8 meters above sea level), Kepanjen (326 m.a.s.l), Gandusari (600 m.a.s.l) and Prigen (760 m.a.s.l). The sub-districts cover different soil types and texture: Vertisol-clay, Inceptisol-silty clay, Entisol-sandy and Andisol-sandy clay loam.

The field experiments were undertaken from December 2014 to 2015 (first cycle), from May to August 2015 (second cycle) and from January to April 2016 (third cycle). We originally planned the third cycle for September to December 2015, but this had to be delayed because of the prolonged dry season in 2015.

3.2.2. Experimental design agronomic practices and animal management

Agronomic practices were consistent across treatments, consisted of (i) a 5:1 *jajar legowo* method, which is a rice-planting method where one out of six plant rows remains empty (to allow better sunlight penetration and facilitate easier plant management), (ii) a trench in the middle of the plots, and (iii) the System of Rice Intensification (SRI) planting method. The practice of SRI consisted of (i) a plant spacing of 25 x 25 cm, which is wider than the common spacing of less than 20 x 20 cm, (ii) transplanting of only 10 days-old single rice seedlings, and (iii) intermittent flooding at early stages of rice growth and was kept flooded from 30 days after transplanting (DAT) until two weeks before the rice was harvested.

The conventional treatments received artificial fertilisers (AF) consisting of 206 kg N ha^{-1}, 81 kg P ha^{-1} and 105 kg K ha^{-1} from *Phonska* (N-P-K: 15-15-15), SP-36 (36% P), KCl (65% K), urea (46% N) and ZA (21% N). *Phonska*, SP-36 and KCl were applied at 5 DAT. Urea and ZA were applied three times at 5, 20, and 50 DAT. Details about the use of pesticides and herbicides are given in Annex Table A3–A6.

Organic plots were treated with duck and green manure without herbicide applications but bio-pesticides were sprayed with frequencies and timing similar to those in conventional plots (Annex Tables A3.3 - A3.6). In CRSs, the percentage of organic fertilisers that was imported from outside the farm was 62% in the first cycle, 29% in the second cycle and 22% in the third cycle. The remaining organic fertilisers were produced on-farm from azolla, sun hemp and animal manure. The description, cultivation and integration methods of the components in the first cycle followed the integration methods described in Chapter 2 except for planting spaces, border plants, fences and fertilisers. Another difference in the current experiment was inoculation of azolla was not supported by artificial-phosphor fertilisers.

CRSs design was slightly adjusted throughout the rice-growing cycles. Sun hemp (*Crotalaria juncea*), vegetables and fruit were grown two weeks before sowing rice seed. In the second cycle, 90% of planted sun hemp was cut every month after the first cut (45 days old) and incorporated into the soil as green manure or dried for feed. The remaining 10% was left to produce flowers and seeds. Due to the low survival rate of fingerlings in the first and second cycles, leading to low fish yields, fish ponds were deepened and widened. Fingerlings changed to adult fish (four to five months old and about 200 gr per fish) to be released in CRS plots. The adult fish density was 500 fish per hectare that can produce fingerlings between 5-10 days after release. Fingerlings that hatched on the rice field could immediately adapt to the environment, which is a crucial factor for successful fish production.

Duck houses were constructed on the bund surrounded by sun hemp. Straw from previous cropping was heaped next to the duck house and pond to be decomposed and later eaten by fish. The total amount of feed supplied to one duck for the duration of 155 days was approximately 20 kg (Annex Table A3.8). In the first cycle, all duck feed was imported, but in the second and third cycles ducks were fed rice bran and corn from previous cycles. Sun hemp and azolla also provided feed for ducks and fish. The ducks also preyed on wild animals and plants, such as weeds, snails, crabs, tadpoles and insects.

3.2.3. Measurements and statistical analysis

3.2.3.1. Weather data

During the experiment, all weather data were recorded using the weather station installed on each experimental farm. Weather conditions of three rice growing cycles in the experimental sites are provided in Figure 3. The precipitation amounts during the experiment were significantly different among growing cycles ($F_{(2,11)}$ = 7.308, P = 0.013), in which growing cycle 2 was the driest, while cycle 3 was the wettest, and cycle 1 was slightly drier than cycle 3.

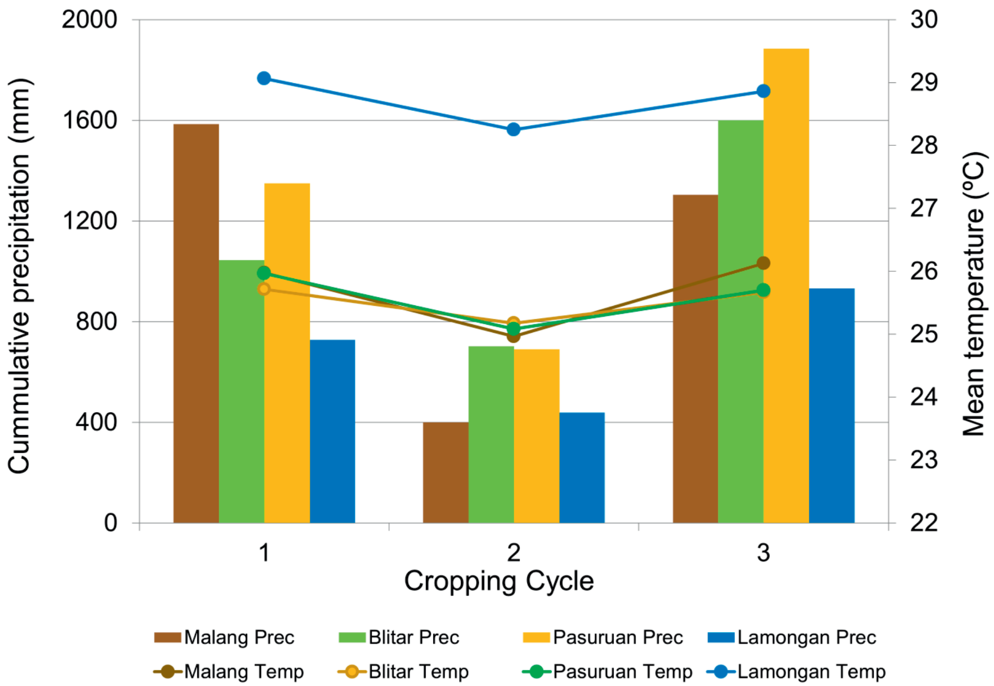

Figure 3. Weather conditions (cumulative precipitation and mean temperature) during the three rice growing cycles of experiment in the four experimental locations in Regencies of East Java Province, Indonesia.

3.2.3.2. Labour inputs

Labour inputs were recorded and presented in Annex Figure A3.1. In general, artificial fertilisers were applied three times during one rice growing cycle in conventional systems, but only once in organic systems, at three to five days before transplantation of rice plants at the second ploughing stage. Fertiliser application in CRS was similar to that in organic plots but the sources were partly supplied by sun hemp and azolla. Labour inputs for weeding and pests management included: (i) agro-chemical applications and hand weeding in conventional, (ii) spraying bio-pesticides and hand weeding in organic and (iii) animal management in CRSs.

3.2.3.3. Measurement of plants and animals

Rice yield was measured by harvesting 6.25 m^2 of rice plants in the middle of the plot at harvesting time. Rice grain was removed from the straw and placed in paper bags to be dried in an oven at 80°C for 48 hours and weighed to obtain the dry matter yield of rice kernels. Fresh weight of fish, ducks and eggs were determined at the end of each cycle. A sample of sun hemp plants was oven dried at 80°C for 48 hours and weighed to record the dry matter mass. Kangkung (*Ipomoea aquatic*) was harvested three times during one rice-growing cycle.

3.2.3.4. Pests and natural enemies assessment

Insects and natural enemies were collected using fine nylon cloth sweep net to assess their abundance. The sweep net was 35 cm in diameter and had a 65 cm length handle. Sweeping was done around 180° from the plant canopy level to the basal region of the plants. Ten nets were swept in each plot at 90 DAT and the insects were kept in a clear bottle containing 75% alcohol. Snails were collected from 1 m^2 of surface soil, washed and counted.

3.2.3.5. Statistical analysis

We tested the normal distribution of data using the Shapiro-Wilk, Skewness and Kurtosis tests. We used log10 and sqrt transformations where necessary. Analysis of variance (ANOVA) was performed to test the experimental treatment effects followed by Tukey's and LSD post-hoc tests to establish significant differences between treatments. Statistical tests were conducted with SPSS 23 software package (SPSS Inc., Chicago, Illinois, USA). We visualized interactions between rice yields, environment, rice production systems and labour inputs using the biplot function in the CANOCO 5 software for Windows.

We used static and dynamic stability analysis approaches in our study. A static approach evaluates rice yield stability across all environments (location*cycle), using the coefficient of variation (CV_i). Low values of CV_i are seen as desirable, implying a constant yield across targeted environments (Francis and Kannenberg; 1978; Lin *et al.,* 1986). A dynamic stability approach was assessed using Finlay and Wilkinson’s regression model (Finlay and Wilkinson, 1963; Borrelli, 2014). The slope of each rice production system was tested against the slope of the overall mean regression line (b = 1) using a t-test, assuming greatest stability for slopes closest to this line (Eskridge; 1990; Evans, 1993; Mühleisen, *et al.,* 2014). To generate a useful comparison to make recommendations, we calculated a yield reliability index (I) that combined yield stability and mean yield (Evans, 1993; Mühleisen, *et al.,* 2014; Kataoka, 1963). The calculation was adopted from Kataoko that takes into account the 'riskiness' of production systems (Ferney, 2006; Annicchiarico; 2002), which is specified as:

$I_i = m_i - Z_{(p)} * Si$,

where m_i is the mean yield of production system *i*, $Z_{(p)}$ is the percentile from the standard normal distribution that reached the value *P*. We defined *P* as a risk of the yield in production system *i* to fall below the mean yield of all production systems, ranging from $Z_{(100\%)} = 3.4$ to $Z_{(0\%)} = -3.4$. *Si* is the square root of the environmental variance that is expressed as:

$$Si = \sqrt{\sum_{i=1}^{n} (xi - x)^2 / (n-1)}$$

where x_i is the yield of production system *i* in a certain environment, x is the mean yield of production system *i* across all environment, and n is the number of environmental combinations.

3.3. Results

3.3.1. Rice yield stability and reliability

Rice yields in our experiment were significantly influenced by all experimental factors (locations, cycles, production systems) and their interactions at *P* level < 0.001. The weather conditions in the second cycle were favourable. Thus, rice yields of the conventional production systems in the second cycle were higher than the first and third cycle ($F_{(2,33)} = 7.979$, $P = 0.001$; Figure 1), and ranged from 6.9 to 9.5 Mg ha^{-1}. Under the favorable weather conditions of the second cycle, conventional yields were generally higher than in the organic system ($F_{(2,33)} = 48.366$, $P < 0.001$) and ranged from 4.7 to 5.6 Mg ha^{-1}. However, the yields of conventional were not higher than second cycle yields in CRS which ranged from 7.6 to 10.0 Mg ha^{-1} (Figure 1).

The values and statistic assessment of the yield stability are presented in Table 1. Although unfavorable conditions also affected yields in CRSs, these yields were still consistently above the mean yield across all systems (Figure 1). This resulted in a low CV_i in CRS ($CV_i = 0.14$), indicating good static stability. The slope value of CRS was also not significantly different from one in the dynamic stability assessment, demonstrating a stable system.

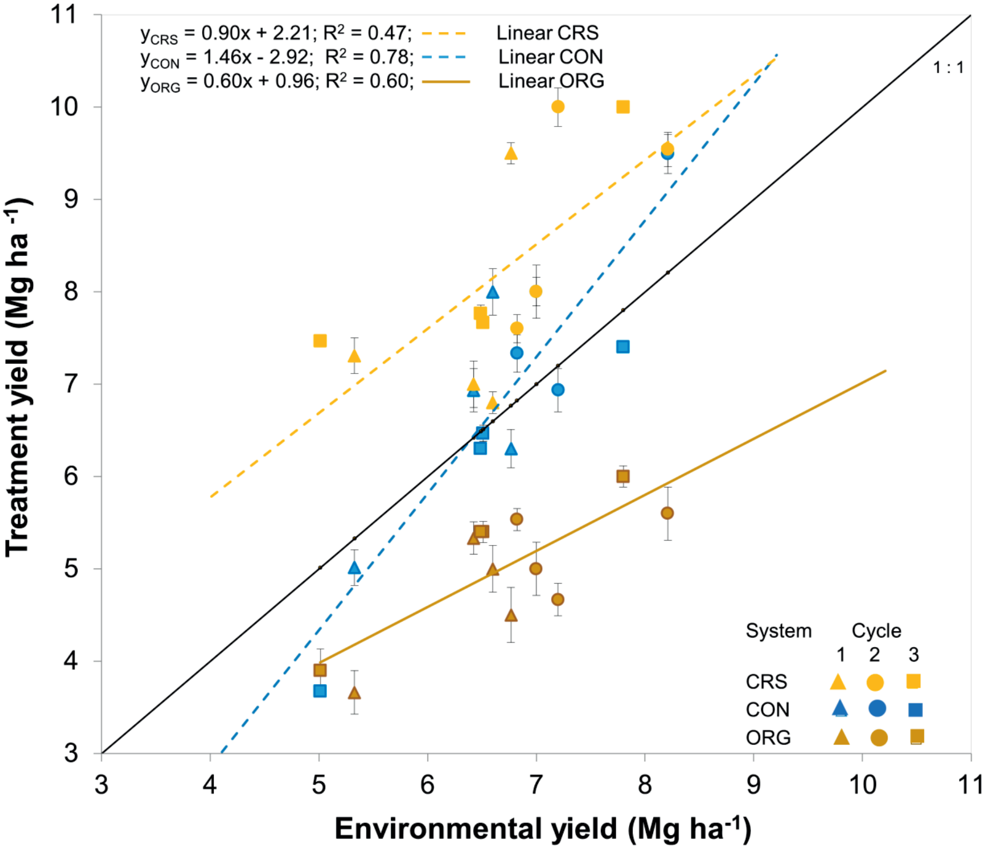

Figure 1. Dynamic yield stability, showing the relationship of rice yields in the three production systems and the environmental mean yields. ORG, organic system; CON, conventional system; CRS, complex rice system. The black line indicates a regression line with slope = 1. The brown line represents the regression line of the yields in the ORG treatments, with a slope significantly lower than 1. The dashed blue and yellow lines represent the regression line of the yields in the CON and CRS treatment respectively, with slopes not significantly deviating from 1.

In contrast, the yields in conventional systems were very sensitive to environmental variations, with remarkably high yields in favourable environments and much lower yields under unfavorable condition. This variability resulted in a high CV_i of 0.22, demonstrating unstable yields according to the static concept. However, the yields in the conventional systems were significantly higher than the mean yields of organic systems ($F_{(12,72)}$ = 9.88, $P < 0.001$) and the slope in the dynamic stability assessment was not significantly different from one, indicating a stable system according to the dynamic concept. Subsequently, the effect of the environmental variations on rice yields in organic systems was small, indicated by a small CV_i of 0.14. Yields in organic systems were therefore stable according to the static concept. However, not only were the yields in the organic treatment consistently lower than the mean yield across all systems, but also the regression slope was significantly lower than one ($t_{(20)}$ = 2.60, P = 0.018), indicating dynamic instability.

Besides having both good static and dynamic stability, CRS had a higher reliability index (I = 12.3) than that in conventional system ($F_{(2,6)}$ = 75, P < 0.001; I conventional = 7.3). Although the static concept demonstrated that the organic yields were stable, their absolute yields were consistently lower than those in both CRSs and conventional systems, as indicated by a low reliability index (I = 2.6; Table 1).

Table 1. Static and dynamic stability analysis of the three rice production systems CV_i, coefficient of variance implies the static stability indices, the significant differences (*P* slope) of the three rice production system slopes to the slope of the mean (X = Y) suggest the dynamic stability. I denotes to reliability index (see Methods). CRS, complex rice system; ORG, organic; CON, conventional.

	N	Mean	SE	Slope	t	*P* slope = 1	Intercept	R^2	CV_i	I
CON	12	6.8	± 0.25	1.46	1.87	0.076	-2.766	0.78	0.22	7.3
ORG	12	5.0	± 0.15	0.60	2.58	0.018*	1.053	0.60	0.14	2.6
CRS	12	8.2	± 0.30	0.90	0.33	0.746	1.713	0.47	0.14	12.3

3.3.2. Interactions of weather conditions, labour input, rice yield and production system

The bi-plot in Figure 2 shows the interactions between weather conditions, growing cycle, labour input, production system and rice yield. Cycle 2 was associated with high yields and this high yield was strongly linked with CRS. Despite the strong relation with the yield variable, CRSs were negatively associated with labour inputs to control weeds and pests. In contrast, labour input for fertilization was also positively related to CRS. Furthermore, the bi-plot presents a negative correlation between yield and cycles 1 and 3 which were associated with high precipitation levels. This high precipitation in cycle 1 was positively correlated with high labour inputs for pest and weed control in conventional and organic systems.

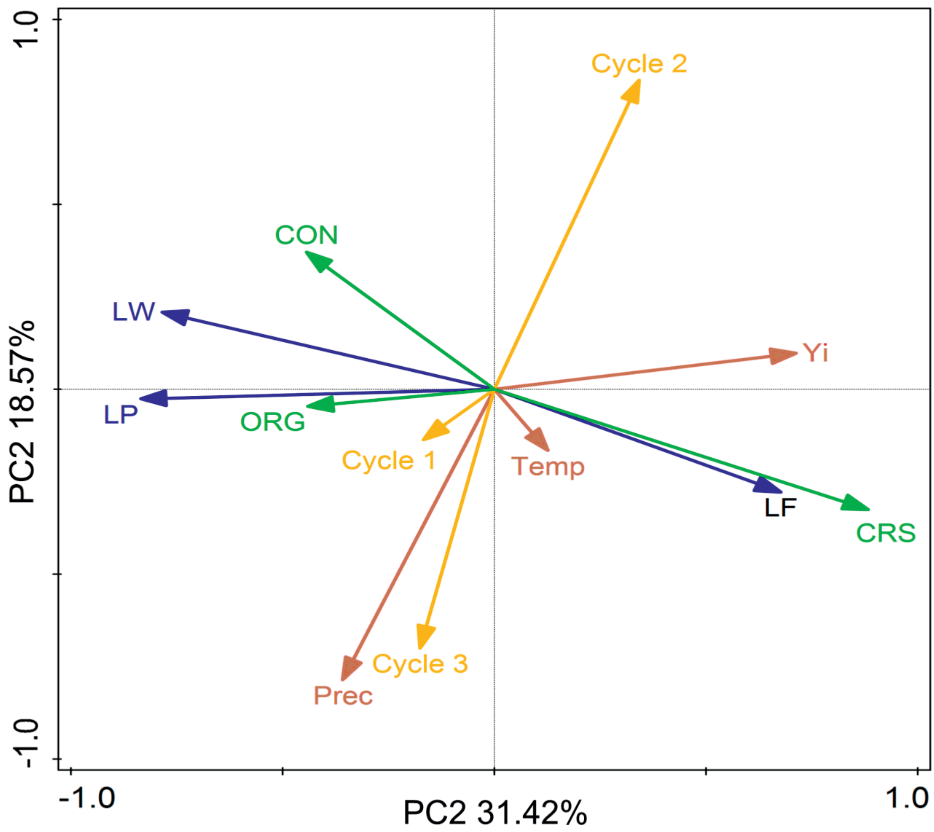

Figure 2. Biplot of the principal component (PC) analysis for the relationships between rice yields (Yi) with the three rice production systems (CON, conventional; ORG, organic; CRS, complex rice systems), labour inputs (LF, labour for fertilization; LP, labour for pest control; LW, labour for weed control), weather conditions (Prec, precipitation; Temp, temperature) and the growing cycle (1, 2 and 3).

3.4. Discussion

Notwithstanding the multiplicity of potential yield-reducing factors, we observed that extreme weather events coincided with pest outbreaks, such as plant hoppers and stem borers during the first and third cycle (Annex Table A3.1). These patterns provided a highly variable weather scenario suitable to test resilience of our three systems. Under variable conditions and with the occurrence of extreme events, the most stable system is not necessarily the system with the highest mean yield. In general, CRSs had the highest mean yield and yields were less affected by unfavorable environments than for the other treatment. Likewise, although the yields in organic were lower than in conventional, however, rice yields were reduced less severely than in the conventional treatment during bad cropping cycles. Nevertheless, the strength of this treatment effects varied by location and between cropping cycles.

In Malang, for example, CRS, organic and conventional yields in the first cycle were 23%, 35% and 47% lower, respectively, than in the second cycle ($F_{(2,6)} = 28.824$, $P = 0.001$). Whereas, in the third cycle, reductions of CRS, organic and conventional yields were 22%, 30% and 61% lower, respectively than in the second cycle ($F_{(2,6)} = 64.871$, $P = 0.001$). The use of bio-pesticides in the organic systems might have been less harmful to natural enemies than by the use of chemical pesticides in conventional rice production. This may help to maintain higher levels of natural enemies (Annex Table A3.2), partly protecting rice plants from pests during unfavourable cycle (Tiwari *et al.,* 2011; Stark, 2013). Besides, organic cropping system obviously eliminates the dependency on agro-chemicals (Annex Tables A3.3 - A3.5), resulting in smaller negative impacts to the environment than conventional systems.

The CRSs appeared to be most resilient to the impacts of extreme weather events on rice yields, by integrating flora and fauna resulting in ecosystem functions of weed and pest suppression and increased nutrient cycling. The feeding and movement behavior of the ducks and fish, combined with the presence of refugia can facilitate natural enemies to control pests and weeds, thereby also reducing labour inputs. The labour input for fertilization in CRS might high, which was allocated to manage green manure biomass, including activities such as cutting, drying and soil incorporation. However, the total labour inputs were much less than those in conventional and organic. The higher the quantity of green manure produced in CRS, resulted in the higher reduction imports of fertilisers (Annex Table A3.3).

In our CRS, duck manure, azolla and sun hemp support the ecosystem function of nutrient cycling (Annex Tables A3.3 and A3.6), which is further accelerated by the ducks and fish activities. Besides, the activities of ducks and fish can increase the oxygen supply which leads to better rice root growth and nitrogen uptake (Xie *et al.*, 2011; Xu *et al.* a, 2017; Xu *et al.* b, 2017). Higher root density increased nutrient uptake to enhance rice yields and might reduce pollutions. Moreover, adding components and outputs to the system such as duck, fish, egg, string bean, corn, taro and papaya could contribute to the stability of whole farm production, especially when one commodity fails during unfavourable weather conditions (Annex Table A3.7).

Our results show that the occurrence of extreme weather events is a deciding factor in reducing rice yields and indeed potentially threatening the stability of global production. The results also revealed that common practices in rice production systems, such as the use of chemicals and extra labour inputs for weeding and pest control, were ineffective to suppress weeds and pests during unfavorable weather conditions to the same degree as in CRSs (Annex Tables A3.4, A3.5 and A3.6; Annex Figure A3.1). Possible explanations for ineffectiveness of pesticides include (i) rain-induced run-off of pesticides, (ii) alkaline hydrolysis and degradation of pesticides to an inactive form, as induced by fluctuations in temperature and water pH, and (iii) phyto-toxicity of some pesticides induced by high temperatures (Akira, 1987; Damalas and Eleftherohorinos, 2011). These effects may be further aggravated in practical situations on smallholder farms, since illiteracy and suboptimal managerial skills of smallholders may cause improper application timing, pesticide mixing and pest identification.

We conclude that CRSs are resilient to the effects of extreme weather events and provide flexible mechanisms to control weeds and pests in unfavourable weather conditions, thus providing more robustness compared to other rice production systems. Finally, the stable and reliable yields of CRSs across strongly contrasting locations in our experiment show that the design is scalable and replicable, warranting out-scaling and prioritizing to other rice producing countries. This can contribute to reducing smallholder risks, while maintaining rice productivity and yield stability to safeguard national food security under climate change.

Annex 3

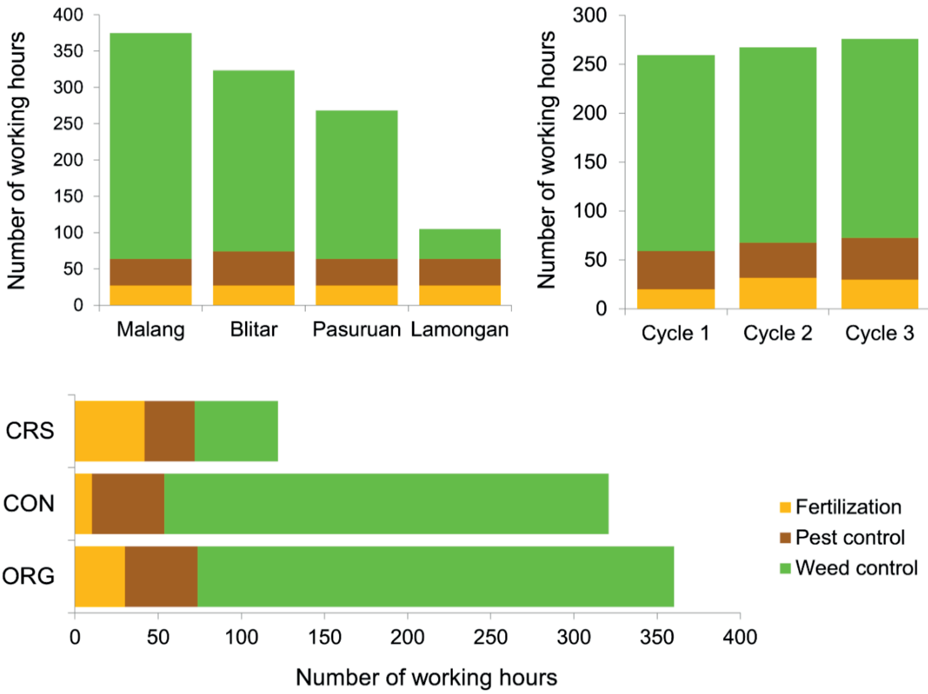

Figure A3.1. Labour inputs for fertilization, pest and weed control averaged for (a) the four locations of our experimental sites in East Java, (b) the first, second and third rice cultivation cycle, and (c) the three rice production systems; CRS, complex rice system; CON, conventional; ORG, organic. The different colors indicate tasks of fertiliser application, pest control and weed control.

Table A3.1. Major pest abundance in rice cultivation experiments during three cultivation cycles in four locations in East Java, Indonesia. The treatments represent alternative rice cultivation systems of CON: conventional, ORG: organic and CRS: complex rice system.

		Stem borers	Leaf folder	Worl maggot	**Brown plant hopper**	Rice bug	Case worm	Grass hopper	Green hopper	Snails
Location	Lamongan	4.37 b	1.11 a	1.37 b	9.74 c	3.89 b	0.96 a	4.11 b	2 b	14.81 c
	Pasuruan	6.44 c	3.93 c	0.81 a	4.15 b	7.89 c	1.52 bc	5.81 c	2.7 c	9.74 b
	Malang	3.81 a	3.67 bc	2.03 c	1.44 a	2 a	1.7 c	3.22 a	1. 33 a	10.30 b
	Blitar	4 ab	3.19 b	2.78 d	4.70 b	10.93 d	1.07 a	3.11 a	2.6 c	0 a
	df	(3,72)	(3,72)	(3,72)	(3,72)	(3,72)	(3,72)	(3,72)	(3,72)	(3,72)
	F	110.111	52.93	53.769	176.121	238.862	7.28	37.32	18.49	345.865
	P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cycle	1	0 a	0.94 a	1.06 b	1.57 b	3.33 c	1.19 a	3.72 b	2.36 a	8.44 a
	2	0.36 a	0.44 a	0.56 a	1.16 a	2.42 a	0.97 a	2.67 a	2.03 a	8.17 a
	3	13.61 b	7.53 b	3.64 c	2.4 c	9.28 b	1.78 b	5.81 c	2.06 a	9.53 b
	df	(2,72)	(2,72)	(2,72)	(2,72)	(2,72)	(2,72)	(2,72)	(2,72)	(2,72)
	F	5997.41	675.1	273	195.847	313.505	13.46	81.303	2.18	6.131
	P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.003
Treatment	CON	6.25 c	3.75 b	1.94 b	8.56 c	7.69 b	1.42 b	5.06 b	3.39 c	11.06 b
	ORG	5.53 b	3.44 b	1.97 b	5.36 b	8.19 b	1.81 c	4.75 b	2.17 b	11.56 b
	CRS	2.19 a	1.72 a	1.33 a	1.11 a	2.64 a	0.72 a	2.39 a	0.89 a	3.53 a
	df	(2,72)	(2,72)	(2,72)	(2,72)	(2,72)	(2,72)	(2,72)	(2,72)	(2,72)
	F	466.564	51.63	13	524.39	187.367	23.42	67.877	99.607	239.765
	P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Table A3.2. Natural enemy abundance in rice cultivation experiments during three cultivation cycles in four locations in East Java, Indonesia. The treatments represent alternative rice cultivation systems of CON: conventional, ORG: organic and CRS: complex rice system.

		CON	ORG	CRS	df	F	*P*
Cycle 1	Lamongan	19±4	57±1	51±3	(2,6)	50.41	<0.001
	Pasuruan	9±2	36±3	31±3	(2,6)	32.78	0.001
	Malang	23±3	36±9	55±2	(2,6)	17.15	0.003
	Blitar	11±1	22±1	20±1	(2,6)	26.68	0.001
	Mean	**16±3 a**	**37±7 b**	**39±8 b**	(2,33)	13.014	<0.001
Cycle 2	Lamongan	22±1	51±9	52±1	(2,6)	25.89	0.001
	Pasuruan	11±2	42±1	39±1	(2,6)	171.72	<0.001
	Malang	23±2	33±4	35±3	(2,6)	6.7	0.029
	Blitar	12±1	38±1	28±2	(2,6)	150.42	<0.001
	Mean	**17±3 a**	**41±4 b**	**39±5 b**	(2,33)	33,26	<0.001
Cycle 3	Lamongan	15±3	52±2	54±2	(2,6)	83.89	<0.001
	Pasuruan	12±1	61±3	56±2	(2,6)	155.79	<0.001
	Malang	13±3	54±2	48±3	(2,6)	87.46	<0.001
	Blitar	9±1	23±2	20±1	(2,6)	44.46	<0.001
	Mean	**12±1 a**	**47±8 b**	**45±8 b**	(2,33)	28,6	<0.001

Table A3.3. Sources and amounts of fertiliser application in three rice cultivation systems of conventional, organic and complex of experimental field farms in four locations in East Java, Indonesia.

Cycle	Conventional					Organic					Complex rice system				
	Sources	Amount (kg ha^{-1})	N	P	K	Sources	Amount (kg ha^{-1})	N	P	K	Sources	Amount (kg ha^{-1})	N	P	K
											External				
1	Urea (46% N)	350	161			Compost+GM	6750				Compost+GM	4200			
	ZA (21% N)	0				3 % N		203			3 % N		126		
	Phonska					1% P_2O_5			68		1% P_2O_5			42	
	15-15-15:N-P-K	300	45	45	45	0.9% K_2O				61	0.9% K_2O				38
	SP-36 (36% P2O5)	100		36							**Internal**				
	KCL (65% K_2O)	100			60						Duck's manure	5930			
											1,3 % N		77		
											1,4% P_2O_5			85	
											1 % K_2O				59
	Total		**206**	**81**	**105**		**6750**	**203**	**68**	**61**		**10130**	**203**	**127**	**97**

Table A3.3. (continued) Sources and amounts of fertiliser application in three rice cultivation systems of conventional, organic and complex of experimental field farms in four locations in East Java, Indonesia.

Cycle	Conventional					Organic					Complex rice system				
	Sources	Amount (kg ha^{-1})	N	P	K	Sources	Amount (kg ha^{-1})	N	P	K	Sources	Amount (kg ha^{-1})	N	P	K
2	Urea (46% N)	225	104			Compost+GM	6750				**External**				
	ZA (21% N)	275	58			3 % N		203			Compost+GM	2000			
	Phonska					1% P_2O_5			68		3 % N		60		
	15-15-15:N-P-K	300	45	45	45	0.9% K_2O				61	1% P_2O_5			20	
	SP-36 (36% P_2O_5)	100		36							0.9% K_2O				18
	KCL (65% K_2O)	100			60						**Internal**				
											Duck's manure	5930			
											1,7 % N		101		
											1,5% P_2O_5			89	
											1 % K_2O				59
											Sun hemp	1500			
											3,5 % N		45		
											0,46% P_2O_5			7	
											1,47% K_2O				22
	Total		**206**	**81**	**105**		**6750**	**203**	**68**	**61**		**9430**	**206**	**116**	**99**

Table A3.3. (continued) Sources and amounts of fertiliser application in three rice cultivation systems of conventional, organic and complex of experimental field farms in four locations in East Java, Indonesia.

Cycle	Conventional					Organic					Complex rice system				
	Sources	Amount (kg ha^{-1})	N	P	K	Sources	Amount (kg ha^{-1})	N	P	K	Sources	Amount (kg ha^{-1})	N	P	K
3	Urea (46% N)	350	161			Compost+GM	6750				**External**				
	ZA (21% N)	0				3% N		203			Compost+GM	1500			
	Phonska					1% P_2O_5			68		3 % N		45		
	15-15-15:N-P-K	300	45	45	45	0.9% K_2O				61	1% P_2O_5			15	
	SP-36 (36% P_2O_5)	100		36							0.9% K_2O				14
	KCL (65% K_2O)	100			60						**Internal**				
											Duck's manure	5930			
											2 % N		119		
											1,5% P_2O_5			89	
											1 % K_2O				59
											Sun hemp	1200			
											3,5 % N		43		
											0,46% P_2O_5			6	
											1,47% K_2O				18
	Total		**206**	**81**	**105**		**6750**	**203**	**68**	**61**		**8630**	**206**	**109**	**90**

Table A3.4. Types and amounts of active ingredients of herbicide application in conventional plots at four locations for three rice cultivation cycles.

Site	Name of Active Ingredient	Amount (g ha^{-1})		
		Cycle 1	Cycle 2	Cycle 3
Lamongan	2,4-D isopropil amina	1038	692	1038
	Total	1038	692	1038
Pasuruan	2.4DMA	169	149	176
	Metil Metsulfuron	22	25	29
	Metil Klorimuron	22	25	29
	Triasulfurom	23	16	27
	Total	236	214	261
Malang	Paraquat	275	275	275
	Ipa Glifosat	243	243	486
	2.4DMA	635	568	568
	Metil Metsulfuron	34	23	23
	Metil Klorimuron	34	23	23
	Triasulfurom	23	23	23
	Total	1243	1153	1396
Blitar	Ipa Glifosat	486	243	486
	2.4 DMA 865 gr/L (DMA, 0,5 L)	433	433	433
	2.4DMA	635	568	635
	Metil Metsulfuron	34	23	34
	Metil Klorimuron	34	23	34
	Triasulfurom	23	23	23
	Total	1644	1311	1644

Table A3.5. Active ingredient types and amounts of pesticide application in conventional plots in four experimental sites at three rice cultivation cycles.

District	Name of Active Ingredient	Amount ($g\ ha^{-1}$)		
		Cycle 1	Cycle 2	Cycle 3
Lamongan	Difenokonazol	173.0	173.0	173.0
	Azoxistrobin	100.0	100.0	100.0
	Total	273	273	273
Pasuruan	Difenokonazol	125.0	125.0	187.5
	Fopronil	25.0	25.0	37.5
	Deltamethrin	18.8	18.8	18.8
	Alfametrin	15.0	15.0	15.0
	Klorantraniliprol	40.0	40.0	40.0
	Total	224	224	299
Malang	Karbofuran	240.0	240.0	240.0
	Difenokonazol	125.0	125.0	188.0
	Fopronil	25.0	25.0	37.5
	Deltamethrin	12.5	12.5	18.8
	Endosulfan	175.0	175.0	262.5
	Kumatetralil	7.5	1.5	7.5
	Total	585	579	753
Blitar	Klorotalonil	375.0	375.0	562.5
	Difenokonazol	226.0	226.0	226.0
	Azoxistrobin	61.5	61.5	61.5
	Permetrin	100.0	100.0	100.0
	Klorotaloni	10.0	10.0	10.0
	Total	773	773	960

Table A3.6. Summary of farm works performed for fertilization, weed and pest management in the three rice production systems, CON: conventional, ORG: organic and CRS: complex rice system.

	CON	ORG	CRS	
Fertilization				
Sources	External	External	External	Internal
Form	AF	AGM	AGM	A, Cj, AE
Application	HS	HP	HP	CI & AA
Frequency	3	1	1	3 & AT
Done by	FW	FW	FW	FW & A
Weed management				
Sources	External	External	External	Internal
Form	H	M	M	M
Application	HS & HW	HW	HW & FD	AA
Frequency	3	3	1	AT
Done by	FM	FM	FM	FM & A
Pest management				
Sources	External	External	External	Internal
Form	P	N	N	N
Application	SP	SB	FD	AA & HM
Frequency	7-9	7-9	AT	AT
Done by	FM	FM	FM	A & N

Form of fertilisers: AF, artificial fertilisers; AGM, animal and green manure; A, azolla; Cj, *Crotalaria juncea* (sun hemp); AE, animal excreta. Form of weed management: H, herbicides; M, manual. Form of pest management: P, pesticides; N, natural. Application of fertilisers by: HS, hand spreading; HP, heaping and ploughing; CI, cut and incorporation; AA, animal activities. Application of weed management: HS, herbicides spraying; HW, hand weeding; FD, feeding ducks; AA, animal activities. Application of pest management: SP, spraying pesticides; SB, spraying biopesticides; FD, feeding ducks; AA, animal activities; HM, habitat management. Works done by: FM, farm workers; AA, animals; N, nature.

Table A3.7.. Alternative products in complex rice systems at four experimental sites over three rice growing cycles

	Pasuruan			Blitar			Malang			Lamongan		
	Cycle			Cycle			Cycle			Cycle		
	1	2	3	1	2	3	1	2	3	1	2	3
Fresh weight animal products (Mg ha⁻¹)												
Fish	0.34	0.72	1.7	0.71	0.76	0.76	0.29	0.41	2.65	0.57	0.64	1.25
Ducks	0.7	0.73	0.7	0.71	0.71	0.74	0.71	0.74	0.72	0.72	0.72	0.72
Eggs	0.06	0.07	0.07	0.05	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Fresh weight crop products (Mg ha⁻¹)												
Bean	0.45	0.43	0.46	0.51	0.46	0.45	0.68	0.72	0.41	0.74	0.61	
Tomatoes		0.54			0.57							
Taro			0.78									
Sweet Potatoes						1.45						
Kangkung									2.35			
Pak choy									0.75			
Fruit (Papaya)									0.24			
Shallot											0.13	
Cucumber											1	0.95
Gourd												1.25
Dry weight green manure/ feed (Mg ha⁻¹)												
Sun hemp	0.67	2.14	1.53	0.65	2.02	1.44	0.66	2.08	1.47	0.69	2.08	1.61

Table A3.8. Feed sources and total amounts of feed for ducks from 0-154 days old in complex rice systems during three cultivation cycles in four locations in East Java, Indonesia.

Sources	Amount of feed per duck (Kg)	Total feed for 400 ducks (Kg)		
		External	Internal	Total
Rice bran	8.75	300	3200	3500
Dried rice	2.24	896		896
Corn	2.17	268	600	868
Dried fish	0.21	84		84
Sun hemp	5.9		2360	2360
Azolla	2.4		960	960
Total (Kg)	21.67	1548	7120	8668
Rice bran	8.75	300	3200	3500
Dried rice	2.24	896		896
Corn	2.17	268	600	868
Dried fish	0.21	84		84
Sun hemp	5.9		2360	2360
Azolla	2.4		960	960
Total	21.67	1548	7120	8668

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Chapter 4

Ecological mechanisms for weed and pest suppression and nutrient recycling in high yielding complex rice systems

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Abstract

Recent research has revealed that complex rice systems (CRSs), in which several plant and animal species, including azolla, fish, ducks and border plants have been integrated, can produce high and stable rice yields over time. However, the mechanisms that support these benefits have not been examined in detail. On-farm experiments were conducted in Indonesia during five rice cropping cycles. We compared three monoculture rice systems receiving chemical or organic inputs, and four organic polyculture rice systems that varied in level of complexity. To investigate the ecological mechanisms of weed and pest suppression and nutrient cycling that determine rice productivity and stability, the dynamics of weeds, pests, nutrients, and rice yields were monitored and related to rice system complexity. The observations revealed that increasing the level of complexity resulted in lower levels of weed and pest infestation. Analysis of duck behaviour and their gizzard composition showed that ducks foraged intensively on weeds, insects, snails and azolla. Furthermore, nutrient cycling was accelerated by ducks via feeding and excretion as well as by their movement in the field. This could explain why rice yields increased along the gradient of complexity, and overall were higher and less variable in the most complex systems in comparison to the rice monocultures. In complex rice systems, increasing the number of species that are compatible to the rice ecosystems and could play a role in generating ecosystem services of weed and pest suppression as well as nutrient recycling, can lead to higher and less variable rice yields.

Key words: analyses of ecological interactions, duck behaviour, ecosystem functions, functional groups of species, functional redundancy, multispecies interactions, rice yield and stability.

4.1. Introduction

The majority of rice fields worldwide are wetlands surrounded by bunds, which are soil constructions that serve to preserve water and to reduce run-off. These bunds are attractive habitats for flora and fauna that require access to both water and land to thrive (Cardarelli and Bogliani, 2014). Prior to the widespread adoption of green revolution technologies in the 1970s, these biodiversity-rich fields were important for the livelihood of rural households as a source of diverse foods and for medicinal purposes (Garaway *et al.,* 2013). Although rice yields from these traditional systems were low (less than 3 Mg ha^{-1} per cultivation cycle), productivity was rather stable due to the use of local cultivars that usually were tolerant to drought and floods. The ecological interactions in the biodiversity-rich agroecosystems and the use of fallow periods following rice harvesting interrupted pest life cycles and could prevent the recurrence of pest outbreaks, thus providing a mechanism to stabilize yields (Litsinger, 2008; Altieri *et al.,* 2015; Brzezina *et al.,* 2016).

In Indonesia, pest outbreaks became more frequent following the introduction of the green revolution in the early 1970s (Mariyono, 2015). The revolution has intensified monoculture practices as well as the use of agrochemicals. Herbicides and pesticides are often ineffective due to extreme weather conditions that can result in their washing off by rainfall or undesirable chemical reactions at high temperatures, leading to phytotoxicity (Zeng & Liu, 1999; Zwertvaegher *et al.,* 2017). Most rice farmers respond to this reduced ineffectiveness by increasing the dosage and frequency of agrochemical application, leading to pest and weed resistance to the herbicides and pesticides and resurgence of secondary pests (Cordeiro *et al.*, 2013; Thornburn, 2015). In addition, on average approximately 20% of the applied nitrogen in chemical fertilisers is lost as ammonia (NH_3) to the air (Wang *et al.,* 2018) or through surface run-off during flooding (Wang *et al.,* 2015).

With the recent rise of extreme weather occurrences, chemical use ineffectiness enhanced pest outbreak and nutrient loss incidences, reducing the yields and the yield stability of many important food crops such as rice and threatening global food security and farmers' livelihoods (Schmidhuber, 2007; Zhao *et al.,* 2017). Given the current practices of conventional rice monoculture systems, it is questionable whether they will be sustainable in the long-term. Alternatively, it might be worthwhile to examine traditional polyculture systems and consider more recent improvements to these systems in order to deal with pest, disease and nutrient deficiency problems in ecologically sound ways.

Several studies have demonstrated that traditional rice polycultures such as rice-azolla, rice-fish and rice-duck could reduce agrochemical use while gaining similar rice yields as those in conventional monoculture systems which received agrochemicals (Kathiresan, 2007; Xie *et al.,* 2011; Long *et al.,* 2013; Fuller *et al.,* 2015). The presence of azolla fern on the water surface of rice fields could reduce weed biomass by 10% to 22% (Biswas, 2005). Meanwhile, according to Sinhababu (2013), fish could suppress weeds by 23% to 63%. Brogi *et al.* (2016) discovered that duck integration could reduce about 27% to 91% of weeds on rice fields.

In addition to weed suppression, Xie *et al.* (2011) reported that fish can also suppress pests like plant hoppers and fungal diseases like sheath blight by touching rice tillers, making insects and dew drops fall into the water and subsequently foraging on those falling insects; and by disrupting fungal mycelia in the water. Ducks have an even greater range of prey species than fish, as they also prey on stem borers, leafhoppers, leaf folders and other major rice pests and diseases (Long *et al.,* 2013).

Integrating ducks and fish into rice crop systems could also increase nutrient recycling through their feeding and excretion activities. The azolla, uneaten duck feed and excreted undigested feed can decompose, mineralise and release nutrients to support rice growth and development (Ali *et al.,* 1998; Ghosh, 2004; Qin *et al.,* 2010; Xie *et al.*, 2011; Long *et al.,* 2013). Furthermore, since azolla flourishes on the water and soil surface, it could reduce ammonia volatilisation from the rice fields (Vlek *et al.,* 1995; Xu *et al.,* 2017).

Given the great synergic opportunities of the species associations, it is surprising that only a few studies have explored the potential of optimal combination of all these elements in rice cropping systems. Cagauan (2000) studied the azolla, fish and duck combination in rice crop systems and focused on rice yields and economic benefits. Khumairoh *et al.* (2012) further developed this innovation by adopting selected rice cultivation methods from the system of rice intensification (SRI). The resulting diversified rice systems later became known as complex rice systems (CRSs). The results of CRS experiments revealed that greater yields were consistently attained from the systems which had a higher level of complexity (Khumairoh *et al.,* 2012). However, the ecological mechanisms that sustain high rice yields and their yield stability by increasing the number of integrated species in rice systems have not yet been investigated in a comprehensive way.

In the present study, we examine the effects of increasing the complexity in rice systems, including monocultures and polycultures in which several plant and animal species were integrated and how the integration can influence the weed, pest and nutrient dynamics. Three experiments, both short and long term were performed with the aim of investigating the ecological mechanisms governing rice yields and yield stability.

4.2. Methods

4.2.1. Material and methods

Three on-farm field experiments were conducted to investigate the effects of multispecies interactions on ecological processes in CRSs. Experiments were carried out over five cultivation cycles from 2013 to 2016 on Inceptisol-silty clay soil in the Kepanjen sub-district of Malang, East Java, Indonesia (8°09′11.82″S - 112°34′33.32″E).

4.2.1.1. Experiment 1: The roles of plant and animal species in rice cultivation systems

Experiment 1 focused on the effects of increasing the level of complexity of polycultures on the abundance of pests, natural enemies, weed biomass, density and nutrient dynamics, with special attention being given to the role of ducks.

In this experiment we used rice (*Oryza sativa*, Var. Ciherang), a nitrogen-fixing azolla fern (*Azolla microphylla*), Nile tilapia fish (*Oriochromis nilotichus*), local ducks (Anas *Platyrhynchos javanicus*) and sun hemp (*Crotalaria juncea*). The cultivation of rice, border plant and animal management, and their integration methods were in accordance with those described in Chapter 2 and Chapter 3. Artificial and organic fertilisers were applied three times: 10, 40 and 70 days after rice transplanting (DAT). Annexes Table A4.1a-c indicate the amounts of fertiliser, pesticide and herbicide which were applied. Sun hemp was sown on the rice bunds two weeks prior to rice transplantation.

The experiment consisted of seven treatments that were randomised in three replicate blocks. Each plot measuring 100 m^2 was surrounded by a one metre wide bund on which sun hemp was grown. The seven treatments were: (1) conventional rice receiving inputs of artificial fertilisers, herbicides and pesticides (CON); (2) rice without fertilisers, herbicides and pesticides (R); (3) organic rice receiving organic fertilisers (ORG); (4) organic rice and azolla (ORGA); (5) organic rice, azolla and fish (ORGAF); (6) organic rice, azolla and ducks (ORGAD) and (7) organic rice, azolla, fish, ducks and border plants (CRS). Blocks were separated by three bunds and two trenches to filter water in and out. Four bamboo bridges measuring 4.5 m were on all four sides of each plot to connect the bunds with the middle of the plots, which enabled sampling to be carried out without disturbing soil and water. The experiment was conducted during two cropping cycles. However, we only performed measurements during the second cycle when all the elements were well integrated. A digital weather station was installed in the middle of the experimental field.

Weeds were collected at 20, 40 and 65 DAT from four quadrants measuring 0.25 m^2 per plot. They were rinsed in clean water, identified, separated according to species, and counted. The samples were then oven dried at 75°C for 48 hours and weighed to determine dry matter mass. Arthropod pests and natural enemies were collected at 30, 65 and 90 DAT using a sweep net, identified and counted, whereas snails were collected from four quadrants measuring 0.25 m^2 per plot, following the method described in Chapter 2. At the same time, the damage caused to plants by stem borers was recorded. Samples of stem borer attacks were taken from three rows of rice hills per plot; each row contained 11 hills. We calculated the proportion of damaged tillers.

Duck gizzard contents were removed from nine ducks and analysed for the presence of weeds and pests. Nine ducks of the ages of 35 days (ducklings), 55 days (young ducks) and 80 days (pre-adults) were taken from the field at 20, 40 and 65 DAT, respectively. The ducks were slaughtered, and the ingested contents were removed from the throats up to the gizzard and weighed. The samples were sieved (1 mm mesh size), and then the weeds, weed seeds, insects, crabs, snails, feed, gravel, and unrecognizable parts were separated. Finally, their weight proportions were calculated.

Duck behaviour (of both ducklings and adults) was monitored by two observers for 17 hours from 05.00 to 22.00. This was repeated three times on days during the same weeks when weather conditions were similar. Observations of the duck behavior were made during 10-minute periods with 5-minute intervals, amounting to 68 observations a day.

Nitrogen dynamics were examined by determining the amount of nitrogen of inputs and outputs of all integrated plant and animal yields (Annex Table A4.2), as well as assessing the decomposition rates (see Annex Method), ammonium (NH_4^+) and nitrate (NO_3^-) concentrations in soil and water, ammonia (NH_3) volatility and NO_3^- leaching. Samples of soil and water were taken at 15, 30, 45, 60, 75, 90 and 110 DAT to assess NH_4^+ and NO_3^- concentrations. Soil cores were taken at 0 to 20 cm from soil surface at nine points per plot, put into plastic bags, and mixed. A handful of samples was taken for analysis. Samples of water were taken using a syringe and stored in plastic bottles. Both water and soil samples were kept in a refrigerator for one day prior to transportation to the laboratory. Nitrogen was measured in both soil and water samples using a spectrophotometer (PerkinElmer® LAMBDA XLS and XLS+ UV/Vis).

Nitrogen losses were estimated by means of NH_3 volatilisation and NO_3^- leaching. NO_3^- leachate was collected for seven days subsequent to the application of fertilisers using modified polyvinyl chloride (PVC) lysimeters (inner diameter 3.2 cm; length 25 cm) that were installed 25 cm below the soil surface in each plot. The lysimeters consisted of an upper part (20 cm long and filled with clay soil from the field), a middle part (2.5 cm long filled with sand, and then covered with mesh at the lower end), and the bottom part (a 2.5 cm long cup connected to a hose which was raised to the surface) (Hua *et at.*, 2007).

Average NH_3 concentration was measured for five successive days following the first, second and third applications of fertilisers on each plot using diffusion samplers proposed by Hofschreuder and Heeres (2002). The samplers as described by Shah *et al.* (2012], had a cylindrical PVC tube (4.1 cm long and 1 cm diameter wide) with two stainless steel grids held by a cap with a rim at one end of the tube. The grids were coated with 60 µL of 10% (w/v) sulfuric acid (H_2SO_4) that was able to bind 9.1 µg NH_3 dissolved in 5 mL water. Filter paper was placed at the other end of the tube and secured by a perforated polyethylene cap (with a 1 cm diameter hole). In order to prevent contamination during transportation, the cap was covered by a PVC lid.

Three diffusion samplers per plot were installed vertically 20 cm apart in a wooden frame with the inlet (holed cap with filter) facing downwards. Wooden frames were placed in the middle of each plot. An identical control wooden frame was placed on the river bank, 100 m away from the experimental farm. Three more samplers remained in the lab's refrigerator and three others were put in a cool box during and after installing the other samplers. Altogether, we used 72 samplers per measurement.

After five days in the field, samplers were collected and stored in a refrigerator for analysis the following day. The NH_3 absorbed by sulfuric acid in the stainless steel grids was dissolved in 5 mL distilled water and the solution was analysed for NH_4^+ using the Nessler method (Jeong *et al.,* 2013). Subsequently, we calculated the amount of NH_3 which had been detected by using the equations developed by Hofschreuder and Heeres (2002) as well as used by Shah *et al.* (2012).

Duck excreta was collected separately from four duck age-categories: duckling (14-41 days), pre-young (42-70 days), young (71-94 days) and adult (> 95 days). The excreta collection was repeated to three ducks per each age-category over six time periods: 06.00-10.00, 10.10-14.10, 14.20-18.20, 18.30-22.30, 22.40-02.40 and 02.50-05.50 over 24 hours. Sackcloth covered the floor in three bamboo cages (50 x 50 x 50 cm^3). The ducks were given the same diet as they had on the plot, as described in Annex Table A3.8 of Chapter 3. Water and azolla were also provided in the cages as they were available in the field. Every four hours, the ducks and sackcloth were replaced. Collected excreta were oven-dried and weighed to determine the amount of excreta produced on a daily basis in accordance with age-category. The mass was multiplied by the number of days in order to reach the next age category and summed up for the entire duration of duck keeping (see Annexes Table A4.3a and b).

Rice biomass was measured at 15, 30, 45, 60, 75, 90 and 110 DAT on four areas of each plot. One particular area consisted of four plants. The whole rice plant was removed and washed and below-ground parts were separated from above-ground parts. The root included the root crown. If panicles had formed, they were separated from the straw. Rice biomass was oven-dried for dry-matter assessment and analysed for nitrogen content. Rice yields were quantified by harvesting 6.25 m^2 of rice plants in the middle of the plot at harvest time. Rice grain was removed from the straw and placed in paper bags, dried for 48 h at 75°C then weighed. Fish and ducks in each plot were weighed and moved into a pond and a shelter, respectively, at the rice flowering stage. The ducks, as egg layers, were weighed again at 155 days of age.

Besides rice biomass, productivity of each integrated species in the CRSs and their residues were quantified. In order to estimate the growth rate of azolla, a sample was taken from five positions using a 1 m^2 wooden box.

Azolla was weighed before and after 48 h drying at 75°C. Measurements were repeated every five days during a period of 40 days after inoculation. Samples of one metre of sun hemp along the bunds on the four sides of each plot were harvested, oven-dried and weighed. Every month during the rice cultivation period, a sun hemp sample of a re-growth plant was taken and summed up to assess the total production per m^2 during one rice production cycle. The total nitrogen content in azolla, sun hemp and excreta was analysed to determine their contributions in CRS as well as the dosage for organic-N fertilisers.

4.2.1.2. Experiment 2: Effects of duck presence and feeding behaviour on weed seed viability and weed abundance

Further assessment was made by testing the seed viability of three weed species in duck excreta: *Cyperus iria L.* (A), *Fimbristylis miliacea (L) Vahl.* (B) and *Echinochloa glabrescens Munro ex Hook. f.* (C) to investigate the effects of duck eating behaviour on weed suppression. Seeds from each of the three species of weed were weighed and counted, and 100 mg of each was mixed together with the duck feed, which was then fed to 27 ducks from three different age groups over a period of 24 hours. In order to prevent contamination from non-target weed seeds, the ducks were not fed for 24 hours prior to the test.

Portions of excreta and spilled feed were collected from the sackcloth on the cage floor after 24 hours. The excreta and spilled feed were then dried and sown on petri dishes in a germination room. The seeds were monitored at 7, 14 and 21 days. The percentage of viable seeds was determined based on the number of germinated seeds. Viable seeds were detected visually as well as chemically using tetrazolium (Soares *et al.*, 2016).

The effect of duck presence on weed abundance was assessed at four 1 m^2 quadrants, by recording the weed density as well as the number and duration of duck visits to the area.

4.2.1.3. Experiment 3: Dynamics of weeds, pests and rice yields

Experiment 3 was set by repeating CON, ORG and CRS treatments in experiment 1 for five cropping cycles from 2013 to 2016 to investigate the long-term effects of the treatments. The 100 m^2 plot sizes were also expanded to 200 m^2 in cycles 3, 4 and 5, with a 20 m minimum distance between plots. This experiment was also laid out in a completely randomised block design with three replicates. The materials used were similar to those used in experiment 1, except that longyard bean (*Vigna sinensis*), water spinach (*Ipomea aquatica*), eggplants (*Solanum melongena*) and papaya (*Carica papaya*) were grown as border plants. Plant and animal management as well as their inputs were adhered according to the methods described in Chapter 3.

Weeds were collected, treated and quantified in accordance with the same method as described in experiment 1; however, weeds were only sampled at 45 DAT and pests, snails, predators and natural enemies were sampled at 90 DAT.

4.2.2. Statistical analysis

We used skewness and kurtosis tests to verify the normal distribution of the data collected. When it was considered necessary to transform data, Log10 and sqrt transformations were used. ANOVA was carried out to determine the effects of the experimental treatment, followed by Tukey post-hoc tests to examine if there were any significant difference between treatments. T-tests were performed to compare the significant differences between duckling and adult duck behaviour as well as stem borer abundance against the total pests. Regression analysis was performed to assess the effects of duck movement on weed abundance. We conducted statistical tests using the SPSS 23 software package (SPSS Inc., Chicago, Illinois, USA) and visualised the interactions between rice yields, precipitation, weeds, pests and rice production systems using the biplot function in the CANOCO 5 software for Windows.

4.3. Results

Under the experimental conditions with full access to shelter, rice fields, water and azolla, the ducks developed normally with low mortality rates (2%). Records of duck behaviour in the rice fields are provided in an ethogram along with a description (Table 1; Annex Table A4.4). The frequency and duration of duck activities differed between the two age groups. In general, the younger ducks were more active than the older ducks with the exception of foraging between rice hills (Table 1; Annex Table A4.4).

Table 1. Frequency and duration of duck movement and feeding activities during 17 hours a day for two different age groups.

	Young	Adult	df	t	*P*
Surface foraging (min)	181±2 b	186±3 a	5	57.503	<0.001
Deep foraging (min)	56±2 b	44±2 a	5	15.191	<0.001
Hill foraging (min)	41±1 a	42±1 a	5	1.710	0.148
Number of jumping-pecking in the air	410±2 b	272±3 a	5	11.024	<0.001
Number of pecking on the ground	898±3 b	757±5 a	5	25.931	<0.001
Number of pecking between hills	691±13 b	445±5 a	5	10.152	<0.001

4.3.1. Weed incidence and suppression

In experiment 1 we identified 19 weed species distributed throughout the treatment plots. Annex Table A4.5 lists names of the species and their abundance. We noted weed biomass decreased with increasing complexity ($F_{(6,56)}$ = 4.467, P = 0.001; Figure 1a). In the long-term experiment (Experiment 3) the weed biomass ($F_{(2,33)}$ = 35.198, P < 0.001) and weed abundance ($F_{(6,33)}$ = 44.889, P < 0.001) in CRS declined throughout five cropping cycles, even when a weed outbreak occurred in the ORG and CON treatments during the fifth cropping cycle (Figures 1b and 1c).

We observed duck movement in relation to weed density and found that the duration of duck presence in a field had a negative influence on weed density (R^2 = 0.449, $F_{(1,25)}$ = 20.392, P < 0.001; Figure 1d).

In addition, we found both weed seeds and weed plant tissue in the duck gizzards (Figure 1e). The seed fraction was higher in the younger ducks ($F_{(2,24)}$ = 12.983, P < 0.001), whereas the fraction of weed tissue was greater in older ducks ($F_{(2,24)}$ = 18.606, P < 0.001).

A further effect of the duck feeding behaviour was shown by germination testing. The viability of weed seeds recovered from duck excreta was lower than that of the untreated control seeds, with the lowest viability for the seeds from the excreta of older ducks ($F_{(3,32)}$ = 54.201, P < 0.001; $t_{(53)}$ = 12.941, P < 0.001; Figure 1f).

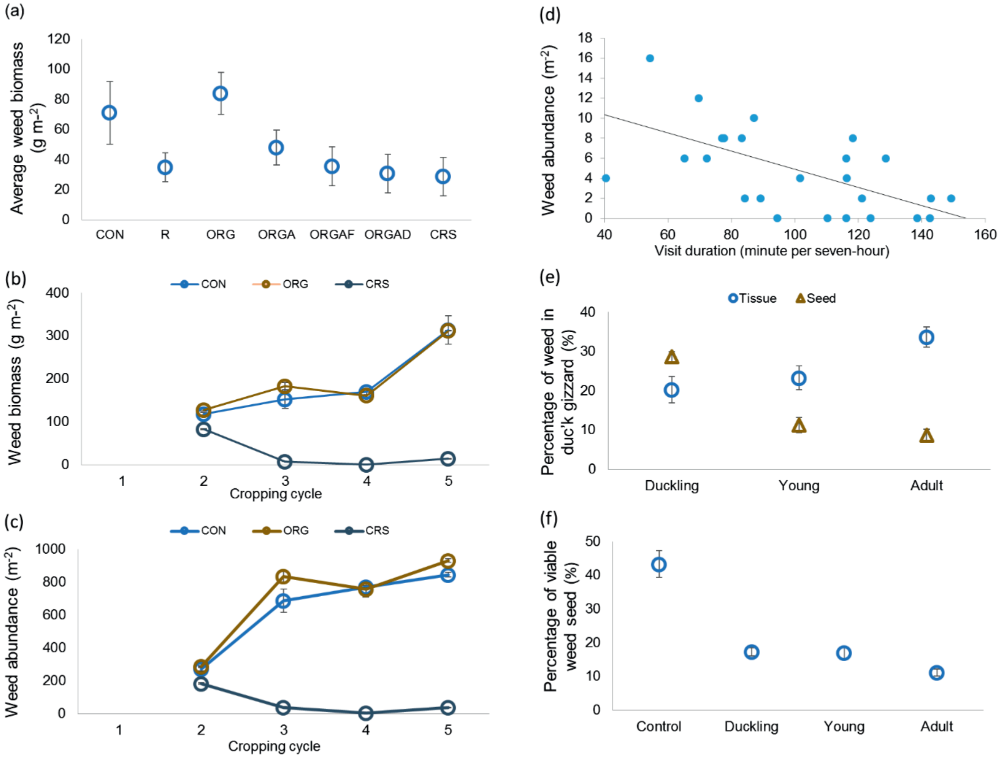

Figure 1. The dynamics of weeds emanating from treatments and their suppression mechanisms. (a) Average weed biomass in seven treatments. (b) Weed biomass in CON, ORG and CRS treatments during five cropping cycles. (c) Weed abundance in CON, ORG and CRS treatments during five cropping cycles. (d) The effect of duck visits on weed density during seven hour observations (Y = -.091X + 13.942, R= 0.45). (e) Proportion of weed tissue and weed seeds in the gizzard content of ducklings, young ducks and adult ducks taken randomly during ORGAD and CRS treatments. (f) Weed seed viability following consumption and excretion by ducklings, young ducks and adult ducks. CON denotes conventional; R represents rice only; ORG designates organic; ORGA indicates organic with azolla; ORGAF denotes organic with azolla and fish; ORGAD stands for organic with azolla and ducks; CRS designates organic with azolla, fish, ducks and border plants.

4.3.2. Pest incidence and suppression

We recorded nine major insect and molluscan pests, 21 natural enemies in experiment 1 and six detritivore species in experiment 1 and 3 (Annex Table A4.6). In general, treatments had a significant effect on pest abundance. The highest density was found in conventional systems which decreased progressively when complexity increased, except in ORGA and ORGAF (Figure 2a; $F_{(6,56)} = 17.564$, $P < 0.001$). Among the nine pests, stem borers comprised 40% (M = 22.49, SD = 10.36) of the total pest population (M = 55.78, SD = 23.97; $t_{(62)} = -18.65$, $p < 0.001$). This resulted in significant damage to almost 8% of the rice plants in CON, ORGA and ORGAF treatments ($F_{(6,56)} = 5.465$, $P < 0.001$).

The ability of ducks to control pests effectively has been associated with their feeding behaviour, which has been proven by the pest presence in their gizzards. The examination of gizzard content indicated that up to 8% and 22% of the ingested material consisted of insects and snails, respectively. We found more insects in the older ducks than in the younger ones (Figure 2b; $F_{(2,24)} = 6.927$, $P = 0.004$). However, the number of snails present in the older and younger duck gizzards was not significantly different ($F_{(2,24)} = 2.955$, $P = 0.073$).

Increasing complexity significantly enhanced the abundance of natural enemies ($F_{(6,56)} = 10.965$, $P < 0.001$; Annex Table A4.7), leading to a decline in the pest and natural enemy ratios (P/NE) ($F_{(6,56)} = 10.041$, $P < 0.001$; Figure 2c). The ability of CRS to maintain a low P/NE was confirmed in the long-term experiment (Experiment 3) (Figure 2d).

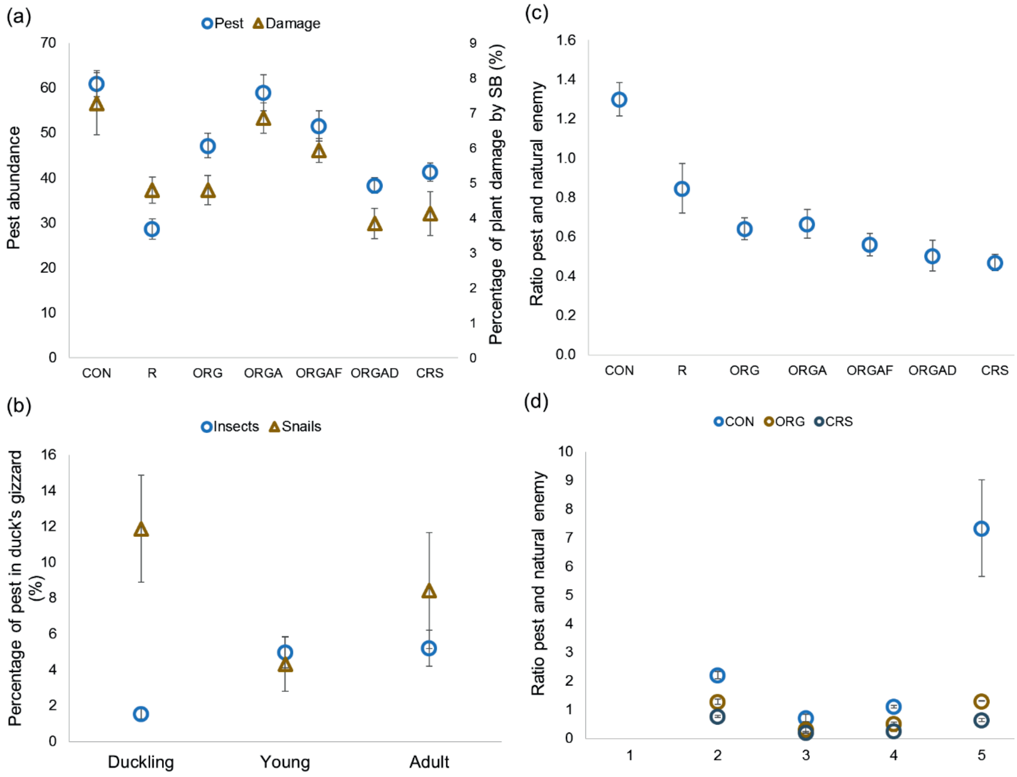

Figure 2. Pest and natural enemy abundance in rice systems with different levels of complexity and pests inside duck gizzards. (a) Pest abundance and percentage of rice plants damaged by stem borers. (b) Percentage of insects and snails in ducks' gizzard content. (c) Ratio of total pest to total natural enemies. (d) The dynamics of the pests to natural enemy's ratio over five cropping cycles. NE is natural enemies; SB is stem borer. CON denotes conventional; R represents rice only; ORG designates organic; ORGA indicates organic with azolla; ORGAF denotes organic with azolla and fish; ORGAD stands for organic with azolla and ducks; CRS designates organic with azolla, fish, ducks and border plants.

4.3.3. Nutrient recycling properties and processes, and rice yield responses

The analysis revealed that the average aerial NH_3 concentration and soil water NO_3^- concentration were higher in the earlier phases of rice growth (10 and 40 DAT) as compared to the end of the growing period at 70 DAT (NH_3, $F_{(2,60)} = 17.633$, $P < 0.001$; NO_3^-, $F_{(2,60)} = 31.102$, $P < 0.001$; Figures 3a and

3b). The average aerial NH_3 concentration in the CON treatment was significantly higher than that of the ecologically managed treatments ($F_{(2,60)}$ = 17.633, $P < 0.001$) (Figure 3). The integration of animals slightly increased NH_3, but it was still lower than that in CON ($F_{(2,56)}$ = 12.249, $P < 0.001$; Figure 3a). In the ORGA treatment, where azolla was used yet without animal integration, NH_3 concentration was lower than in ORG (10 DAT, P = 0.011; 40 DAT, $P < 0.001$). In contrast to the average aerial NH_3 concentration, the average NH_3 content in water was higher in the ecologically managed treatments than in the conventional treatments ($F_{(2,56)}$ = 3.802, P = 0.003).

Finally, weeds, pests, NH_4^+ and NO_3^- concentrations and NH_3 (associated losses) together influenced rice grain yields. Increasing inputs and complexity increased rice yields ($F_{(6,14)}$ = 45.389, $P < 0.001$; Figure 3c). The abundance of weeds and pests, the concentrations of NH_4^+ and NO_3^- in soil and the NH_3 and NO_3^- losses together had an enormous effect on rice grain yields. Rice yields in the ORG treatments were lower than in the CON treatment (P = 0.002), while rice yields in the ORGAD were equal to that estimated for CON (P = 0.998). Furthermore, rice yields in CRS were higher than that in CON (P = 0.05). These yields were also confirmed in the long-term experiment, suggesting that CRSs consistently outperform CON and ORG (Figure 3d).

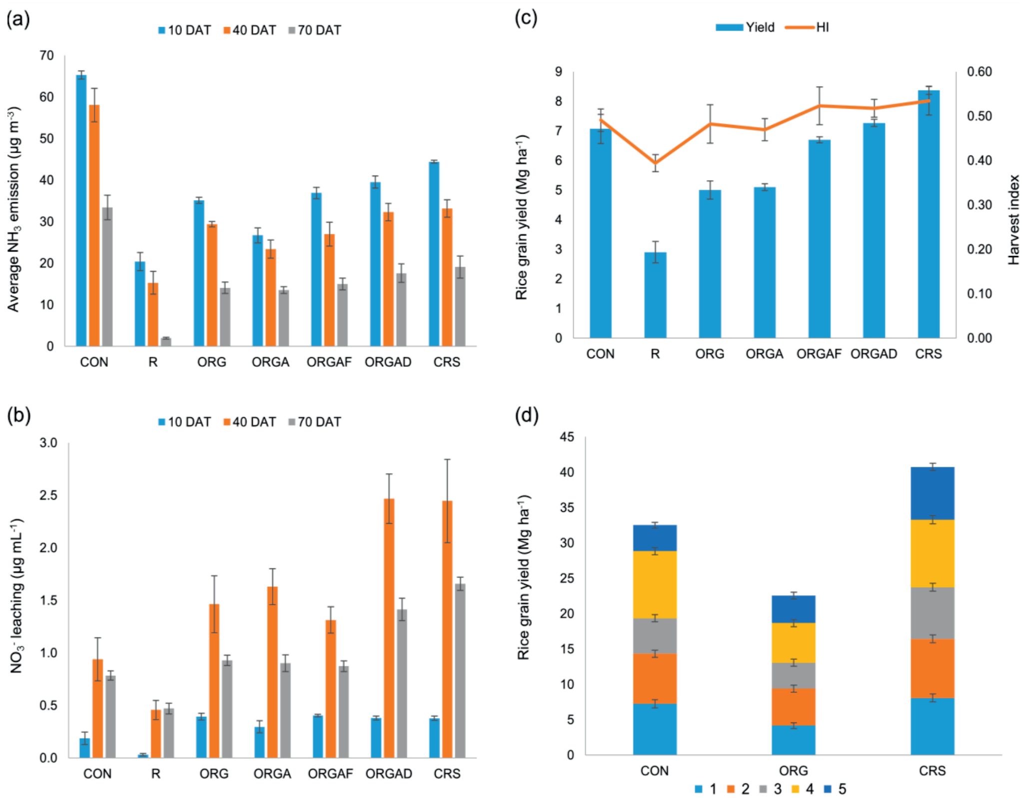

Figure 3. Average NH_3 and NO_3^- concentration and rice yield with different levels of rice cultivation system complexity. (a) Average NH_3 volatilisation. (b) Average NO_3^- leaching. (c) Rice yields and harvest index in experiment 1. (d) Rice yield dynamics. CON denotes conventional; R stands for rice only; ORG designates organic; ORGA indicates organic with azolla; ORGAF denotes organic with azolla and fish; ORGAD refers to organic with azolla and ducks; CRS designates organic with azolla, fish, ducks and border plants.

4.4. Discussion

Our results show a strong relationship between rice yields and yield stability along the gradient of complexity. Rice yields during five cropping cycles in the conventional systems were fluctuated than those in the ecologically-managed systems. This fluctuation might be associated with weed and pest infestations that were greatly stimulated by the weather conditions (Figure 4b; Annex Table A4.8) and nutrient recycling in the systems under investigation (Annexes Figure A4.1; Table A4.2; A4.3; A4.9; A4.10). Under normal weather conditions, when pests attack rice plants, applying agro-chemicals could effectively boost rice growth to compensate for the resulting yield loss of the damaged tiller (Reay-Jones, 2008; Litsinger, 2009). However, under extreme weather conditions, the problems could become more complicated, including increased pest outbreak and incidences of nutrient loss, all of which could drastically reduce rice yields in conventional systems.

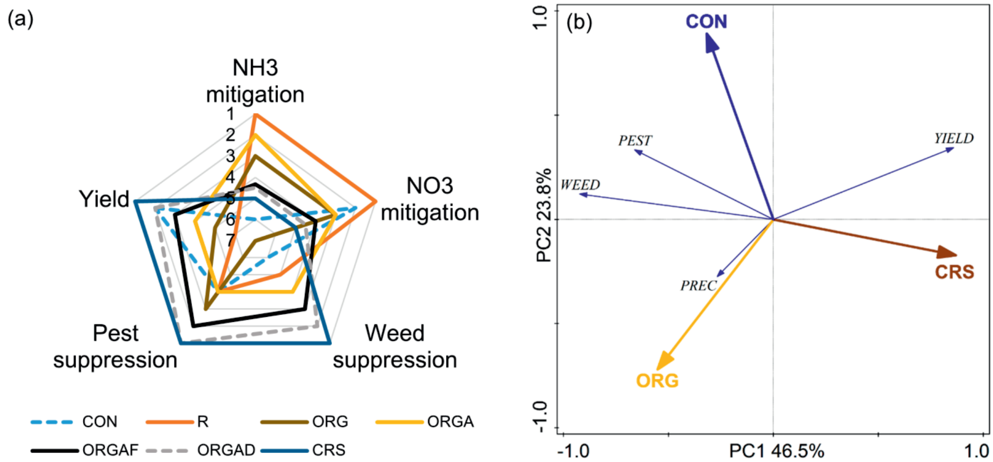

Figure 4. Factors that reduce and limit rice yield, affected by complexity. (a) Effects of complexity management on pests and weeds, on rice yields, and on average NO_3^- leaching and NH_3 emission. (b) Interactions between rice systems, precipitation, pests and weeds affecting yields. CON denotes conventional; R represents rice only; ORG designates organic; ORGA indicates organic with azolla; ORGAF denotes organic with azolla and fish; ORGAD represents organic with azolla and ducks; CRS designates organic with azolla, fish, ducks and border plants.

On the contrary, extreme weather events (Annexes Table A4.8a and b) had a lower impact on rice yields in ecologically managed systems (Figures 4a and 5) as shown in experiment 3 and Chapter 3 in cycles 1 and 3. Increasing the level of complexity in ecologically managed systems shown in experiment 1 increased rice yields. Reduced weed and pest infestations and the enhancement of nutrient recycling could be mechanisms of this rice yield and its yield stability improvement. For example, in experiment 1, only 2.9 Mg ha^{-1} rice yield could be produced without fertiliser application in R as the simplest treatment. When applying organic fertilisers (ORG), the yield increased by 42% to 4.6 Mg ha^{-1}. Because of larva pest outbreaks during experiment 1, adding azolla in ORGA plots did not significantly increase their rice yields. During this experiment, azolla attracted larva pests that reduced its cover and biomass by 35% after 21 days of inoculation (Annex Table A4.9), however, dead azolla might still be able to release nutrients for rice tiller recovery that prevented further grain losses in ORGA.

More complex treatments that added tilapia fish in the ORGAF system increased the grain yield by 24% from yields in ORG and ORGA systems. Fish integration complemented the weed suppression function of azolla. In this experiment fish consumed the spillover of duck's feed. However, as an omnivore and a detritivore, tilapia eats weeds, algae, plankton, dead organic matter (Turker *et al.,* 2003; Wurtsbaugh, 2007) and pests (Xie *et al.,* 2011) that increase the nutrient recycling.

When fish roles were replaced by ducks in the ORGAD system, rice yields increased by 30% from yields in ORG and ORGA systems, which were equivalent to the yields in the conventional systems. Ducks could complement the azolla function by feeding and trampling on weeds above the water surface, which is unreachable by fish. Ducks reduced weed seed viability (Figure 1f) via digestion and internal enzymatic processes. The digested seeds are therefore less viable after excretion. Ducks search actively for food above and below the water surface. During the observation, we saw they jumped to catch flying insects as well as to eat tall weeds. They also foraged for pests between rice tillers and on azolla as well as on the water's surface which might be to eat floating weeds and fallen pests. Finally, we observed they foraged below water surface that might be related to the hunting behavior for snails and crabs. Therefore, duck integration could be more effective than fish in suppressing pests and weeds.

When the rice ecosystem was disrupted by larva pest outbreaks in experiment 1 where azolla integration attracted more larva pests, adding ducks created so called push-pull schemes. Azolla attracted pests, which were then preyed upon by ducks, and the removal of infected azolla allowed patches of healthy azolla to grow quickly and steadily. When there are fewer pests, azolla in ORGAD system could flourish, enabling azolla to perform a vital weed suppressing function. Closely joined colonies of azolla prevent sunlight from reaching weeds and block weed emergence from below the water surface. In addition to weed suppression, azolla can also serve as fish and duck feed, which is partly excreted. Excreta may decompose and mineralise quicker (Annex Figure A4.1) than fresh azolla, which accelerates nutrient cycling. Nevertheless, greater species activities and nutrient release may also increase nitrate leaching (Kramer *et al.,* 2006) and the growth of organisms such as algae, plankton and aquatic larvae in the water body (e.g. mosquitoes) (Annex Figure A4.2). If their abundance is not managed, this may cause human health problems. However, duck and fish activities can oxygenate water, which improved root growth, and in turn increased nutrient uptake (Annex Figure A4.3) to reduce nitrate leaching and aerial NH_3 concentration, leading to the enhancement of nutrient use efficiency (Figure 4a).

Furthermore, adding fish in ORGAD system increased rice yields in CRS by 13% and 15% from yields in ORGAD and CON systems, respectively. Fish might extend food chains in CRS by eating algae, plankton, mosquitos and other harmful organisms in the water (Turker *et al.,* 2003; Wurtsbaugh, 2007) which might not only increase the efficiency of nutrient recycling but also solve problems created by the unwanted development of harmful organisms. Increasing farm resilience and self sufficiency is still possible in this CRS for example in experiment 3 which added sun hemp, vegetables and fruits on the rice bunds to deter natural enemies and provided feed for fish and ducks (Annexes Table A4.2; A4.7; A3.7 Chapter 3).

In conclusion, the roles of those integrated species and their interactions that effectively suppressed weeds and pests and enhanced nutrient cycling underlay the ecological mechanisms of rice yield and its yield stability improvement in CRSs. These findings extend our understanding of how to exploit the roles of plant and animal species to generate ecosystem functions that result in sustainable food production. Increasing the level of complexity may also increase competition, but that is not necessarily a problem. On the contrary, it may fill empty potential niches above and below the water surface, thus increasing farm productivity (Annex Table A4.2). In CRS system for example we consider the possibility that the competitive interactions between azolla, algae, border plants and rice can be transferred to compensatory interactions (Long *et al.,* 2013; Creissen *et al.,* 2016; Al-Namazi, 2017) by which azolla and border plant production supply nutrients to rice plants and algae to fish. This could increase the production of fodder, green manure and other food to reduce external inputs (Annexes Table A4.1-3).

Finally, increasing the level of rice system complexity with the prospect that species exploit resources in different niches can enhance ecosystem functions such as weed and pest suppression as well as nutrient recycling. Moreover, large species diversity may respond differently to condition changes, as they are compensating for a particular species that fails to perform well. All of these mechanisms could contribute to ensuring the long-term provisioning of ecosystem functions, and can explain why rice yields and their stability in most complex system were higher than those in conventional rice monocultures. Further research, for instance on the appropriate balance of animal densities under contrasting agro-ecological conditions or the selection of adaptive species in rice ecosystems, might help to ensure the ease and convenience of CRS management, as well as to reduce recurring nutrient losses. Therefore, better insight into these mechanisms can help us to underst and how complex rice systems can be made more practical and may provide inspiration for other crop/animal-based farming systems.

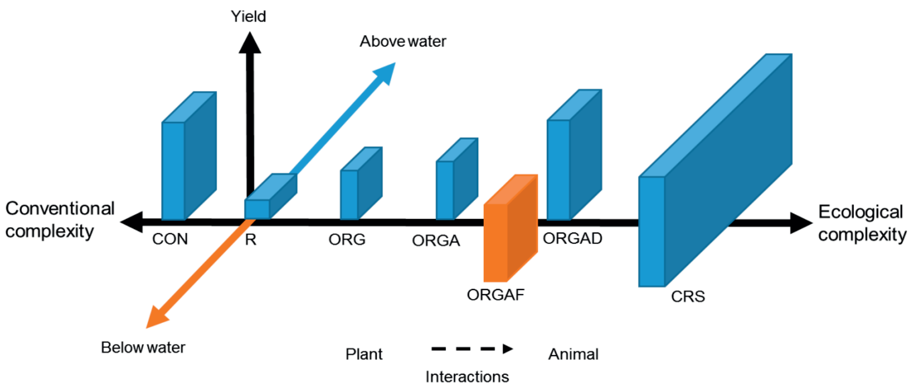

Figure 5. Schematic representation of effects of elements in polycultures on rice yields in conventionally and ecologically managed systems with increasing complexity, promoting interactions above and below the water surface. CON denotes conventional; R represents rice only; ORG designates organic; ORGA indicates organic with azolla; ORGAF denotes organic with azolla and fish; ORGAD represents organic with azolla and ducks; CRS designates organic with azolla, fish, ducks and border plants.

Annex 4

Method A4.1. Decomposition

Decomposition rates of rice straw and duck manure were assessed by using 20 x 20 cm litter bags made of 1 mm poly net mesh cloth. Straw was cut into lengths of 10 cm. Both straw and duck manure were air dried for two weeks. The initial total nitrogen content in both litters was analysed. Litter bags were filled with 22.5 g of either material and labelled accordingly. Seven straw-filled and seven manure-filled litter bags were buried under 5 cm of soil during the transplanting of rice. In order to prevent loss, each bag was tied to a bamboo stick in the ground. One bag of each litter per plot was taken from the field at 15, 30, 45, 60, 75, 90 and 110 days after placement (DAP). The litter bags were washed carefully, alien materials were removed, and the remaining litter was oven dried at 65°C for 48 h. The dried litter was weighed and analysed to estimate the total amount of N.

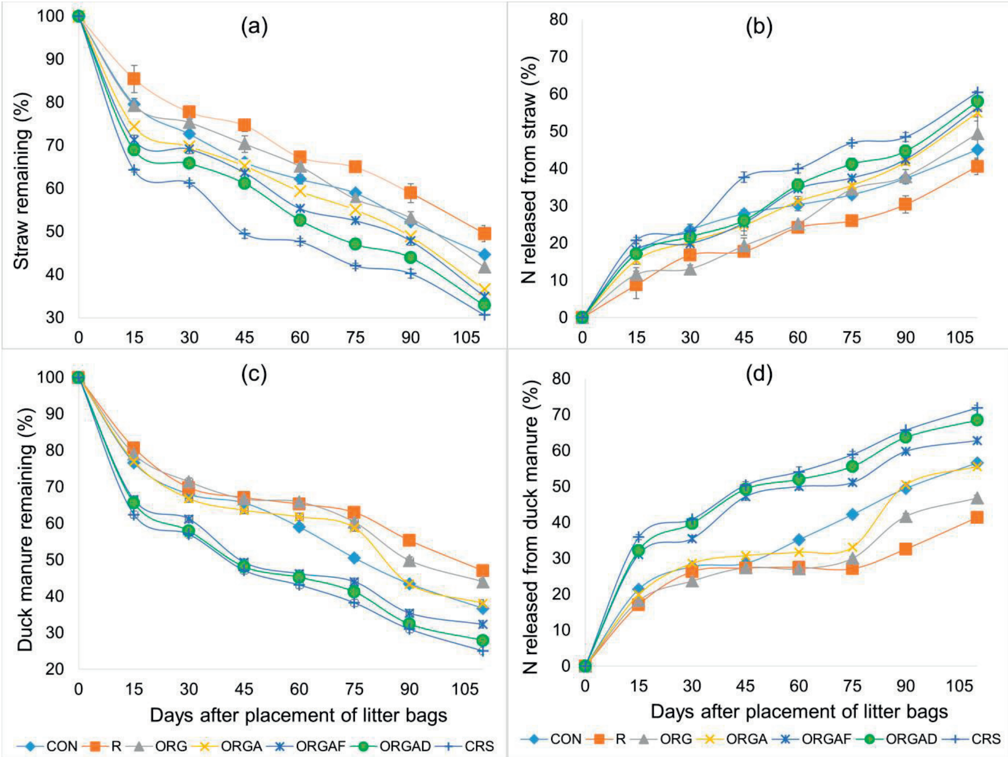

Figure A4.1. Straw and duck manure decomposition and nitrogen release rates for rice systems with different levels of complexity. (a) Percentage of straw remaining in the litter bags. (b) Percentage of nitrogen released from straw in the litter bags. (c) Percentage of duck manure remaining in the litter bags. (d) Percentage of nitrogen released from manure in the litter bags. CON denotes conventional; R represents rice only; ORG designates organic; ORGA indicates organic with azolla; ORGAF denotes organic with azolla and fish; ORGAD represents organic with azolla and ducks; CRS designates organic with azolla, fish, ducks and border plants.

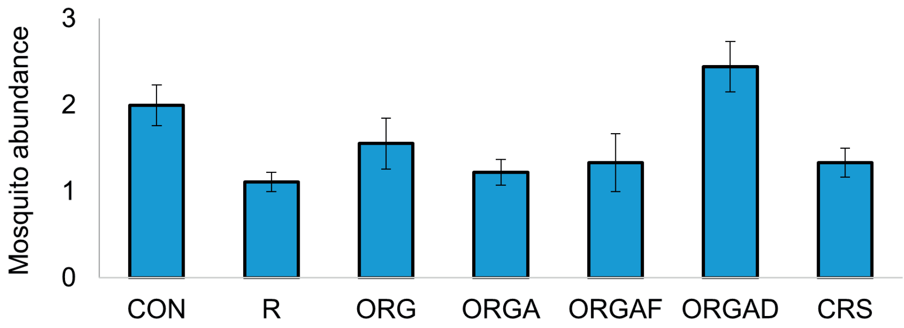

Figure A4.2. Mosquito abundance at rice systems with different levels of complexity. CON denotes conventional; R represents rice only; ORG designates organic; ORGA indicates organic with azolla; ORGAF denotes organic with azolla and fish; ORGAD represents organic with azolla and ducks; CRS designates organic with azolla, fish, ducks and border plants.

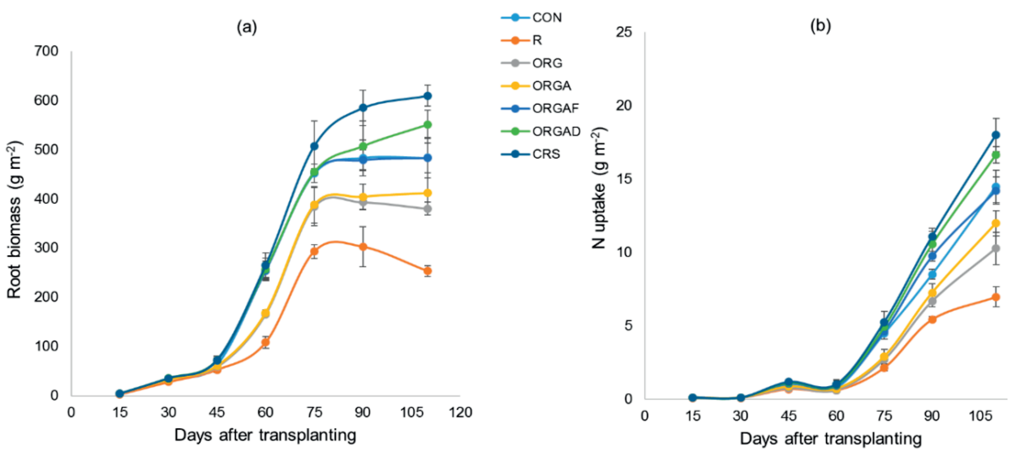

Figure A4.3. Belowground biomass and nitrogen uptake by rice plants at various rice growth and development stages for rice systems with different levels of complexity. (a) Root biomass. (b) Nitrogen uptake. CON denotes conventional; R represents rice only; ORG designates organic; ORGA indicates organic with azolla; ORGAF denotes organic with azolla and fish; ORGAD represents organic with azolla and ducks; CRS designates organic with azolla, fish, ducks and border plants.

Table A4.1a. The amounts of fertilisers applied for each treatment in Experiment 1.

Fertiliser Sources	Amount ($kg\ ha^{-1}$)	N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)
Conventional (CON)				
Urea (46%N)	350	161		
Phonska (15%N: 15%P: 15%K)	300	45	45	45
SP-36 (36% P2O5)	100		36	
KCL (65% K_2O)	100			60
Total	850	206	81	105
Rice only (R)	0	0	0	0
Organic (ORG)				
Compost (manure, food & dead livestock)	6600			
3.1 % N		205		
1.5% P_2O_5			99	
1.6% K_2O				106
ORGA	6600	205	99	106
ORGAF	6600	205	99	106
ORGAD	6600	205	99	106
CRS	6600	205	99	106

Table A4.1b. The amounts of active ingredients of herbicides applied in each cropping cycle (Experiments 1 and 3).

Name of Active Ingredient	Amounts per growing cycle (g ha^{-1})				
	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Paraquat	275	275	275	275	275
Ipa Glifosat	172	243	243	243	486
2.4DMA	583	583	635	568	568
Metil Metsulfuron	1.4	1.4	34	23	23
Metil Klorimuron	1.4	1.4	34	23	23
Triasulfurom	10	22.5	23	23	23
Total	1043	1126	1243	1153	1396

Table A4.1c. The amounts of active ingredients of pesticides applied for each cropping cycle (Experiments 1 and 3).

	Amount (g ha^{-1})				
Name of Active Ingredient	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Karbofuran	120	330	240	240	240
Difenokonazol	10	188	125	125	188
Fopronil	38	25	25	25	38
Deltamethrin	19	13	13	13	19
Endosulfan	180	175	175	175	263
Kumatetralil	175	2	8	2	7.5
Total	542	733	585	579	753

Table A4.2. Inputs of integrated species and product outputs per hectare (Experiment 3).

		Input		Output			
Species	Cycle	Amount	Remark	Marketable	Remark	Residues	Remark
Rice	1	19	kg seed	8.1±0.55	Mg grain	6.6±0.09	Mg straw
	2	19		8.4±0.56		6.7±1.39	
	3	19		7.3±0.54		6.3±0.18	
	4	19		9.5±0.56		7.5±0.39	
	5	19		7.5±0.50		7.3±0.13	
Fish	2	5000	Fingerlings	0.3±0.01	Mg fresh		
	3	5000		0.29±0.01			
	4	700	Adult fish	0.41±0.06			
	5	700		2.65±0.03			
Ducks	2	400	Ducklings	0.4±0.01	Mg fresh meat	2.55±9.5	Mg manure
	3	See Chapter 3	Feed	0.71±0.01		5.96±1.1	
	4			0.74±0.02		5.96±1.1	
	5			0.72±0.01		5.96±1.1	
	2			0	Mg egg		
	3			0.07±0			
	4			0.07±0			
	5			0.07±0			
Azolla	2	120	kg DM innoculant	0.77±0.07	Mg DM		
	3			0.92±0.02			
	4			0.80±0.04			
	5			0.78±0.01			
Sun hemp	2	19	kg seed	1.07±0.03	Mg DM		
	3	19		2.08±0.03	Aboveground		
	4	19		1.47±0.05	3-4 cuts		
	5	19		2.00±0.06			
Bean	2	1	kg seed	0	Mg fresh pod		
	3			0.67±0.04		0.29±0.01	Mg DM
	4			0.72±0.02		0.31±0	
	5			0.41±0		0.20±0.01	
Water spinach	5	4.5	kg seed	2.35±0.03	Mg fresh (planting 4x)		
Pakchoy	5			0.73±0.01	Mg fresh		
Papaya	5			0.27±0.02	Mg fresh		

Table A4.3a. Collected duck excreta (kg) for 24 hours (Experiment 1).

Ranged time	Duckling	Pre-young	Young	Pre-adult	Adult
1	5.4±0.5	11.1±0.2	18.5±0.2	20.9±0.4	Idem
2	4±0.6	9.1±0.6	17.3±0.3	18.4±0.1	Idem
3	2.6±0.1	3.5±0.2	8.8±0.2	9.5±0	Idem
4	4.2±0.3	5.9±0.3	12.8±0.2	11±0.1	Idem
5	3.9±0.2	6±0.4	12.7±0.2	10.2±0.1	Idem
6	8.7±0.3	16.6±0.3	23.5±0.3	32.8±0.2	Idem
Total (kg/)	28.7±0.7	52.2±1.6	93.5±0.2	102.7±0.3	Idem
Keeping days	14	14	21	32	83
Dry matter (g)	401.8	730.8	1963.5	**3286.4**	**8524.1**

Table A4.3b. Collected duck excreta (kg) per keeping cycle (Experiment 1).

	Keeping days	Excreta (kg/duck)	Duck number	Tot excreta (kg)	N outputs
Cycle 2	81	6.4	400	2553	51
Cycle 3, 4, 5	164	14.9	400	5963	119

Table A4.4a. Frequency and period of non-foraging behavior of the observed ducks (Experiment 1).

Behaviour	Young	Adult
Preening (min)	92±2	131±3
Stretching (e; x)	25±3	17±1
Roosting (min)	53±1	88±2
Loafing (min)	112±1	69±1
Feeding on supplied feed & drinking (min)	32±2	99±3
Walking (min)	128±4	133±1
Sleeping (min)	326±5	288±6

Table A4.4b. Ethogram and the description of the observed behavior of ducks in ORGAD and CRS (Experiment 1).

Behaviour	Description	State/ event
Pecking on air	A rapid wide opening and closing of the bill concentrated on air area at a specific direction of food source such as flying insects, while sometimes jumping.	Event
Deep foraging	Eyes are looking down while the bill searching food underwater or digging into the soil.	State
Surface foraging	Eyes are above water and substrate and bill opens and closes simultaneously that parallel to the water surface in order to search food on the water surface mostly while walking.	State
Rice hill foraging	Bill skimming each tiller in a rice hill and move sidelines along the tillers in order to find preys.	State
Eating supplied feed	Picking feed using bill from the feed container that provided by farmer	State
Drinking	Submerging bill in water involves throat motions to take water and raising the neck swallow the water.	State
Paddling	Moving forward with legs stroke to the water	
Walking	Moving forward with standing legs on the shallow water surface or on the area without water such as bunds and shelter	
Preening	Using bill to straighten the feathers on the breast, neck, wings, legs or tail which is done either on the water or on land. Sometimes proceeded by dipping the head into the water with neck motions to wet feathers.	State
Stretching	Head and neck out straight, parallel to the ground. Both wings are lifted up. Legs are lifted and straightened alternately.	Event
Loafing	Laying, sitting or standing with feet on the ground or floating on water	State
Sleeping	Laying with closed eyes, head usually tucked	State

Table A4. 5a. Weed species and abundance at 20 days after rice transplanting (Experiment 1).

No	Species	CON	R	ORG	ORGA	ORGAF	ORGAD	CRS
1	Ludwigia adscendens	46±8	22±5	35±7	28±14	41±16	4±2	0
2	Ludwigia octovalvis	5±3	3±2	6±3	0	0	0	0
3	Eclipta prostrata (L.)	4±2	0	3±2	0	0	0	0
4	Ageratum conyzoides L	0	0	0	0	3±3	0	0
5	Monochoria vaginalis (Burm. f.) C. Presl.	67±39	8±4	18±1	23±12	22±8	10±5	0
6	Pistia stratiotes L.	33±10	9±5	31±7	12±6	2±1	8±4	13±6
7	Marsilea minuta L.	32±22	9±4	12±7	35±12	19±10	11±3	0
8	Salvinia molesta	7±7	0	0	0	0	0	9±4
9	Alternanthera sessilis	13±5	3±2	15±4	10±5	8±4	2±2	1±1
10	Limnocharis flava	15±8	10±5	22±5	9±5	0	0	0
11	Commelina diffusa Burm. F	13±7	7±4	21±5	5±4	2±1	0	0
12	Echinochloa glabrescens Munro ex Hook. f.	67±17	13±2	74±4	4±2	3±2	0	0
13	Cyperus iria L.	67±17	13±4	101±30	9±5	0	8±4	0
14	Cyperus rotundus	0	0	0	0	0	0	0
15	Fimbristylis dichotoma (L.) Vahl	67±11	8±5	86±11	9±5	5±3	5±3	0
16	Cyanodon dactylon	54±4	5±3	49±7	17±9	9±1	7±1	0
17	Digitaria ciliaris (Retz.) Koel	0	0	0	0	0	0	0
18	Digitaria sefigera (Roth ex R & S)	0	0	0	0	0	0	0
19	Eleusine indica	0	0	0	0	0	0	0

Table A4 5b. Weed species and abundance at 40 days after rice transplanting (Experiment 1).

No.	Species	CON	R	ORG	ORGA	ORGAF	ORGAD	CRS
1	Ludwigia adscendens	5±1	4±1	2±0	4±1	0	0	0
2	Ludwigia octovalvis	2±0	1±0	3±1	1±0	2±1	0	1±0
3	Eclipta prostrata (L.)	2±1	1±0	2±1	1±0	2±0	0	0
4	Ageratum conyzoides L	2±1	1±0	3±0	1±1	1±0	0	0
5	Monochoria vaginalis (Burm. f.) C. Presl.	18±2	22±3	29±1	10±3	12±2	11±4	11±2
6	Pistia stratiotes L.	30±5	23±2	30±0	17±2	21±2	19±0	17±1
7	Marsilea minuta L.	22±6	27±3	26±3	17±2	16±2	15±1	16±2
8	Salvinia molesta	17±2	22±3	27±2	13±1	12±6	14±2	17±1
9	Alternanthera sessilis	7±2	2±1	5±0	4±1	3±1	0	1±0
10	Limnocharis flava	31±4	18±2	26±2	18±2	17±2	10±3	11±2
11	Commelina diffusa Burm. F	10±1	7±0	13±2	7±1	8±1	6±2	8±3
12	Echinochloa glabrescens Munro ex Hook. f.	19±1	13±0	29±3	19±1	19±0	18±1	22±1
13	Cyperus iria L.	27±7	14±0	20±1	19±1	20±3	22±2	20±1
14	Cyperus rotundus	15±0	12±0	12±1	14±1	16±1	18±2	19±1
15	Fimbristylis dichotoma (L.) Vahl	20±6	17±2	29±3	25±1	22±3	20±2	21±1
16	Cyanodon dactylon	19±6	14±0	19±2	20±0	16±1	17±1	16±1
17	Digitaria ciliaris (Retz.) Koel	15±2	4±1	6±1	4±1	5±1	3±1	0
18	Digitaria sefigera (Roth ex R & S)	0	0	4±1	0	0	0	0
19	Eleusine indica	5±4	1±0	3±1	1±0	1±0	2±1	2±1

Table A4.5c. Weed species and abundance at 65 days after rice transplanting (Experiment 1).

No.	Species	CON	R	ORG	ORGA	ORGAF	ORGAD	CRS
1	Ludwigia adscendens	0	0	0	0	0	0	0
2	Ludwigia octovalvis	1±0	1±0	1±1	1±1	4±1	0	0
3	Eclipta prostrata (L.)	0	0	0	1±0	0	0	0
4	Ageratum conyzoides L	1±1	1±0	2±0	1±1	0	0	0
5	Monochoria vaginalis (Burm. f.) C. Presl.	1±1	2±1	5±1	2±1	1±1	1±0	0
6	Pistia stratiotes L.	0	0	0	0	0	0	0
7	Marsilea minuta L.	0	0	0	0	1±1	0	0
8	Salvinia molesta	0	0	0	0	0	0	0
9	Alternanthera sessilis	1±1	1±0	1±0	1±1	2±1	1±0	1±0
10	Limnocharis flava	3±0	2±0	5±0	2±1	1±1	1±0	0
11	Commelina diffusa Burm. F	1±1	2±0	2±0	0	1±0	0	0
12	Echinochloa glabrescens Munro ex Hook. f.	5±1	3±0	8±0	2±1	2±1	1±0	1±0
13	Cyperus iria L.	0	4±0	5±1	0	0	1±0	1±0
14	Cyperus rotundus	0	0	0	1±0	1±0	0	0
15	Fimbristylis miliacea (L) Vahl	2±1	3±1	4±0	3±0	8±4	2±1	2±1
16	Cynodon dactylon (L) pers	7±4	2±1	4±1	3±1	0	1±0	1±0
17	Digitaria ciliaris (Retz.) Koel	2±1	1±1	2±1	2±1	2±1	0	0
18	Digitaria sefigera (Roth ex R & S)	3±1	3±0	4±1	3±1	1±0	0	0
19	Eleusin indica	4±4	2±1	2±1	1±1	0	0	0

Table A4.6a. Detritivore abundance at cropping cycle two (Experiment 1).

		CON	R	ORG	ORGA	ORGAF	ORGAD	CRS
30 DAT	Tipula sp.	4±0.3	0	4±0.6	3±0	3±0.7	3±0.3	3±0.3
	Psilopa sp.	1±0.6	1±0.3	4±0.3	2±0.7	2±0.7	3±1	3±0.3
	Sarcophaga sp	1±0.3	0	1±0.3	0	1±0.3	0	0
	Calliphora sp	1±0.3	0	1±0	0	1±0.3	2±0.6	1±0.3
	Sminthurus sp	0	0	0	0	0	0	1±0.3
	Isotoma sp	0	0	0	0	0	1±0.3	1±0.6
65 DAT	Tipula sp.	4±0.6	4±0.3	5±0.6	5±0.7	6±1	7±1.3	6±1
	Psilopa sp.	1±0.3	1±0.3	6±0.9	3±0.6	4±0.3	5±0.6	2±0.3
	Sarcophaga sp	1±1	1±0.9	2±1.2	1±0.6	1±0.3	0	3±0.3
	Calliphora sp	1±0.3	2±0.7	2±0.3	1±0	3±1	3±0.7	4±0.9
	Sminthurus sp	0	0	2±0.9	1±0.6	2±0.3	3±1.2	3±0.6
	Isotoma sp	0	0	0	1±0	1±0.3	2±0.6	3±0.9
90 DAT	Tipula sp.	4±1.2	4±0.9	5±1.2	4±0.9	7±1	4±0.6	5±0.3
	Psilopa sp.	2±0.3	2±0.6	5±0.3	5±0.3	4±0.9	5±0.6	5±0.9
	Sarcophaga sp	0	0	1±0.3	0	3±1.2	3±0.3	4±0.3
	Calliphora sp	1±0.3	1±0.3	1±0.3	2±0.3	1±0.3	3±0.3	3±0.3
	Sminthurus sp	0	1±0.3	4±0.3	4±0.3	3±0.3	4±0.9	6±0.9
	Isotoma sp	0	0	2±0.3	2±0.3	4±0.3	3±0.3	5±0.3

Table A4.6b. Detritivore abundance at cropping cycle 2, 3, 4 and 5 (Experiment 3).

Cycle		Tipula sp.	Psilopa sp.	Calliphora sp	Sminthurus sp	Isotomidae	Sarcophaga sp
2	CON	4±1.2	2±0.3	0	1±0.3	0	0
	ORG	5±0.9	5±0.3	1±0.3	0	4±0.9	1±0.9
	CRS	5±0.3	5±0.9	4±0.3	3±0.3	6±0.3	5±0.3
3	CON	0	1±0.6	0	0	3±0.3	0
	ORG	2±0.7	1±0.6	0	0	7±0.9	0
	CRS	2±0.3	1±0.6	1±0.7	0	6±0.3	1±0.3
4	CON	2±1.5	1±0.3	0	0	3±1.5	0
	ORG	0	1±0.3	2±1.2	1±0.7	5±1	1±0.6
	CRS	3±2	1±0.7	2±1.2	2±0.9	7±0.6	0
5	CON	0	0	0	0	0	1±0.3
	ORG	10±0.3	3±0.3	2±0.3	4±0	6±0.9	1±0.3
	CRS	9±1.2	1±0.3	1±0.3	4±0.3	6±0.3	1±0.3

Table A4.7. Abudance of natural enemies (Experiment 1).

		Species	Abundance	Simpson's index (D)	Shannon's index (H')	E
30 DAT	CON	13 ± 1	25 ± 2	0.88 ± 0.01	2.2 ± 0.00	0.87 ± 0.01
	R	16 ± 1	42 ± 3	0.91 ± 0.01	2.5 ± 0.10	0.90 ± 0.01
	ORG	16 ± 1	57 ± 9	0.92 ± 0.01	2.5 ± 0.10	0.92 ± 0.01
	ORGA	19 ± 0	75 ± 4	0.92 ± 0.01	2.7 ± 0.05	0.92 ± 0.01
	ORGAF	19 ± 1	73 ± 9	0.94 ± 0.01	2.8 ± 0.01	0.94 ± 0.02
	ORGAD	18 ± 1	64 ± 5	0.94 ± 0.00	2.7 ± 0.04	0.94 ± 0.00
	CRS	18 ± 1	69 ± 3	0.94 ± 0.00	2.3 ± 0.50	0.80 ± 0.15
	df	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)
	F	6.5	10.3	5.7	1.2	0.7
	P	0.002	< 0.001	0.004	0.353	0.647
65 DAT	CON	15 ± 1	33 ± 5	0.83 ± 0.00	2.2 ± 0.01	0.80 ± 0.01
	R	14 ± 2	35 ± 3	0.91 ± 0.01 a	2.4 ± 0.10	0.90 ± 0.01
	ORG	18 ± 1	77 ± 2	0.91 ± 0.01	2.6 ± 0.05	0.90 ± 0.01
	ORGA	20 ± 1	93 ± 5	0.90 ± 0.01	2.6 ± 0.04	0.86 ± 0.02
	ORGAF	20 ± 0	78 ± 3	0.92 ± 0.00	2.7 ± 0.01	0.90 ± 0.00
	ORGAD	19 ± 1	98 ± 7	0.91± 0.01	2.6 ± 0.11	0.88 ± 0.01
	CRS	20 ± 1	100 ± 2	0.91 ± 0.01	2.6 ± 0.11	0.88 ± 0.02
	df	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)
	F	7.3	47,3	20.8	7.1	7.9
	P	0.001	< 0.001	< 0.001	0.001	0.001
90 DAT	CON	12 ± 0	27 ± 2	0.82 ± 0.03	1.9 ± 0.10	0.81± 0.03
	R	8 ± 2	16 ± 3	0.83 ± 0.02	1.8 ± 0.20	0.87 ± 0.01
	ORG	13 ± 2	41 ± 2	0.85 ± 0.01	2.2 ± 0.10	0.84 ± 0.01
	ORGA	11 ± 1	45 ± 1	0.85 ± 0.01	2.1 ± 0.04	0.84 ± 0.01
	ORGAF	12 ± 0	52 ± 1	0.87 ± 0.00	2.2 ± 0.03	0.88 ± 0.01
	ORGAD	12 ± 1	36 ± 1	0.87 ± 0.00	2.3 ± 0.04	0.86 ± 0.00
	CRS	12 ± 1	43 ± 5	0.89 ± 0.00	2.2 ± 0.10	0.88 ± 0.01
	df	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)
	F	4.4	25.7	3.4	3.0	4.1
	P	0.011	< 0.001	0.028	0.041	0.015

Table A4.8a. Total precipitation per year during the experiment (mm/year) (Experiments 1 and 3).

	2013	2014	2015	2016
January	319	235	316	215
February	299	305	238	474
March	328	268	213	315
April	357	285	245	300
May	732	220	155	330
June	277	91	0	300
July	49	0	0	250
August	0	0	0	320
September	65	0	0	250
October	277	65	0	399
November	567	491	120	400
December	567	540	239	400
Total	3837	2500	1526	3953

Table A4.8b. Total precipitation per cropping cycle (mm) (Experiment 1 and 3).

Cycle	Month	Precipitation
1	Dec 2013 – April 2014	1234
2	June 2014 – Sept 2014	91
3	Nove 2014 – Feb 2015	1727
4	April 2015 – July 2015	542
5	Jan 2016 – April 2016	1446

Table A4.9. Azolla mass (kg/ 100 m^2) after inoculation (Experiment 1).

	Days after inoculation				
	0	7	15	21	42
ORGA	20±0	41±1	69±5	127±2	83±1
ORGAF	20±0	41±3	75±3	131±1	125±3
ORGAD	20±0	43±3	76±3	128±7	136±2
CRS	20±0	42±1	71±6	126±4	134±1

Table A4.10. Nitrogen concentration in soil and water within rice systems with different levels of complexity, and measured at different rice growth and development stages (DAT, days after transplanting). CON= conventional; R= rice only; ORG= organic; ORGA= organic with azolla; ORGAF= organic with azolla and fish; ORGAD= organic with azolla and ducks; CRS= organic with azolla, fish, ducks and border plants.

		15 DAT	30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	110 DAT
NH_4^+ soil	CON	33.2±1.1 c	11.6±0.5 c	45.9±3.2 c	12.3±2.1 a	31.4±3.5 c	15.4±0.7 ab	9.0±1.1 ab
	R	12.1±0.8 a	7.1±0.4 a	23.6±1.1 ab	5.8±1.1 a	10±0.4 a	11.8±0.5 a	7.6±0.3 a
	ORG	22.5±2.4 b	9.6±0.2 b	17.7±1.5 a	8.1±0.5 a	20.8±1.9 b	12.9±1 ab	15±0.6 cd
	ORGA	22.8±2.5 b	9.6±0.5 b	30.1±1.1 b	9.1±1.9 a	28.2±1.5 bc	17.2±1 bc	17.3±0.7 de
	ORGAF	24.2±1.7 b	11.4±0.4 bc	48.3±1.8 cd	9.4±1.1 a	28.8±1.3 bc	21.2±1.6 c	11.9±0.1 bc
	ORGAD	24±1.5 b	12.0±0.3 c	55.8±1.7de	9.7±1.9 a	30.7±1 c	22.3±0.5 c	18.1±1.4 de
	CRS	27.9±1.6 bc	12.1±0.5 c	61.0±0.9 e	10.7±2.2 a	30.8±1.6 c	21.7±1.6 c	20±1 e
	df	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)
	F	13.2	20.4	89.8	1.5	18.2	16.8	30.6
	P	< 0.001	< 0.001	< 0.001	0.2	< 0.001	< 0.001	< 0.001
NO_3^- soil	CON	11.1±0.4 b	1.6±0.1 b	13.6±0.2 bc	2.6±0.1 bc	3.9±0.2 b	14.2±0.2 cd	1.9±0.1 a
	R	3.5±0.2 a	0.5±0.0 a	7.1±0.2 a	0.9±0.1 a	1.8±0 a	6.1±0.2 a	1.6±0.0 a
	ORG	11±0.4 b	1.4±0.2 ab	12.8±0.1 b	2.5±0.2 b	3.5±0.3 b	10.4±0.1 b	2.1±0.0 ab
	ORGA	11.6±1.3 b	1.1±0.3 ab	17.2±0.2 d	4.0±0.1 d	3.6±0.1 b	12.3±0.2 bc	2.6±0.2 b
	ORGAF	9.0±0.4 b	1.5±0.1 b	14.7±0.3	2.8±0.1 bc	4.3±0.3 b	13.1±0.5 c	3.7±0.0 c
	ORGAD	11.8±0.1 b	1.6±0.1 b	13.2±0.1 b	3.0±.00 bc	4.8±0.0 b	14.5±0.8 cd	3.9±0.0 c
	CRS	12.4±0.3 b	1.7±0.1 b	13.9±0.2 bc	3.1±0.1 c	4.8±0.2 b	15.8±0.1 d	4.1±0.1 c
	df	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)
	F	15.5	4.1	117.3	61.4	10.9	39.0	73.7
	P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
NH_4^+ water	CON	8.3±0.2 c	1.9±0.1 a	4.1±0.0 f	1.7±0.1 b	3.4±0.2 a	1.3±0.1 e	
	R	1.6±0.2 a	1.6±0.1 a	1.1±0.1 a	0.6±0.1 a	2.0±0.2 a	0.2±0.0 a	
	ORG	5.0±0.2 b	1.8±0.2 a	1.5±0.0 ab	1.2±0.7 ab	2.1±0.5 a	0.7±0.0 b	
	ORGA	8.2±0.1 c	1.7±0.1 a	2.1±0.3 bc	1.2±0.1 ab	2.3±0.1 a	0.8±0.0 c	
	ORGAF	3.8±0.2 ab	1.4±0.2 a	2.8±0.0 cd	1.3±0.1 ab	2.5±0.2 a	0.8±0.0 c	
	ORGAD	4.9±0.4 b	1.1±0.1 a	3.3±0.1 de	1.6±0.1 b	2.6±0.6 a	1±0.0 d	
	CRS	3.6±0.8 ab	1.3±0 a	3.6±0.2 ef	1.6±0.1 b	3.5±0.1 a	1.2±0.0 e	
	df	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)	
	F	23.3	1.9	46.3	5.9	1.0	409.2	
	P	< 0.001	0.200	< 0.001	< 0.001	0.400	< 0.001	
NO_3^- water	CON	1.7±0.0 d	0.3±0.0 a	1.8±0.1 bc	1.0±0.0 b	0.9±0.0 ab	0.7±0.1 bc	
	R	0.4±0.0 a	0.1±0.0 a	0.5±0.0 a	0.2±0.0 a	0.6±0.0 a	0.2±0.0 a	
	ORG	0.7±0.1 b	0.4±0.1 a	1.6±0.1 b	0.9±0.0 b	1.0±0.1 b	1.1±0.0 c	
	ORGA	2±0.0 d	0.4±0.1 a	2.6±0.2 c	1.9±0.1 d	1.2±0.1 bc	1.1±0.0 c	
	ORGAF	0.9±0.0 b	0.5±0.0 a	1.6±0.1 b	0.8±0.0 b	1.4±0.0 cd	0.7±0.0 b	
	ORGAD	1.4±0.0 c	0.4±0.0 a	2.0±0.0 bc	1.4±0.1 c	1.6±0.1 d	0.8±0.0 bc	
	CRS	1.7±0.1 d	0.4±0.0 a	2.0±0.0 b	1.6±0.0 c	1.7±0.0 d	0.8±0.1 bc	
	df	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)	(6,14)	
	F	97.4	1.2	12.0	90.7	37.0	19.5	
	P	< 0.001	0.300	< 0.001	< 0.001	< 0.001	< 0.001	

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Chapter 5

Modifying the farmer field school method to support on-farm adaptation of complex rice systems

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(***In press***)

Picture by Andre Sparta

Abstract

Complex rice systems (CRSs) are polycultures of plants and animals that enhance ecological processes, contributing to sustainable and profitable farming systems. However, the contextual management complexity can hamper adoption despite the large long-term benefits that CRSs offer. This paper aimed to provide a method that encourages active farmer involvement and integrates farmer's feedback to deliver timely adaptations to CRS management by modifying and simplifying farmer field schools (FFSs). FFSs that are commonly used in guiding rural development processes involve a long process of preparation, weekly meetings and an emphasis on dissemination rather than the adaptation of technologies. We have simplified all FFS components and modified its curriculum focusing on training and integrating farmers' feedback into adaptation measures. Surveys were conducted and their results were validated through focus group discussions, which provided an adequate database to simplify the steps in the FFS approach. Only four meetings for agroecosystems analysis that emphasized an analytical and reflective learning style generated suitable adaptation measures selected from farmers' feedback. Repetition of the shortened FFS over several rice cropping cycles proved more effective than the frequent meetings within one cropping cycle. The modified FFS process could be considered as a promising approach to training farmers, whilst simultaneously identifying and discovering adaptations of agricultural innovations and monitoring the evolution of complex polycultures like CRSs, under diverse conditions. The modified FFS provides participants additional time to reflect on the training topics, resulting in a significant improvement in their knowledge, as well as improving the performance of the CRS. The modified FFS approach is focused on experiential and reflexive learning, and adaptation of innovations. Therefore, it is highly suitable for management of complex polycultures such as CRSs.

Keywords: agricultural innovations, farmer feedback, participatory learning, stakeholder participation, agricultural training, experiential and reflective learning.

5.1. Introduction

Agricultural innovations can make significant contributions to address serious global crises such as hunger, malnutrition, health, poverty and environmental sustainability (Leitgeb *et al.,* 2011; De Luca *et al.,* 2018). However, innovations may be site or context specific, and not be transferable to other conditions. In these cases, innovations must be adapted to local conditions, instead of being presented as a fixed package of technological innovation (van der Venn, 2010; Droppelmann *et al.,* 2017). Without making adaptations, the outcome of implementing a new innovation might not be satisfactory, even may experience difficulties during the adoption process.

Complex rice systems (CRSs) that combine elements of several agricultural approaches (e.g., mixed species, organic farming and the System of Rice Intensification, known as SRI) are a relevant example of innovation that potentially offers sustainable solutions to food security challenges (Cagauan, 2000; Khumairoh *et al.,* 2012; Stoop *et al.,* 2017). Recent studies demonstrated that rice yields under CRSs were higher and more stable than in conventional monoculture systems (Khumairoh *et al.,* 2012; Khumairoh *et al.,* 2018). However, CRSs are also associated with a higher initial cost of species integration and increased management complexity (Khumairoh *et al.,* 2012). For successful implementation of CRSs, farmers must be equipped with sufficient skills and knowledge. This includes knowledge on managing mixed species in order to facilitate their synergetic interactions and their response to the biophysical conditions of rice fields, which are variable across locations and in time. Guiding the rural development process and knowledge transfer to inform adaptations to support CRS implementation requires understanding of the farmers and their farming context, as well as their 'decision spaces' (Blazy *et al.,* 2009; Kuehne *et al.,* 2017; Falconnier *et al.,* 2017; Makate *et al.,* 2018). This socio-technical contextual understanding of optionality and challenges is a prerequisite for delivering timely and fitting adaptations to lubricate CRS management.

A participatory learning approach can effectively facilitate this experiential learning and adaptation process (Mackinson *et al.,* 2011; von Münchhausen & Häring, 2012; Mancini, 2014), for example by using participatory learning of farmer field schools (FFSs). With its experimentation-based learning method that involves groups of participating farmers, FFSs offer a potential approach to disseminate adaptation measures tailored to local conditions, and could be used for the mainstreaming of CRSs. The positive outcomes of FFSs have been confirmed by their success stories in introducing knowledge of integrated pest management during the late of 1990s, which reduced the use of chemicals in Indonesia (Van den Berg and Jiggins, 2007; Ketelaar and Abubakar, 2012; Pretty, 2015). However, since it has been introduced, FFS implementation emphasises dissemination of technologies rather than the adaptation of technologies, while farmers' feedback is often overlooked. In addition, current FFSs also involve a long process of preparation and weekly meetings, making it a rather costly approach (Gallagher *et al.,* 2006).

In response, we aimed to simplify and modify FFS components and its curriculum, enabling FFSs to generate feedback from farmers to identify and discover adaptation measures suited for local conditions in cheaper and more effective ways. To this end, we combined the FFS approach with elements of iterative learning methods, which are commonly used to facilitate mutual co-learning to identify the constraints and explore the options to re-design farming systems (Groot and Rossing, 2011; Falconnier, 2017; Descheemaeker *et al.,* 2016). Such re-design approaches can be employed to analytically: (i) characterize and describe the farming context, farm resources, technologies and practices, (ii) explain the performance and constraints of production systems, (iii) explore innovative options to improve farm configuration based on farmers' observations and reflections, and (iv) redesign the farm based on the proposed ideas from earlier steps. FFSs are identified as the only generally applied approach for transferring knowledge to farmers in the rural areas of Indonesia, but their implementation is often impeded by limited resources (financially) and the static nature of the method. Therefore, we analysed the potential for simplification of FFS components and modifying its curriculum in order to provide a cost-effective and appropriate training approach for farmers.

5.2. Materials and Methods

5.2.1. Study sites

The study was conducted in four districts of East Java, Indonesia: Blitar, Malang, Pasuruan and Lamongan, where the shortest distance between the two sub-districts is 28 km, and the longest is 113 km (Figure 1). The features of the four districts including their farming background are displayed in Table 1.

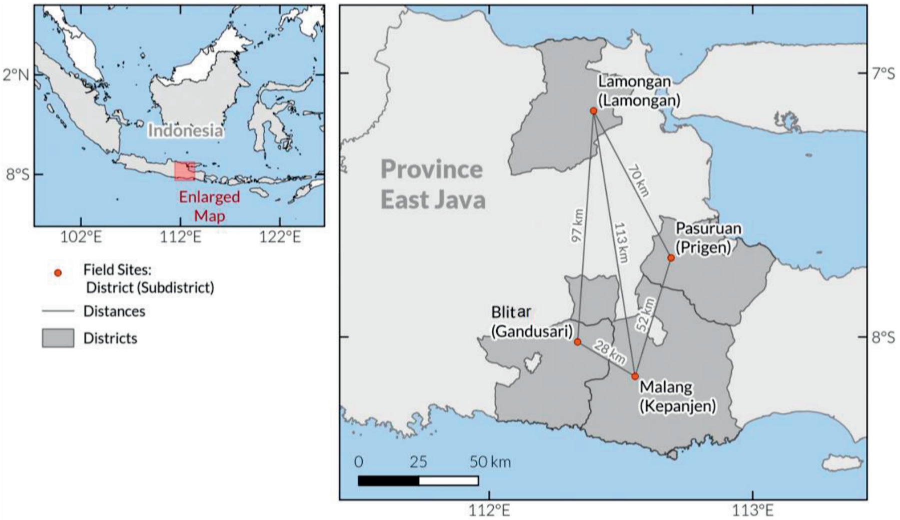

Figure 1. Location of the farmer field schools to support the adaptation measures of complex rice systems.

Table 1. The location and main farming activities of the study sites in four districts of East Java, Indonesia.

Variable	District			
	Lamongan	Pasuruan	Malang	Blitar
Coordinates	7o08’27,10”S-112o23’46,79”E	7o41’49,82”S-112o37’40,44”E	8o09’11,82”S-112o34’33,32”E	7o59’34,14”S-112o18’21,79”E
Altitude (m)	8	760	325	600
Soil type	Vertisol clay	Andisol sandy clay loam	Inceptisol silty clay (calcareous)	Entisol sandy
Mean temperature	26 °C	23 °C	24 °C	24 °C
Mean precipitation	1600 mm	3126 mm	2321 mm	3270 mm
Distance to larger town	50 km	59 km	118 km	150 km
Main farm products	Fish, rice, corn	Rice, vegetables	Rice, sugarcane	Rice, vegetables
Main livestock types	Chicken	Chicken	Chicken, duck	Chicken, duck, goat
Access to machinery	Renting, manual labour	Renting, use of animal traction	Renting, limited	Renting, limited

5.2.2. Participatory learning methodology

The study was carried out from June 2014 to June 2016 by employing an adjusted FFS method. This FFS method consisted of three main steps: preparation, implementation and evaluation (FAO, 2016). In the original FFS set-up, each step consists of several activities, which are often repetitive and long-lasting. To improve its efficiency and to explore the potential of FFSs as a means for improving the adaptability of CRSs, we modified each FFS component (or step), which is illustrated in Figure 2.

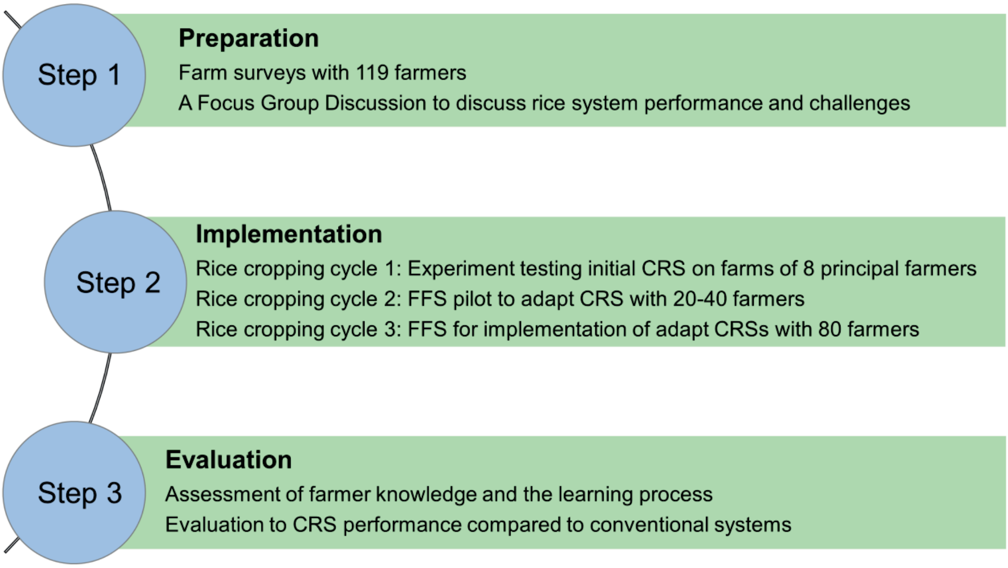

Figure 2. Components of the three-step FFS method for CRS adaptation applied in four districts of East Java, Indonesia. CRS, complex rice system; FGD, focus group discussion; FFS, farmer field school. Cycles 1 to 3 indicate consecutive cultivation periods of rice crops.

5.2.2.1. Step 1: Preparation

Surveys and Focus Group Discussions (FGDs) were performed as inception activities to understand the local context of rice farming systems and to prepare the implementation of CRSs. The surveys comprised interviews and farm visits to 119 farmer households to collect information of the biophysical characteristics, farming methods and the relation of farming to the environment and socio-economics (Annex Table A5.1).

As part of the preparation phase, two FGD sessions were organised in each district. The first FGD aimed to validate the results from the household surveys with 7-10 key informant farmers and a representative of the local authorities. The general results of our surveys were shared and discussed with the participants. The second FDG was designed to introduce CRSs and to select experimental farms while recruiting the FFS participants. A set of objectives to improve the current performance of rice farming systems was established, including increased rice yields and gross margins as well as product diversity and reduced agrochemical use.

The collected data regarding the performance of the rice farms, in relation to their locations, were statistically analysed by ANOVA using normally distributed data sets. When transformation was necessary, log10 or sqrt data transformation were used to obtain normal distributions. Subsequently, Tukey post-hoc tests were employed to determine significant differences of the categorised variables between locations. A non-parametric statistical test of Kruskal-Wallis was also performed for data sets which were not normally distributed (labour inputs for weeding and fertilising). The results from this Kruskal-Wallis test were further followed by the post-hoc test of Mann-Whitney to determine the rank between groups tested.

5.2.2.2. Step 2: Implementation

The FFSs took place in farmers' fields, centred around on-farm experiments ranging in size from 1800 to 10,000 m^2 and comprising three repetitions of treatments. The treatments consisted of CRSs, conventional rice monocultures and organic rice monocultures. The original CRS design (Khumairoh *et al.,* 2012) was tested at all study sites during the first cycle (rice cropping period) of the experiment, and adjusted to the local socio-biophysical conditions of each site in the second and third cycles. The working agenda is presented in Annex Table A5.2. This FFS agenda was modified by focusing on the agroecosystem analysis (AESA), a set of activities including observations and measurements of plants, animals and the environment and then followed by a presentation and discussion), field days and an exchange programme. The AESA meetings were held only three to four times during the most important stages of rice development, namely at tillering, booting, flowering or grain filling and harvesting. During the AESA meetings, farmers were guided to analyse and reflect on the results of their observations and measurements. By applying the explorative redesign steps, farmers were also guided to identify the constraints of the system tested and to provide feasible feedback. The feedback generated during the AESA meetings was recorded. At the last meeting (i.e. at harvesting time), the feedback was discussed, reviewed and selected to be implemented in the following cycles.

5.2.2.3. Step 3: Evaluation

A participatory evaluation was performed to assess the adaptation and performance of the CRSs after three cropping cycles. The assessment was made by asking farmers collectively to rank the performance of the CRSs in comparison with the conventional monoculture systems using six indicators. These indicators were established based on the objectives, including rice yields, self-sufficiency (feed and organic fertilisers), food diversity, gross margin and the environment. Moreover, one session was also allocated to test the farmers' knowledge using 'ballot box test' Annex Text 1. Ideally, the knowledge gained by farmers is evaluated by comparing the pre-test and post-test scores of FFS participants. However, when pre-tests are not possible, comparison to the knowledge of a control group of non-participants is also appropriate as demonstrated by Godtland (2004). The non-participants were selected from the same districts as the FFS participants, but were not familiar with our FFS project. The knowledge gained by the FFS participants was compared with the knowledge of non-participant farmers based on their mean scores of the test results. The questions tested farmer's understanding of recent agricultural innovations, existing management strategies of weeds, pests and nutrients, as well as polycultures. Differences were assessed by Cohen's d (Cohen, 1988):

$$\mathrm{d} = \frac{\mathrm{M1-M2}}{\mathrm{SD}\ pool} \qquad (1)$$

Where M1 and M2 are the mean test scores of FFS participants and non-participants, respectively, while the SD pool is the pooled standard deviation of the sample that was calculated as follows:

$$\mathrm{SD}\ pool = \frac{\sqrt{SD1^2 + SD2^2}}{2} \qquad (2)$$

SD1 and SD2 represent the standard deviations for the test scores of FFS participants and non-participants, respectively. According to Cohen (1988) the effect size is small if d=0.2, medium if d=0.5 and large if d=0.8.

5.3. Results

5.3.1. Step 1: Preparation: rice system characterisation and challenges

Table 2 shows the strong contrasts between the districts in agronomic and socio-economic farm characteristics, which are relevant for CRS implementation. This frames the challenges associated with scaling out CRSs, which are shown in Table 3. For example, the high rice bunds in Lamongan could not be easily accessed by ducks to express their behaviour of intermittently walking to dry and wet spots for resting and playing. Narrow rice bunds in other districts could be broken during heavy rain when water flows suddenly and strongly, which would result in fish loss.

Table 2. Agronomic and socio-economic characteristics based on surveys on 119 farms in four districts of East Java, Indonesia.

Variable	District			
	Lamongan	Pasuruan	Malang	Blitar
Irrigation (% of farms)				
• Simple	-	43	-	-
• Semi-technical	100	27	22	28
• Modern	-	30	78	72
Bund size (cm)	>100	<40	<40	<40
Water level (cm)	40-60	<25	<25	<25
Bund height (cm)	75-100	<30	<30	<30
Transplanting method*	DS/TP	TP	TP	TP
Cycles per year (% of farms)				
• 1	7	-	-	-
• 2	93	39	22	40
• 2.5	-	-	78	60
• 3	-	61	-	-
Access to manure	Limited	Limited	Limited	Limited
Weed problems**	1	2	3	2
Pest problems	Snail, blast	Leafhopper	Rat, stemborer	Stemborer, rice bug
Polycultures (%)	93	67	37	40
Fallowing (%)	100	33	100	68
Pesticide (kg AI/ha/year)	0.7±0.08	1.5±0.18	2.4±0.30	2.4±0.24
Herbicide (kg AI/ha/year)	0.5±0.07	1.0±0.31	1.2±0.37	2.0±0.60
Artificial fert. (kg N/ha/year)	326±8.7	456±18.6	493±25.7	424±21.0
Organic fert. (kg N/ha/year)	2±0.7	24±5.6	37±16.0	4±14.1
Own:hired labour	0.76±0.07	0.82±0.15	0.73±0.09	0.85±0.04
Male:female labour	2.6±0.12	1.2±0.06	0.99±0.05	0.85±0.02
Markets other than rice	Fish and vegetables	-	-	-

*Planting: DS, direct seedling; TP, transplanting. **Weed problems: 1, minimum; 2, moderate; 3, acute.

Table 3. Challenges for the implementation of different CRS elements originating from biophysical and field conditions on rice farms in four districts of East Java, Indonesia.

Conditions	District			
	Lamongan	Pasuruan	Malang	Blitar
Temperature	Azolla	-	-	-
Soil	-	-	Fish	-
Rice bund dimensions	Ducks	Ducks, fish	Dicks, fish	Dicks, fish
Water level	Rice, azolla	-	-	-
Predators	Fish	Ducks	-	-
Resources (inputs)	Manure, azolla	Manure	Manure	Manure
Safety	Ducks	Ducks, fish	Ducks, fish	Ducks
Markets available	Ducks	Fish	All products	Ducks, fish

Annual rice production in Malang was the highest for monocultures (16,6 Mg ha^{-1} $year^{-1}$), while polyculture systems performed well in Blitar (16,2 Mg ha^{-1} $year^{-1}$; Figure 3a). The lowest production was obtained in Lamongan ($F_{(7,111)}$ = 16.178, P <0.001; Figure 3a), resulting from a lower number of cycles per year (Table 2). However, the labour inputs per annum, especially for weeding in Lamongan were the lowest ($X^2_{(7)}$ = 94.732, P<0.001; Figure 3b), due to low weed incidence associated with the deep-water systems (Table 2). Economically, the highest gross margin was obtained in the polyculture systems in Malang and the lowest in the conventional monoculture systems in Pasuruan ($F_{(7,111)}$ = 4.212, P < 0.001; Figure 3c).

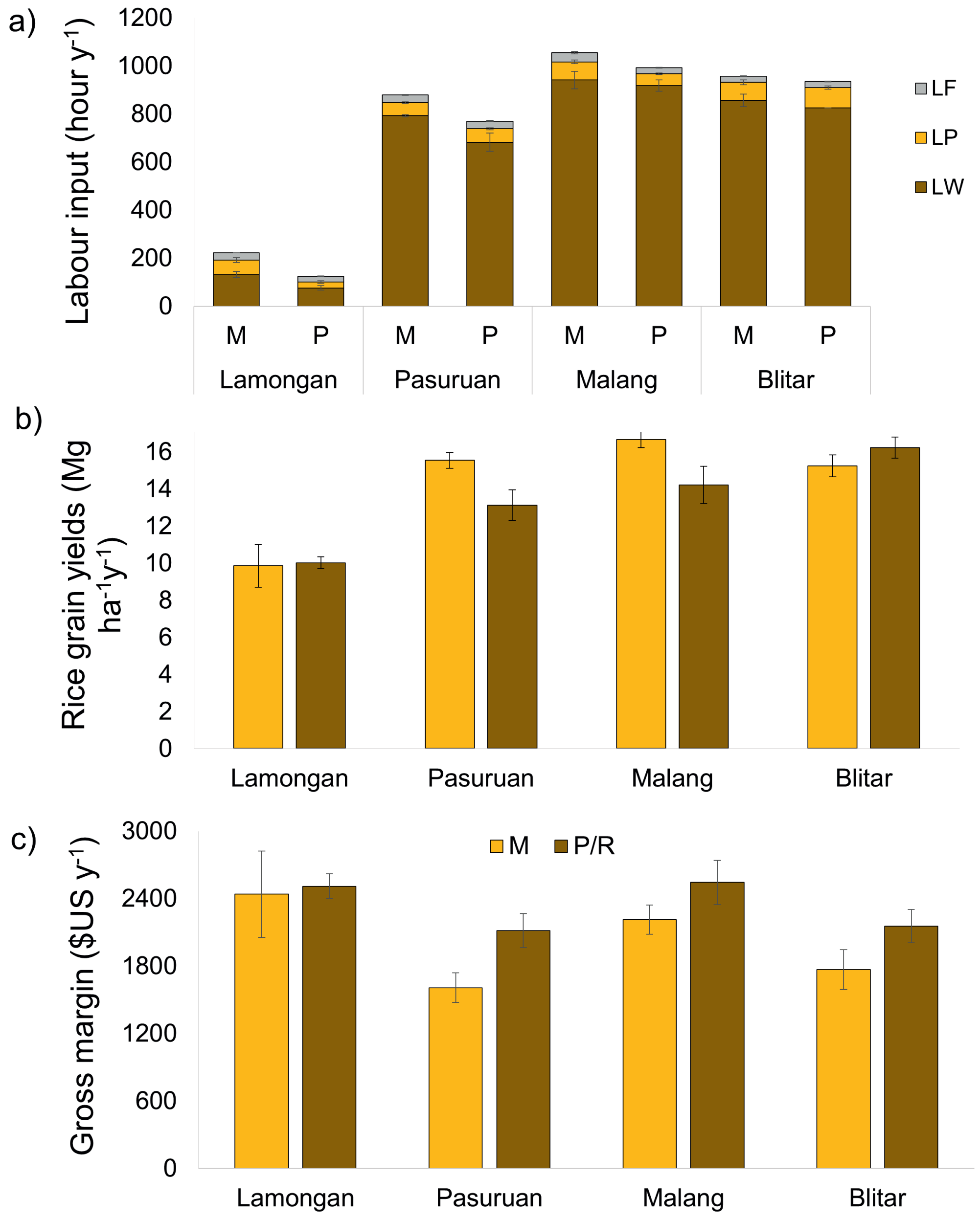

Figure 3. Performances of rice farms based on the surveys of 119 farm households in four districts of East Java. (a) Grain yields; (b) Labour inputs for weeding (LW), pest control (LP) and fertilization (LF); (c) Gross margin. M, monoculture; P/R, polyculture and/or rotation.

5.3.2. Step 2: Implementation: CRS adaptations with modified FFS*s*

5.3.2.1. Modification of the FFS approach

The FFS components of Step 2 were modified to comply with our objectives as outlined in Table 4. During the implementation of FFSs, the number of meetings, timing, curricula and learning styles were modified. Morning meetings were only for AESA to minimise interruption of farmer working hours. A field day and the FFS exchange programmes were combined with a more attractive event (e.g. an exhibition or a quiz) to motivate the participating farmers whilst disseminating CRSs to others. A cross visit that was originally organised through the exchange visit programmes between two FFSs of different locations was changed into watching videos of other FFSs or farming practices in Lamongan and Blitar. Finally, the evaluation was focussed on farmer's knowledge gained and the performance of CRSs using indicators from Step 1.

Table 4. Modifications of the FFS approach in relation to objectives of the method

Objective	Original	Modified
Analysis local context	Surveys, consultations, one full day PRA + transect walk	Surveys and FGD
Focus cropping period	One rice cropping cycle	Three cropping cycles
Meetings per cycle	Weekly	Seven meetings
Timing	Half day always in the morning	3-4 mornings for AESA and the rest is flexible
Duration	4-5 hours	Approximately 3 hours
Participants	The farmer (head of family, mainly men)	Anyone representing a member of farmer household
Participant recruitment	Registered in the list of extension officers	Both from extension officers and selected randomly
AESA & discussion	Small groups assigned similar tasks	Small groups assigned different tasks, but the results were shared during discussion
Group dynamics	Games lead by facilitator	Any activities lead by anyone
Special topics	Insect zoo, pest life cycles & other topics related to weed and pest management	Managing polyculture, food & feed, economics, pest, weed and nutrient management
Special topic focus	IPM	Broader
Field days	Visit each other's FFSs	Exhibition by inviting multiple stakeholders
Comparative learning	Cross visit	Either watching videos or cross visit
Experimental fields	One farm	Repetitions on multiple farms
Facilitator	Extension, a farmer leader	Extension, researcher, farmers
Evaluation	Broad	Gained knowledge and CRS

5.3.2.2. Context-specific adaptations to CRS

Site-specific adaptation measures to overcome challenges during our study included (Table 5):

Table 5. Adaptations to the CRS set-up dependent on the field configurations and constraints in four districts of East Java, Indonesia. Numbers indicate the rice cropping cycle (1st, 2nd or 3rd) in which the adaptation was implemented.

Conditions	Adaptation	District			
		Lamongan	Pasuruan	Malang	Blitar
Temperature	More additions azolla	1,2,3			
	Azolla nursery added			2,3	
	Planted border plants	2,3	2,3	2,3	2,3
Soil	Plastic wall fish pond			3	
Rice bund dimensions	Sloped	2,3			
	Ladder added	2,3			
	Straw heaps added	3			
	Widened bunds		2	2	2
Water level	Deep trenches		1,2,3	1,2,3	1,2,3
	Connected to pond		3	3	3
	Papaya leaves		2	2	2
	Use adult fish		3	3	3
Predators	5% pond area w/o rice plants	2,3			
	Traps		2,3		
Resources (inputs)	100% imports	1	1	1	1
	Border plants + manure 30%	2	2	2	2
	Border plants + manure 60%	3	3	3	
Safety	Tree branches covering pond		3	3	

- Temperature: In Lamongan azolla was frequently imported as it did not grow well due to high temperatures (Nordiah et al., 2012; Nhamo et al., 2014). Azolla grew well in Pasuruan and Blitar, but inoculants had to be imported for each cropping cycle. A nursery was built in Malang to supply inoculants for the next following rice cropping cycles. Growing border plants helped to substitute and complement azolla functions as animal feed and green manure, especially in Lamongan.
- Soil: The installation of plastic on the pond wall having calcareous and porous soil like in Malang retained water to support fish growth.

- Bund dimensions: The narrow rice bunds in Malang, Blitar and Pasuruan were widened, and the steep rice bunds in the deep rice water system in Lamongan were sloped to improve the ease of duck keeping in CRSs. Furthermore, heaping straw adjacent to the duck house and at some points in rice fields of the deep-water system in Lamongan facilitated flexibility for the ducks to rest. Straw was also eaten and decomposed by fish, increasing nutrient availability for rice.
- Resources (input): Growing high-biomass border plants increased feed and green manure self-sufficiency and provided shady areas for ducks and fish.
- Predators: Trap systems for predators of duck and fish proved useful for areas with predator problems, such as in Pasuruan. Providing open spaces, i.e. approximately 5% of rice fields without rice plants, reduced fish predation by snakes in Lamongan.
- Safety: Having fish and ducks in distant fields attracted theft. Ponds in Pasuruan and Malang were covered with tree branches to overcome this challenge. However, safety was not a concern in Lamongan where fish culture is prevalent.
- On-farm market: Fish culture combined with on-farm sales was practised in Lamongan. In Malang, Pasuruan and Blitar no market chain was developed. Hence, farmers brought their produce to the closest traditional shop or market to sell their products, except for rice.
- Water level: A general adaptation was made by constructing deep trenches surrounding rice fields in the shallow-water rice systems in Malang, Blitar, and Pasuruan. In Malang, greater challenges with limited water availability and calcareous porous soil weakened fish and resulted in high mortality. Farmers suggested to distribute papaya leaves on the rice field as feed, believing that it has antiseptic, anti-parasitic and antimicrobial effects (Valladão, 2015; Jafari et al., 2018). Thus, three papaya trees were grown on rice bunds. A further adaptation was made by constructing a deeper pond separated by a rice bund with a gate for fish to access both rice field and pond. Instead of introducing fingerlings, tilapia fishes at four months of age are more tolerant and could hatch their eggs on the rice fields within a few days, resulting in fingerlings that rapidly adapted to the shallow rice ecosystems.

5.3.3. Step 3: Evaluation

The mean scores for knowledge about agronomic practices and innovations were higher for FFS participants than for non-participants ($t_{(25)}$ = 12.634, P<0.001; Figure 4). The Cohen's d index index indicated a large effect of FFS training (larger than 0.8; Figure 4).

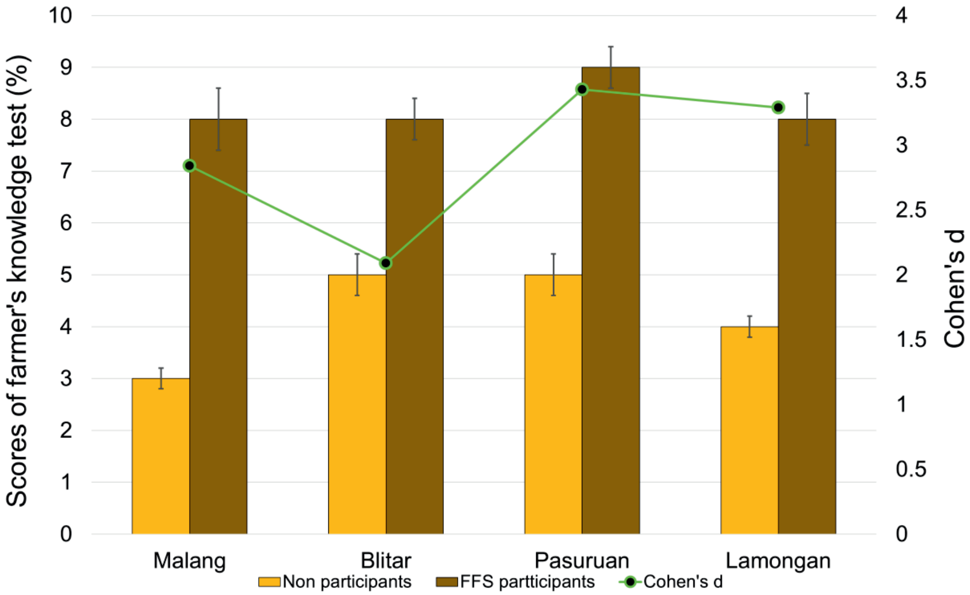

Figure 4. Knowledge level of FFS participants compared to non-FFS participants in the four districts of the study sites. FFS: farmer field school.

Figure 5 demonstrates the results of participatory evaluation of farm performance throughout the three consecutive cropping cycles that were ranked on a scale by farmers. The perceived performance of CRSs was better than of conventional systems. Having zero pesticides and herbicides, yet approximately 20-70% additional manure was produced by the ducks fed on azolla and sun hemp, the rice yields of CRSs were consistently higher than those from conventional systems, except for the first growing cycle in Blitar (Figure 5). The rice yields of CRSs in Malang were higher than in conventional during extreme weather. Without costs for agrochemicals, the increased quantity of edible and marketable products in CRSs resulted in a better gross margin than in the conventional system.

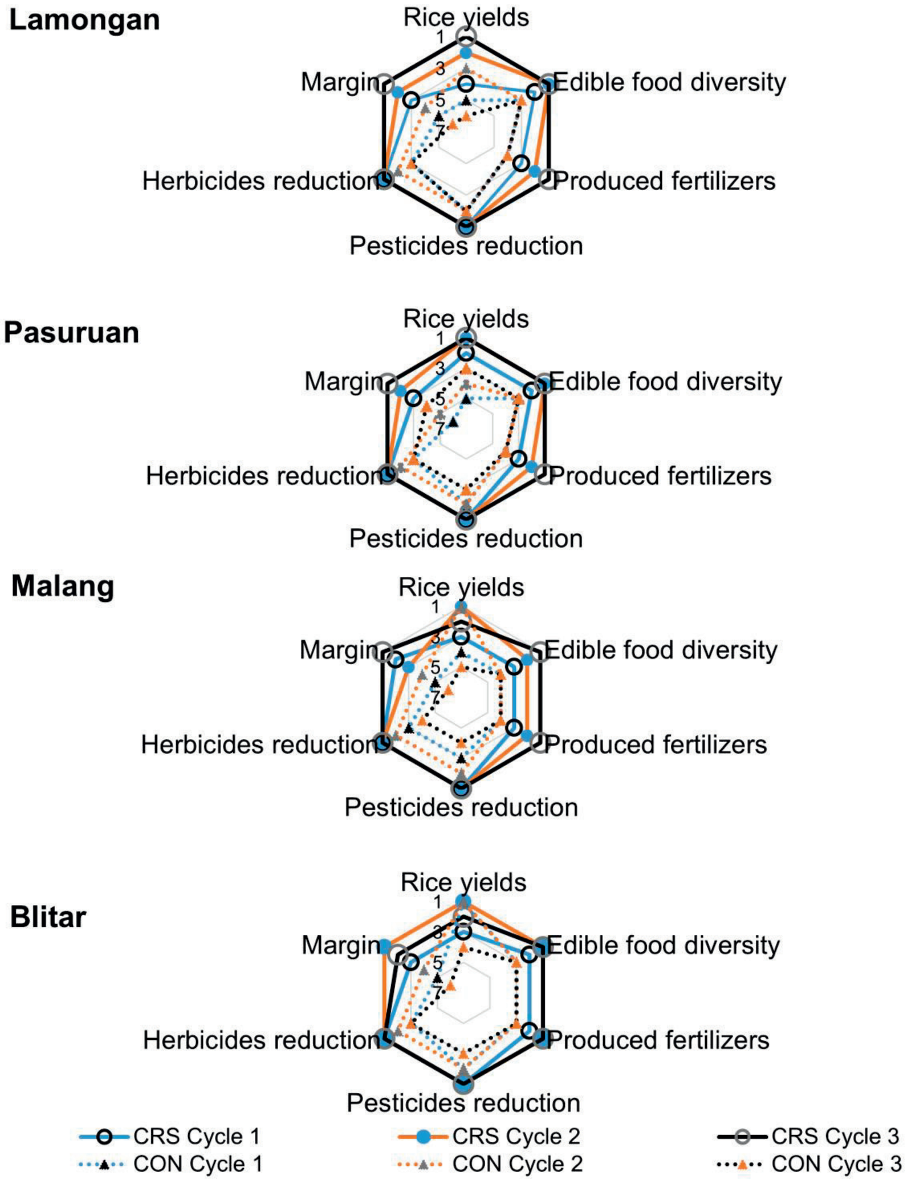

Figure 5. The results of the participatory assessment on CRS performance in comparison to the conventional rice production system using six indicators at four study sites in West Java, Indonesia. CRS, complex rice system; CON, conventional.

5.4. Discussion

The initial purpose of designing CRSs was to exploit the roles of all integrated elements to suppress weeds and pests as well as to recycle nutrients effectively and ecologically, resulting in high rice yields and yield stability (Khumairoh *et al.,* 2012; 2018). However, the most optimal configuration of CRSs is highly dependent on the local socio-biophysical conditions, as well as the knowledge, skills and the attitude of farmers. This study highlighted the required adaptation process for implementation of CRS for contrasting specific conditions along with knowledge transmission to support the implementation of CRSs.

5.4.1. Adaptation of complex rice systems

Adapting CRSs within the local context and experiencing the benefits of these systems by farmers is essential for making them meaningful and relevant in solving current local problems of rice farming. The adaptation process in the four districts in our study provided an example of how specific conditions challenged the implementation of CRSs. Variation of biophysical conditions such as temperature, soil, rice bund size and water level have been identified as factors that influenced the variability of CRS performance. Some infrastructures were built or modified as measures to reduce the effects of biophysical heterogeneity, for example, expansion of rice bund and pond areas. Sun hemp, corn and other border plants were also added to substitute or complement azolla functions.

A step-by-step strategy allows for the prioritisation of specific objectives for individual farms during the conversion period. For example, overcoming the main problems of weeds and pests by duck integration was prioritised in Malang and Blitar, so that farmers could benefit immediately from the reduction of labour requirements, pesticides and herbicides. Contrastingly, in Lamongan, optimisation of rice bund areas with border plants was considered more straightforward and less risky and was therefore prioritised. In addition, the step-by-step strategy eased the financial constraint of initial capital requirements for implementation of CRSs (Khumairoh *et al.,* 2012). This step-by-step strategy enabled distribution of investments over several cropping cycles to reduce the impacts of failure.

5.4.2. Modifications of the farmer field school approach

Farmers who want to shift from their current rice farming systems to CRSs require sufficient skills and knowledge to successfully implement CRSs on their rice farms. Training is considered as a major investment that positively correlates with farmer's attitude, adoption rates of agricultural innovations and farm performances (Mudombi, 2013; Xayavong *et al.,* 2016). The modification of FFS components in our study guided farmers to produce feedback based on their observations and measurements on plants, animals, environment (biophysical and weather conditions) and infrastructure during the AESA sessions. The modified FFS approach contributed significantly to improving farmers' knowledge as demonstrated in the mean of test's scores (Figure 4). This suggests that a mere four meetings of AESA and seven meetings in total could lead to a substantial improvement in farmers' knowledge, demonstrating that a repetitive learning approach, spread over three cropping cycles is more important than the number of meetings per cycle per se.

The modifications to the number of the meetings, the flexibility of their timing, the number of FFS cycles followed and the curriculum enhanced the effectiveness of the FFS to deliver the objectives for CRS adaptation. The use of the FFS approach to collect information and the capacity to improve CRS performance in this study shows the effectiveness of the adjusted FFS method as a means of innovation development.

5.4.3. Implications and suggestions for further research

Reducing the number of meetings from weekly to only 6-7 per rice cropping season certainly lowered FFS costs. The costs remaining can be allocated more effectively to repeat FFSs in consecutive rice cropping cycles to allow for the validation of the innovations tested under different weather conditions and other temporal variations. Lower costs, flexible timing and an optimised number of meetings make it possible for groups of farmers to organise FFSs by themselves in the following cropping cycles after the project finished, ensuring the sustainability of FFS as a means for farmers to update their knowledge and to gain or exchange information.

For practical implementation in Indonesia, the trade-off associated with the complexity of management of CRSs might be alleviated by implementing CRSs at a 'hamparan' scale, which is a cluster of small farms connected to each other, instead of individual farms. This enables collective management, which may integrate other agricultural innovations to support CRS development. For instance, widening rice bunds may become a concern due to rat problems (Brown *et al.,* 2003a; Hogan, *et al.,* 2016) in endemic areas, which may be overcome with a trap barrier system (TBS) (Brown *et al.,* 2006b; Kabir & Hosain, 2014). Implementation at 'hamparan' scale may also encourage construction of more permanent and shared infrastructures, creating shared security systems either from theft or predators, and may build a new market to sell the diverse products of CRSs. This may generate opportunities for a multi-stakeholder partnership in the cluster that encourage landscape transformation and further development which are interesting subjects for following-up studies.

The adaptation process in this study suggests that further studies are required to identify the numerous locally available resources that have similar functions and that could substitute or complement other elements to sustain the regulation of the ecological processes. Concerning the exchange programmes and field days in the FFS curriculum, they are essential for showcasing new innovations to a broader range of stakeholders. Augmenting those activities, for example by means of a farm contest, may attract other farmers to adopt the innovations. However, this needs to be developed further and should be tested for efficacy. The field day curriculum and the FFS exchange programme were also modified, but have not been investigated in detail. Thus, the question arises as to whether the modification of both the field day and the exchange programme will positively change farmers' perspectives toward the new innovation, and therefore encourage further adoption.

We propose a modification and simplification of the FFS curriculum to enable integration of farmer's feedback into the process to make adaptation measures of CRSs effective. CRSs that outperformed conventional systems on FFS experimental farms demonstrated the adaptive capacity of CRSs and the potential of this modified FFS to support the development of agricultural innovations.

Respecting the local context and active participation of farmers in our approach is particularly relevant for rural development process, thereby enhancing the multitude of potential adopters. By using this simpler modified FFS, this study contributes to the improvement of the FFS method as a means of knowledge transfer to farmers as well as to the enhancement of its cost-effectiveness, while showcasing the adaptation process of a new innovation. A key policy priority should be to plan implementation of FFSs in related to agricultural extension policy formulation. Broader implementation should be supported by supervision, capacity building and partnership with multiple stakeholders working in conjunction to enhance the sustainability and scalability of the innovative and adaptive CRSs.

Annex 5

Table A5.1. Variables collected for farm characterization in four districts of East Java, Indonesia.

Category	Variable	Unit
Physical conditions	Mean precipitation	mm $year^{-1}$
	Mean temperature	°C
	Soil type	-
	Irrigation type	-
	Bund width	cm
	Water depth	cm
	Distance water surface to bund top	cm
Inputs	Pesticide use (active ingredients)	kg ha^{-1} $year^{-1}$
	Herbicide use (active ingredients)	kg ha^{-1} $year^{-1}$
	Artificial fertilizer nitrogen use	kg N ha^{-1} $year^{-1}$
	Organic fertilizer nitrogen use	kg N ha^{-1} $year^{-1}$
	Seedling transplanting method	-
	Number of rice cultivation cycles	$year^{-1}$
	Rating of access to inputs	-
	Rating of weed problems	-
	Rating of pest problems	-
	Rating availability equipment and machinery	-
	Percentage of mono- and polycultures	%
	Percentage fallow	%
Farm performance	Rice grain yield	Mg N ha^{-1} $year^{-1}$
	Labor use for weeding	h $year^{-1}$
	Labor use for pest control	h $year^{-1}$
	Labor use for fertilizer application	h $year^{-1}$
	Gross margin	US$ $year^{-1}$
Socio-cultural setting	Ratio household / hired labor	-
	Ratio female / male labor	-
	Rating of organization level	-
	Rating of market access	-
	Other stakeholders involved	-

Table A5.2. Agenda of farmer field schools to support the adaptation of complex rice systems. AESA, agroecosystem analysis; DEED, describe, explain, explore, design; OM, observation and measurement; DF, discussion and feedback. Cycles 1 to 3 indicate consecutive cultivation periods of rice crops.

Component	Rice cultivation cycle		
	Cycle 1	Cycle 2	Cycle 3
Meeting	1 introduction 3 AESA + special topic 1 harvesting, evaluation	1 introduction 4 AESA and special topic 1 harvesting, evaluation 1 field day and exchange	1 introduction 4 AESA and special topic 1 harvesting, evaluation 1 field day and exchange
Time	3 morning, 2 afternoons	4 mornings, 2 afternoons, 1 night	4 mornings, 2 afternoons, 1 night
Methods	Experiment, OM, DF	Experiment, OM, DF	Experiment, OM, DF
Special topics	Duck-fish keeping, azolla growing	Border plants, feed management	Weed-pest-nutrient management, economics
Participants	Principal farmers, researchers	Principal farmers, neighboring farmers, researchers	Principal farmers, neighboring farmers, researchers, extension agents
Number of participants	20	40	80
Facilitator	Researcher	Researcher, principal farmer	Farmer, extension agent, researcher

Annex Text 1. Ballot box

1. One of SRI principles:
   a. narrow spaces between rice plants
   b. deep water systems
   c. planting young seedlings less than 12 days

2. The benefit of *jajar legowo* system:
   a. required less water
   b. rice plants can receive more sunlight to increase their growth
   c. does not need fertilisers

3. One of seed selection techniques before sowing:
   a. boiled
   b. using saturated salt solution
   c. grinded

4. The benefit of using organic fertiliser is
   a. improve soil texture, aeration, and drainage
   b. kills weeds
   c. quickly absorbed by plants

5. Rice straw should be
   a. burned
   b. composted or incorporated back into the soil
   c. removed from the field

6. Which one is a not rice weed?

a.  b.  c. 

7. Which one is natural enemy?

a.  b.  c. 

8. Blast is caused by?
   a. insects
   b. fungi
   c. bacteria

9. Stem borer can be controlled by:
   a. applying N fertiliser all at once
   b. splitting N fertilisers into several applications
   c. lowering water level

10. Below is stem borer

a.  b.  c. 

11. Growing rice bunds with plants other than rice can:
    a. invite natural enemies and protect rice plants from pests
    b. invite rice plant enemies
    c. promote more weeds

12. Integrating duck into rice production system will:
    a. damage rice plants and reduce rice yields
    b. suppressed weeds and pests
    c. increase weed abundance

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Chapter 6
General discussion

6.1. Introduction

By applying integrative ecological approaches, this thesis has developed sustainable rice-based production systems containing diverse plant and animal species that combine traditional and modern rice cultivation methods. Created with the understanding that weeds, pests and nutrients are the major constraints in crop production, these systems are referred to as complex rice systems (CRSs). Here, selected plant and animal species which are known for their roles in weed and pest suppression as well as nutrient cycling were combined to replace chemicals which are often overused in conventional rice production systems (Wu *et al.*, 2018; Lee *et al.,* 2017). The selection of the species (azolla, fish, ducks and border plants) was made based on both their ecological functions and compatibility in flooded rice ecosystems. Towards a more integrative approach, selected cultivation methods of the system of rice intensification (SRI), *jajar legowo* and organic rice production were adopted.

Nevertheless, the complex nature of CRSs cannot be fully understood by a single analysis. Therefore, several analytical approaches as well as empirical methods were employed in this thesis, including analysis of agronomic traits, economics, weather, plant enemies and protection, animal behaviour, socio-biophysical conditions, and knowledge transfer.

In Chapter 2 it is demonstrated that rice grain yields increased progressively in compliance with a gradual increase of the number of integrated elements (compost, azolla, fish, and ducks) during a growing season with extremely high rainfall. As a result, the gross margin was increased due to the additional marketable products generated from these CRSs.

Chapter 3 confirmed that CRSs not only show static and dynamic stability of rice yields, but also have the highest reliability index, and thus outperform the conventional and organic monoculture systems.

The mechanisms behind these high rice yields and their stability were investigated in Chapter 4. This study revealed that increasing the level of complexity reduced weed and pest incidences due to intensive foraging activities of fish and ducks on weeds, insect pests and snails. Besides acting as cover crops, azolla, together with sun hemp supplied feed for ducks and fish and in return duck and fish excreted manure, thus enhancing nutrient cycles in rice ecosystems via feeding and excretion. While rainfall can wash off agro-chemicals, azolla, fish, ducks and border plants may function well under the rain. Consequently, the overall rice yield was higher and less variable in the most complex systems compared to the conventional rice monocultures, especially during extreme rainfall events.

Finally, Chapter 5 provided an effective and inexpensive method to guide the implementation of CRSs by showcasing adaptation processes in different socio-biophysical conditions. This method is a modification and simplification of the original setup of the farmer field schools (FFSs), which are familiar to stakeholders in many developing countries.

6.2. Concepts and dynamics of complex rice systems

The concept of CRSs is an optimisation of rice ecosystems by integrating various natural resources (biotic and abiotic) above and below the water surface as well as the rice bunds to promote mutual interactions for sustainable rice production in order to improve rice yield and rice farm productivity per unit area while protecting the environment. This concept comprises spatial decision support elements that allow the provision of ecosystem services including weed and pest suppression as well as nutrient cycling services.

The interactions among the various elements in CRSs are depicted in Figure 1, where rice plants and the unique wetland rice ecosystem can attract many floral and faunal species, including pests and weeds. Integrated azolla can cover water and soil to prevent weed infestation. With its ability to fix nitrogen from the air, azolla also provides nitrogen for rice. The addition of ducks and fish suppresses weeds stronger than merely utilizing azolla, while also controlling pests via their feeding and movement behaviour. In addition, fast-growing azolla provides feed for ducks and fish. Adding border plants can invite and safeguard natural enemies to add plant protection strategies in the rice ecosystems. Sun hemp and other border plants can also be used as feed for ducks and fish or as green manure. Together with azolla, which is eaten by ducks and fish, these border plants enhance nutrient cycling via feeding and excretion processes, providing sufficient nutrients for rice from the mineralised excreta and green manures.

This intensive nutrient cycling in CRSs may also lead to nitrogen excesses and losses as has been demonstrated in Chapter 4. However, the uptake of nutrients by plants and azolla cover avoid unfavorably high nutrient (ammonia) concentrations in the water.

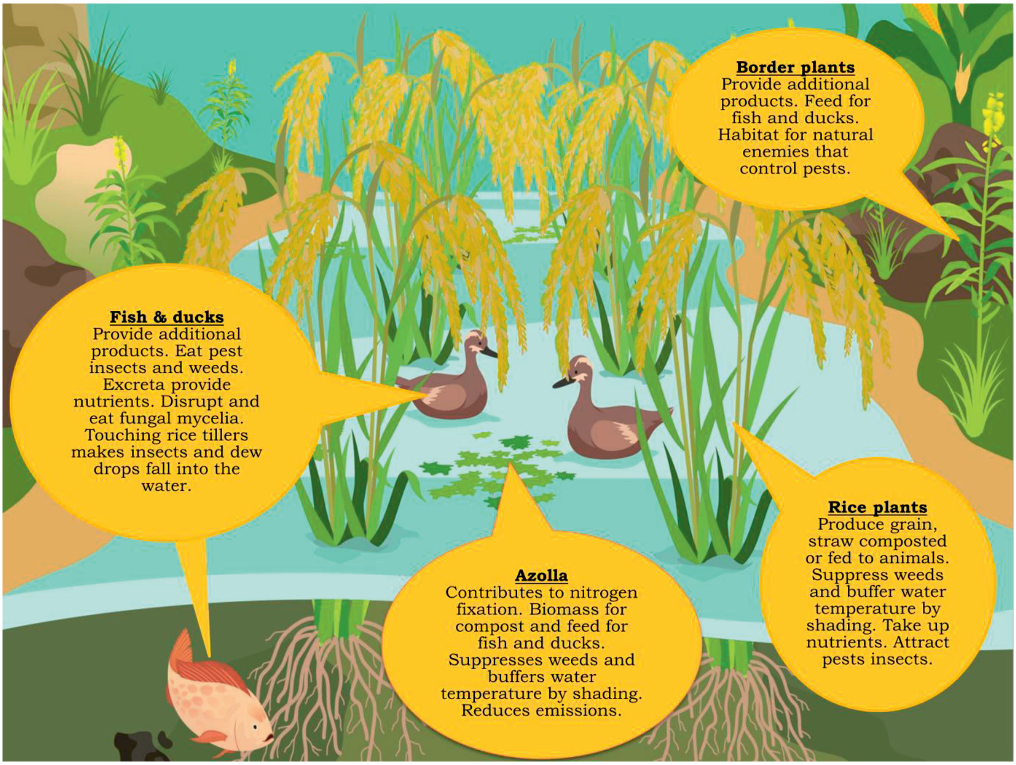

Figure 1. Conceptualisation of complex rice systems and their species interactions.

6.3. Contribution of CRSs to food security

Historically, rice has been a dominant staple food in Indonesia (van der Kroef, 1952), where it was first domesticated before 1600 B.C. with *Javanica* (Indonesian: *padi bulu*) as the originating genotype of Indonesian rice (FAO, 1993). The dynamics of rice consumption patterns in Indonesia are closely aligned with their rice production levels (Mears, 1984). For example, during the '*cultuurstelsel' (Dutch)* programme in the 1800s (referred to as '*tanam paksa'* in *Indonesian,* which translated to *enforcement planting*), Indonesian people were forced to grow export crops on their rice fields as a tax payment to the Dutch (Silean, & Smark, 2006; Multatuli, 1868). As a result, rice was scarce, and Indonesian staple food shifted to tubers (Boomgard, 2003) until the '*tanam paksa'* programme was ended. After independence, rice consumption continuously increased, reaching 460 g per person per day especially during the golden era of Green Revolution in the 1980s. However, the Indonesian monetary crisis in the late 1990s increased agricultural inputs prices, reducing rice production (Erwidodo and Ratnawati. 2004; Haryati and Aji, 2005), thus affecting daily rice consumption to less than 400 g per capita (Panuju *et al.,* 2013; Statistics Indonesia, 2014). This period was the starting point of a number of programmes that diversified staple food to reduce rice consumption in Indonesia.

However, with the exception of a smartly supported family planning programme in the early 1980s (Elson, 2001), many unsuccessful attempts have been made to achieve rice self-sufficiency, such as creation of new rice fields to improve rice production while reducing rice consumption. Extreme weather events occurring more frequently resulted in the further decline of rice yields and have become a greater challenge for rice production (Lesk *et al.,* 2016). Altogether, this put immense pressure to the Indonesian government to secure a national rice stockpile. The 'One-day without rice' programme has been promoted but failed to reduce rice demand in Indonesia (Indonesia-Investement, 2017). Furthermore, a programme of 'no single day without rice planting and harvesting' (Shofyanty, 2018) has also been promoted in the last five years by the Ministry of Agriculture of the Republic of Indonesia, showing the urgency of meeting the national demand for rice.

Presently, as the fourth most populous country in the world, Indonesia has become one of the top three rice consuming countries and the leading rice importer even though its rice production is also among the top three in the world (FAO, 2016). Therefore, with a high population density along with high rice consumption per capita, food security in Indonesia is under threat. To improve its food security, the Indonesian government has provided subsidy schemes since the 1970s (Warr and Yusuf, 2014; World Bank, 2011) for chemical inputs and stable rice prices (Simatupang and Timmer, 2008; Fane and Warr, 2008; Mcculloch and Timmer, 2008). Unfortunately, the subsidy schemes only benefit conventional rice farmers because the subsidy is only available through the mechanisms of low prices for agro-chemicals. These chemicals are prohibited in organic production systems, whereas organic inputs and organic management measures are not subsidized by the government. In general, despite premium prices, this makes the gross margin of organic rice almost similar to that in conventional systems. Based on our communications with farmers, several organic rice farmers reverted back to conventional production methods, whereas the number of new organic farmers was limited. As a result, the production volume of organic rice in Indonesia has not changed significantly since it was initiated in the late 1980s (Suharjo *et al.,* 2016).

The findings in Chapters 2 and 3 revealed that besides producing more stable and higher rice yields, the contribution of CRSs to improve food security was also due to their ability to produce more diverse food products than in monocultural conventional and organic systems. By taking the example of an average de-hulled rice yields of 7.5 Mg per ha per cropping cycle (based on communications with farmers in East Java) and assuming a whole grain weight loss of about 35% after milling, the carrying capacity of CRSs compared to rice monocultures is shown in Table 1. Based on a current daily diet of 2550 kcal for an Indonesian consumer (FAO 2014), the results of calculations show that CRSs can produce 19% more energy than a monoculture system. With the average of 2.5 times amount of rice growing per year in our study sites (Laborte *et al.,* 2017), energy produced in CRS can feed 58 people, while only 47 people per year can be fed with rice monoculture systems. Above and beyond energy produced, CRS can produce more protein, fulfilling the requirements of 80 people per year, while protein for only 39 people can be produced in monoculture. Since CRSs produce a larger array of products, they contribute to dietary diversification by providing more nutrition food groups.

Table 1. Calorie and protein produced per cropping cycle in monoculture CRS per hectare.

Products	Production (kg cycle^{-1} ha^{-1})	Energy (kcal in thousands)		Protein (kg)	
		Monoculture	CRSs	Monoculture	CRSs
Hulled rice	4875	17550	17550	322.2	322.2
Duck meat (density = 400)	600		2424		69
Duck eggs	140		259		22.4
Fish	600		576		120
String bean	400		188		11.2
Water spinach	2000		560		60
Pak choi	500		65		7.5
Papaya	96		41		0.5
Total		**17550**	**21600**	**322.2**	**612.8**

Source of nutrient composition: USDA

6.4. Other benefits of complex rice systems

In conventional monoculture systems the role of agricultural biodiversity is usually overlooked. On the contrary, CRSs are mainly dependent on species diversity for ecological processes to buffer plants from pest, weed and nutrient problems. The concept of CRSs that combines various techniques of rice cultivation methods and integration of several plants and animal species offers many benefits. In addition to safeguarding food security as explained in Section 6.3, CRSs extend their benefits to food and income diversity, labour shortage solutions, improvement of environmental qualities and farm self-sufficiency.

CRSs offer income diversity to farmers, and fish and ducks can provide higher income than rice for these farmers. As mentioned in Chapter 2, the gross margin of farming with the most complex system was 114% higher than the gross margin in the common organic monoculture treatment (rice and compost combination only). The calculation in this most complex system did not include border plants that may further increase gross margin.

Further benefits of CRSs include potential solutions for human labour shortages in the current global aging agricultural labour population (Guo *et al.,* 2015) in which existing machinery is not suitable for small-scale rice farms in developing countries. Based on the results of the surveys and experiments in this thesis, Figure 3 presents a comparison of labour inputs for fertilization and weed and pest management among conventional systems, organic systems and CRSs. Among these three activities, presently, labour inputs are largely allocated to hand weeding in both conventional and organic production systems, while spraying pesticides and herbicides account for about 10% of the hours for hand-weeding (Annex Figure 1 of Chapter 3). Fewer weed and pest incidences and higher soil nutrient status in the higher complexity systems demonstrated in this study suggest lower labour inputs are required in CRSs. Thus, although additional labour inputs are needed in the earliest stage of the transformation (which are not included in the calculation in Figure 3), implementing CRSs can be a solution for human labour shortages in the long-term. This gives more flexibility on rice production management while mitigating delays in weed and pest control as well as fertilization.

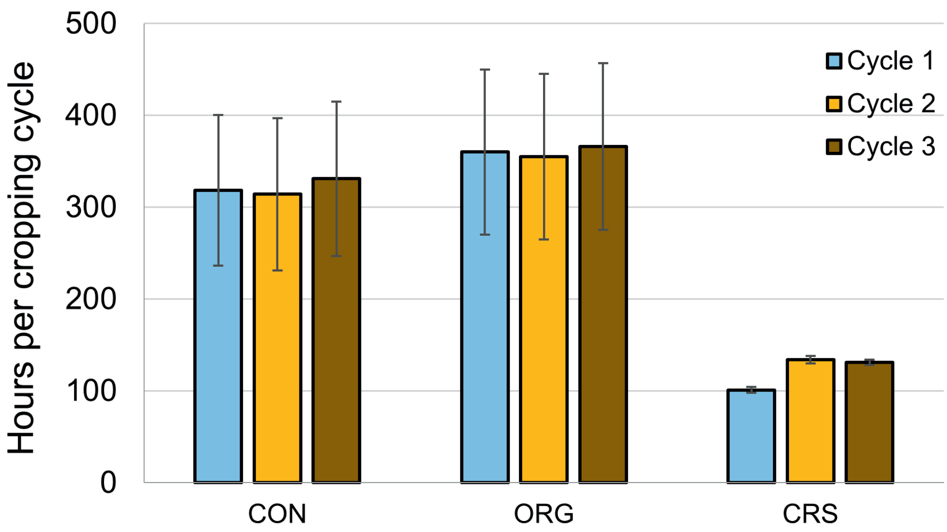

Figure 3. Labour inputs of weed, pest and nutrition management per rice cropping cycle of the three rice production systems during the experiment. CON, conventional; ORG, organic; CRS, complex rice system.

Pesticides, herbicides and fertiliser excesses are considered as sources of pollutants that are harmful to human, animals, and ecosystems. Based on the surveys and experimental data results of this study, implementation of CRSs potentially reduces the load of chemicals that originates from conventional farms, which was presented in Table 2 in Chapter 5. The benefit of CRSs is that the interactions among integrated elements in CRSs can generate ecological processes of weed and pest suppression and nutrient cycling, replacing pesticides, herbicides and artificial fertilisers. Altogether, the synergy between integrated elements in the rice ecosystems is more robust against extreme weather than agrochemicals. Therefore, CRSs are not only supporting the improvement of rice yields in the short-term but also providing long-term services for the stability of high rice yields. The positive impacts of CRS implementation in this aspect are both the reduction of the costs to purchase chemicals and the restoration of many ecosystem services, as explained in Chapter 4.

6.5. Trade-offs

Having combinations of rice cultivation methods in organic rice production with diverse species, CRSs promise many benefits and exhibit a wide range of options which may provide integrated solution strategies. Notwithstanding the benefits offered by CRSs, biophysical and socio-economic variations may complicate the implementations of CRSs, engendering their trade-offs. Some examples of CRS trade-offs along with their possible alleviation strategies, are presented in this section.

6.5.1. High and stable rice yields versus investment in knowledge

To implement CRSs, farmers are required to have knowledge in a wide range of rice cultivation methods and biodiversity management. This becomes a trade-off due to the fact that many smallholder rice farmers are illiterate and lack access to pertinent information (Chapagain and Raizada, 2017). Furthermore, implementation of CRSs in different socio-biophysical conditions also needs adaptation process to the local conditions as elaborated in Chapter 5. Therefore, appropriate training that considers curricula for illiterate farmers is a prerequisite while guiding the adaptation process. A group of farmers is probably able to organise such training, however, initial costs for steps such as hiring a facilitator and setting up an initial experiment maybe too high for them. Interventions of other actors such as government, NGOs, or universities are essential to initiate the training and to ease the burden of the initial training costs. Once the training is initiated, further training along with following cropping cycles can be organised by the farmer group itself, as was mentioned in Chapter 5. Finally, linking the national programmes for rural development and food security that have been initiated in the last five years in Indonesia with the training agenda for farmers might be an option to accelerate the development.

6.5.2. High farm productivity versus high initial capital outlay

Diverse commodities integrated in CRSs can enhance farm productivity per unit area of production, leading to the generation of income diversity and farm income improvement. However, the higher the complexity of the integrated components, the higher the initial capital outlays need to be. These initial capital outlays are required to: (i) purchase materials for fencing and duck housing, (ii) purchase inputs of organic fertilisers, ducklings, fish, azolla and border plant seeds and (iii) pay labourers who re-construct infrastructures, such as enhancement of rice bunds and making fish pond as well as duck houses. Integrating animals into the rice production systems also means additional management such as feeding, which requires daily attention. When farmers want to be more self-reliant, feeding management can lead to forage management (growing forage on rice bunds, etc). However, in the long-term, the required labour inputs for feed and forage management have been included in the calculation for labour inputs in CRSs in Figure 3. These inputs are still much lower than those in conventional and organic systems as shown in Figure 3.

As it may be difficult for smallholders to pay all capital outlays in the same period of time, alleviating this trade-off will require the establishment of priorities by maximising opportunities based on locally available resources. A 'Pareto-optimal' approach with a step-by-step implementation strategy over two to three rice-cropping cycles to split costs and risks exists as a solution. This would imply that at least one preference criterion can be improved without impairing any other system evaluation criteria. With these step-wise adaptations, a little improvement may significantly contribute to the enhancement of farm performance (Groot *et al.,* 2012). For example, starting with vegetables as border plants on the bunds that are wide enough in the first cropping cycle can provide immediate cash as an incentive to motivate farmers to further implement other CRS elements in the following cropping cycles. Further element integration will depend on the socio-biophysical conditions. For example, having a deep water system and clay soils that have a better ability to hold water, provides an immediate favourable environment for fish to be integrated after growing border plants in Lamongan. It can then be followed by duck integration when the facilities for ducks to access both dry and wet areas are established. In Malang, under slightly different conditions, azolla and ducks can be integrated after border plants are grown while waiting for the soil of the rice bunds to harden after being widened. As shown in Figure 1 in the annex of Chapter 3, immediate effects by prioritizing duck integration can be seen from the reduction of costs for hand weeding which is the main problem for farmers in Malang.

6.5.3. Long-term labour reduction versus short-term labour burden

CRSs offer a solution for labour shortages that have already occurred and will worsen in the future, by exploiting the potential role of biota, especially those of ducks that can replace hand weeding, spraying pesticides and herbicides, and fertilization. However, integrating many elements into current industrialised monoculture rice production systems requires not only various input purchases but also facilities to manage the integrated elements as mentioned in Section 6.5.2. This means short-term extra work to build the facilities such as ponds for fish, azolla nurseries, duck housing and fencing, as well as reconstruction of rice bunds. As a consequence, this will need increased labour inputs during the early phase of CRS establishment, which might even distract farmer's focus from producing rice to only preparing the CRS infrastructure. However, once rice bunds have been widened and facilities for CRSs are constructed, further maintenance will be similar to that in current systems. Furthermore, longer-term labour inputs can be significantly reduced from the current systems (Figure 3). Nonetheless, solutions to alleviate this trade-off exist, again, using a step-by-step strategy. For example, instead of managing all elements at the same time, in the early phase of CRS implementation, rice farmers may invite duck farmers to herd their ducks into their fenced rice fields in exchange for duck feed or other small incentives. The extra work may be allocated only for widening rice bunds in this phase before rice planting, while weed and pest management are executed by ducks through this exchange without burdening rice farmers to manage the ducks. Thus, rice is not abandoned while rice bunds are ready to be used to fully implement CRS in the next cropping cycle.

6.5.4. Environmental protection versus limited community awareness

While working with many conventional rice farmers during the study periods of this thesis, many of them had a similar opinion that growing border plants can attract pests. Rice bunds should be cleared and constructed very narrowly (IRRI, 2016). In contrast, agro-biodiversity is the key to ecosystem function restoration in CRSs. This is especially true for weed and pest suppression and nutrient cycling to replace agrochemicals. Implementation of CRSs may generate conflicts between specialist rice farmers and CRS farmers who use rice bunds to grow plants other than rice, with the former assuming that they can be sources for birds to perch and for rats to reproduce. Stronger tension can occur between rice and duck farmers. For example, there were many signs prohibiting duck farmers from herding their ducks in several clusters of rice farms in the early project implementation in our study sites. Balancing information and educating farmers as well as the community is needed to raise community awareness for environmental protection through CRS dissemination. Therefore, the only way to solve the challenges associated to this trade-off is to build a pilot-scale farm from which farmers and community can learn, as was discussed in Chapter 5.

Moreover, many rice farmers are sharecroppers with variety of agreements. This may give rise to trade-offs in which further agreement between sharecroppers and the owners is needed where communication between them should be mediated. Involvement of both sharecroppers and owners is important in the process of CRS development. Further trade-offs, such as market availability, need to be managed collectively, and further organisation of communal management is necessary. Finally, these all require multiple actors with diverse interests working in conjunction, keeping open communication, and maintaining government involvement in embracing multidisciplinary approaches.

Agricultural Extension Officers are those who have the closest relation with farmers in Indonesia. Their roles are crucial for agricultural development, thus, their knowledge should be advanced regularly. This upgrading and reformulating their roles in an evolutionary manner may ensure the implementation of agricultural development in synergy with government programmes. This is also in line with the alleviation of the cost reduction trade-off from Section 6.5.1 to hire a facilitator since extension officers under the Ministry of Agriculture of Indonesia are paid by the government. Raising farmer awareness about the environment and agro-ecosystem functioning is important for CRS implementation. A contest to design their farms, as was mentioned in Chapter 5, may attract farmers. By supporting initial capital for the transformation and providing awards or incentives, this contest may motivate farmers to implement CRSs.

6.6. The outlook for future research

The findings of this thesis contribute to current knowledge on the roles of azolla, fish, ducks, and border plants in mediating ecological processes of weed and pest suppression as well as nutrient cycling in rice ecosystems. Optimal use of available resources and space with more compatible biodiversity affirms ecosystem service persistence in rice ecosystems. Integrative approaches of SRI and *jajar legowo* cultivation methods in organic rice production create favourable conditions to assure maximal rice plant performance. These integrative approaches seemed to complicate management of contemporary conventional farming, but adaptation measures were identified to mainstreaming CRS implementation. Nevertheless, this thesis still leaves some questions open for further investigation.

As was mentioned in Section 6.4, two challenges of CRS should be addressed immediately for further research. First, the results discussed in Chapter 4, show that although NH_3 concentration in CRSs was lower than that in conventional systems, it was higher than in organic without animal components. Second, current NO_3^- concentration ($N\text{-}NO_3^-$) in the groundwater of CRSs (2 mg/ L) was the highest among all the treatments despite still far below the maximum contaminant level (10 mg/L; US EPA, 2017) in this experiment. The integration of water plants that can be matched with rice as biological nitrogen absorber in CRSs can be explored for NH_3 and NO_3^- mitigation studies.

Another subject that deserves further study involves the roles of the housewives, as they are crucial in Indonesia in preparing food for the family and in managing household food expenditure. Their knowledge on nutrition will influence the choices regarding the household diet that may also influence the decision on food diversification on the farm according to the objectives of CRSs. Women should therefore be involved in the training and other nutrition improvement programmes. Therefore, their perception on CRSs and associated objectives and constraints, as well as their preferences on the types of integrated elements after being exposed with the CRS development programmes would be a very interesting study topic.

In addition, research is also needed to understand the factors affecting the stability of azolla growth that demonstrated variability from place to place as shown in Chapter 5. Chapter 2 and Chapter 3 have answered the research question on the effects of the complexity on the attainability of rice yields and their yield stability, revealing that the rice yields were progressively improved by an increase of complexity levels. Referring to the results of duck behaviour observation in Chapter 4 which showed that ducks were less active during the night, beging the question whether letting the ducks on the rice fields day and night will have the same effects as letting them on the rice fields only during the day. It would be interesting to have this question answered for practical reasons to reduce risks from predators and theft that mainly occurs during the night as addressed in Chapter 5.

In addition, the questions addressed on how stable rice yields can be achieved in CRS have also been revealed in Chapter 4. The mechanisms include duck and fish feeding and movement behaviour that were identified to be directly responsible for ecological processes of weed and pest suppression as well as nutrient cycling. However, plant physiological processes may also be affected by both direct and indirect interactions among integrated elements of the various biota with rice plants and could be further investigated. Their interactions, for example, may create environmental conditions that allow the diffusion of nutrients to the rice plants. Consistent contact with the ducks and fish may stimulate the process of leaf thickening of rice plants, which increases plant protection capacity from pest attacks.

To conclude, this thesis contributes to the development of a new innovation in the rice production system that integrates various sustainable cultivation methods and biodiversity. The selection of functional groups of species having roles in recycling nutrients and suppressing weeds and pests in CRSs, leading to high-stable rice yields, has reconciled the conflict between food production and biodiversity conservation. This may apply to other agricultural systems, especially those that are highly dependent on external inputs. For example, poultry production is the most important livestock farming in Indonesia that is highly dependent on imported feed. Integration of corn, legumes and poultry may make nutrient cycling in poultry production systems more efficient while also making the systems more self-sufficient. This is because corn and legumes provide feed for the poultry, and poultry manure provides nutrient for the plants. A free-range poultry system established after a corn-legume intercrop may also provide plant protection against pests and weeds.

Short and long-term on-farm experiments across several biophysical conditions together with a thorough analysis of ecological processes, plant performance, animal behaviour and other farming aspects under diverging weather conditions, confirmed the positive outcomes of CRSs in this thesis. Showcasing adaptation measures provided by this thesis can guide a rural development programme for scaling out CRSs. With respect to the large number of questions left in this thesis, further studies will give more insight to how develop better management strategies in order to improve the ease of implementation while further improving ecological sustainability of CRSs. Finally, CRSs are not necessarily complicated for implementation if communication between stakeholders is further developed and opportunities to access knowledge and appropriate training are equal for all across gender, social and educational background, age, and farm ownership status.

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Summary

English summary

This thesis aimed to develop bio-diversified rice-based farming systems by combining diverse plant and animal species, and traditional and modern rice cultivation methods. This approach is referred to as complex rice systems (CRSs) as an integrative solution to improve rice yields along with their yield stability and whole farm productivity in an ecological way. Functional groups of species selected based on their compatibility with each other to fit into rice ecosystems, leading to the nomination of azolla that lives on the water surface, fish that live underwater, ducks that enjoy foraging on wetlands, and border plants that can optimise rice bund use. They also must have potential roles in suppressing weeds and pests and accelerating nutrient cycles to release nutrients.

Azolla is an N-fixing water fern that can contribute to nutrient enrichment while covering the water surface to inhibit weed emergence. Fish and duck foraging behaviours can suppress weeds and pests. Border plants on rice bunds can facilitate natural enemy development. Altogether, their interactions can release nutrients via feeding and excretory processes to support rice growth and development.

To maximise performances of all integrated elements, sustainable rice cultivation methods such as the system of rice intensification (SRI), *jajar legowo*, and organic rice production were integrated in CRSs. Organic production that prohibit chemical use thrive fish and duck production. Meanwhile, by adopting principles of SRI, the single young rice seedlings per hill and wider spacing to reduce competition result in healthy and vigorous root growth that allow optimal nutrient uptake and the development of each plant, leading to better rice grain yields.

This thesis comprehensively introduces, examines, and synthesis the concept of CRSs based on short and long-term on-farm experiments and action research, which aredistributed throughout six chapters. The main chapters (Chapters 2, 3, 4 and 5) provided an overview of the analyses of attainable rice yields along with their yield stability and whole farm productivity, including the adaptation measures, which were related to extreme weather conditions, complexity levels and socio-biophysical conditions.

Chapter 1 describes the rationale and scope of this study. The objectives of the study and the research questions were also addressed along with methodical approaches to answer the research questions and to achieve the goals. Chapter 2 attempts to investigate the effects of the combined

elements, revealing that by adding combinations of compost, azolla, ducks and fish resulted in strongly increased grain yields and revenues in a season with extremely adverse weather conditions. The highest grain rice yield was obtained under the most complex system comprising all components. The net revenues of this system from sales of rice grain, fish and ducks were higher than rice cultivation with only compost as fertiliser. These results demonstrate how complex agricultural systems can contribute to food security in a changing climate as well as income diversity from various secondary products.

Chapter 3 confirms the stability of high yields and stability of grain rice under CRSs. The chapter demonstrates that the introduction of additional elements into the rice cropping system enhanced the adaptive capacity of CRSs to extreme weather events in all tested locations and cropping cycles. CRSs showed both static and dynamic stability, and had the highest reliability index, thereby outperforming the conventional and organic monoculture systems. Chapter 4 provides an explanation of the mechanisms underlying high and stable rice yields under CRSs during five cropping cycles in on-farm experiments. The observations revealed that increasing the level of complexity resulted in lower levels of weed and pest infestation. Analysis of duck behaviour and their gizzard composition showed that ducks foraged intensively on weeds, insects, snails, and azolla. Furthermore, nutrient cycling was accelerated by ducks via feeding and excretion as well as by their movement in the field. Altogether, these explain why the rice yields increased along the gradient of complexity, which were consistent over time. Chapter 5 presents a case study of CRS adaptation measures to various socio-biophysical conditions using a simplified and modified farmer field school (FFS) approach. By means of simplification and modification of current FFSs, feedback from farmers was generated as adaptation measures of CRS, while improving the cost-effectiveness of FFS.

In Chapter 6, it is concluded that the development of a new innovation in the rice production system that integrates various cultivation methods and diverse plant and animal species produced highly stable rice yields can contribute to safeguarding food security, improving food and income diversity and offers a solution for the human labour shortage. Despite offering many benefits, CRSs implementation also arises trade-offs. Together with the strategy of alleviation, these trade-offs are assessed in Chapter 6. To sum up, CRS is an example model of an agrobiodiversity that can reconcile food production and biodiversity conservation. Examples of the adaptation measures provided in this thesis can be a guide for scaling out CRSs as a rural development programme. Further studies are recommended to focus on better management strategies to reduce nitrogen losses from the systems and improve the ease of CRS implementation. Finally, stakeholder communication and equal opportunities to access knowledge and appropriate training for all community members are the keys to implement CRSs.

Nederlandse Samenvatting

Dit proefschrift heeft als doel een biologisch-gevarieerd en op rijst gebaseerd bedrijfssysteem te ontwikkelen doormiddel van het combineren van diverse plant- en diersoorten en traditionele en moderne teeltmethoden. Deze zogenoemde complexe rijst systemen (CRSen), als een integrale oplossing de rijstoogst te verbeteren en de productiviteit van het bedrijf als geheel op een ecologische wijze. Functionele soortgroepen werden geselecteerd op basis van hun compatibiliteit met elkaar en geschiktheid voor rijst-ecosystemen, wat resulteerde in: azolla dat op het wateroppervlak leeft, vis dat onderwater leeft, eenden die hun voedsel verzamelen op het waterrijke land en planten die op de kant groeien die het gebruik van dijkjes in het rijstveld kunnen optimaliseren. De soorten moeten ook een potentiele rol hebben in het onderdrukken van onkruiden en plagen en in het versnellen van de nutriëntencycli voor het vrijmaken van voedingsstoffen.

Azolla is een N-bindende watervaren dat kan bijdragen aan voedingsstoffenverrijking en tegelijkertijd opkomende onkruiden kan onderdrukken door het wateroppervlak te bedekken. Het foerageergedrag van vissen en eenden kan onkruiden en plagen onderdrukken. Planten op de dijkjes op de kant van het rijstveld kunnen de ontwikkeling van natuurlijke vijanden faciliteren. Samengenomen kunnen de interacties tussen de soorten nutriënten vrijmaken door opname- en uitscheidingsprocessen wat de rijstgroei en -ontwikkeling ondersteund.

Voor het maximaliseren van de prestaties van alle geïntegreerde elementen werden duurzame methoden van rijstteelt, zoals het systeem van rijst intensivering (SRI), *jajar legowo*, en biologische rijstproductie geïntegreerd in CRSen. In biologische productie, waarin het gebruik van chemicaliën is verboden, kan de productie van vis en eend goed gedijen. Het tegelijkertijd toepassen van principes van SRI, waarmee de jonge rijstzaailingen alleen worden geplant en meer tussenruimte krijgen per heuvel om competitie te verminderen, resulteerde in gezonde en krachtige wortelgroei en maakte optimale voedselopname mogelijk en dat elke plant zich kon ontwikkelingen wat leidde tot betere opbrengst van rijstkorrels.

Op uitgebreide wijze introduceert, onderzoekt en synthetiseert dit proefschrift in zes hoofdstukken de concepten van CRSen gebaseerd op korte- en lange termijn praktijkexperimenten en actie-onderzoek (action research). De belangrijkste hoofdstukken (Hoofdstukken 2, 3, 4 en 5) geven een overzicht van de analyse van haalbare rijstopbrengsten samen met hun opbrengststabiliteit en de productiviteit van het bedrijf als geheel, dit omvat ook de adaptatie maatregelen die waren gerelateerd aan extreme weersomstandigheden, niveaus van complexiteit en sociaal-biofysische omstandigheden.

Hoofdstuk 1 beschrijft de rationale en scoop van deze studie. De doelstellingen van de studie en de onderzoeksvragen worden ook geadresseerd samen met de methodische benaderingen om de onderzoeksvragen te beantwoorden en de doelen te bereiken. Hoofdstuk 2 tracht de effecten te onderzoeken van de gecombineerde elementen en laat zien dat door het toevoegen van de combinaties van compost, azolla, eenden en vis de rijstkorrel opbrengst en inkomsten sterk toenamen in een seizoen met extreem ongunstige weersomstandigheden. De hoogste rijstkorrel opbrengst werd bereikt in het meest complexe systeem bestaande uit alle componenten. De netto inkomsten van dit systeem door verkoop van de rijstkorrel, vis en eenden was hoger dan van rijstteelt met alleen compost als meststof. Deze resultaten tonen aan hoe complexe landbouwsystemen kunnen bijdragen aan voedselzekerheid in een veranderend klimaat, evenals inkomensdiversiteit van verschillende secundaire producten.

Hoofdstuk 3 bevestigd de stabiliteit van hogere opbrengsten en stabiliteit van de opbrengst van de rijstkorrel bij CRSen. Het hoofdstuk laat zien dat de introductie van additionele elementen in het rijstteeltsysteem het adaptatievermogen verhoogd van CRSen tegen extreme weersomstandigheden op alle proeflocaties en in alle gewascycli. CRSen laten zowel statische als dynamische stabiliteit zien en hadden de hoogste betrouwbaarheidsindex en presenteerden daarbij beter dan conventionele en biologische monocultuursystemen. Hoofdstuk 4 geeft een verklaring voor de mechanismen onderliggen hoge en stabiele rijstopbrengsten onder CRSs gedurende vijf gewascycli. De waarnemingen laten zien dat een toename van het niveau van complexiteit resulteert in lagere niveaus van onkruid- en plaaguitbraken. Analyse van het gedrag van eenden en de samenstelling van hun spiermaag laat zien dat eenden intensief foerageren op onkruiden, insecten, slakken en azolla. Daarnaast werd de nutriëntenkringloop versnelt door eenden via hun voedingsopname en uitscheiding als ook door hun bewegingen in het veld. Samengenomen laten deze resultaten zien waarom de rijst opbrengsten toenamen langs de gradiënt van complexiteit die consistent waren gedurende de tijd. Hoofdstuk 5 presenteert een casestudie van CRS adaptatiemaatregelen bij verschillende sociaal-biofysische omstandigheden met behulp van een vereenvoudigde en aangepaste 'farmer field school' (FFS) aanpak. Door vereenvoudiging en aanpassing van bestaande FFSs werd feedback van boeren gegenereerd als adaptatiemaatregelen van CRS terwijl de kosteneffectiviteit van de FFS werd verbeterend.

In hoofdstuk 6 wordt geconcludeerd dat de ontwikkeling van een nieuwe innovatie in het rijstproductiesysteem, waarin verschillende teeltmethoden en diverse plant- en diersoorten zijn geïntegreerd, zeer stabiele rijstopbrengsten opleverde wat kan bijdragen aan het waarborgen van voedselzekerheid, voedsel- en inkomensdiversiteit verbeteren, en biedt een oplossing voor het tekort aan menselijke arbeid. Ondanks het feit dat het veel voordelen biedt, leidt de implementatie van CRS ook tot compromissen. Samen met de mitigatiestrategie worden deze compromissen in Hoofdstuk 6 geëvalueerd. Samenvattend is CRS een voorbeeldmodel van agrobiodiversiteit dat voedselproductie en behoud van biodiversiteit kan verzoenen. Voorbeelden van de adaptatiemaatregelen die in dit proefschrift worden gegeven kunnen een leidraad zijn bij het opschalen van CRSen als een programma voor plattelandsontwikkeling. Verdere studies worden aanbevolen om te focussen op betere managementstrategieën om stikstofverliezen van de systemen te verminderen en de implementatie van CRS te vergemakkelijken. Ten slotte zijn stakeholdercommunicatie en gelijke kansen op toegang tot kennis en passende training voor alle leden van de gemeenschap de sleutel om CRSen te implementeren.

Ringkasan bahasa Indonesia

Penelitian ini bertujuan untuk mengembangkan sistem pertanian padi berbasis keragaman hayati dengan menggabungkan beragam spesies tanaman dan hewan yang dipadukan dengan berbagai metode bercocok tanam padi tradisional dan modern. Sistem ini selanjutnya disebut sebagai sistem pertanian padi komplek (PK) yang dalam bahasa Inggris disebut sebagai complex rice system (CRS). Tujuan utama dari sistem PK ini adalah untuk meningkatkan hasil panen padi beserta stabilitas hasil panennya sekaligus produktivitas lahan sawah secara keseluruhan dengan menggunakan cara-cara ekologis sebagai sebuah ‘solusi terpadu’. Kelompok-kelompok hewan dan tanaman yang digabungkan pada sistem PK ini dipilih berdasarkan kemampuannya untuk dapat hidup berdampingan satu sama lain dan yang dapat beradaptasi dengan ekosistem sawah diantaranya azolla, ikan, itik dan tanaman pematang. Kelompok tanaman dan hewan tersebut dipilih juga karena kemampuannya yang berpotensi untuk dapat menekan gulma dan hama serta mempercepat siklus nutrisi yang dapat dilepas ke ekosistem sawah.

Azolla adalah sejenis tanaman paku yang hidup diatas permukaan air dan memiliki kemampuan untuk mengikat nitrogen di udara bebas sehingga dapat berkontribusi untuk pengayaan unsur hara tanah pada ekosistem sawah. Dengan habitat hidupnya yang berada diatas permukaan air, azolla juga dapat menghalangi gulma muncul ke permukaan air sehingga pertumbuhannya terhambat. Perilaku ikan dan bebek yang gemar mengais dan memakan gulma dan hama, baik dibawah maupun diatas permukaan air dapat berperan dalam pengendalian gulma dan hama. Sedangkan pematang sawah yang ditanami tanaman dapat memikat dan memfasilitasi berkembangnya musuh alami sebagai salah satu strategi untuk pengendalian organisme pengganggu tanaman. Peningkatan keragaman hayati ini akan meningkatkan intensitas hubungan makan dimakan antara komponen-komponen yang dipadukan yang akan melepaskan unsur hara yang bermanfaat bagi tanaman padi maupun komponen lainnya.

Untuk memaksimalkan kinerja dari semua komponen yang dipadukan, metode bercocok tanam seperti SRI (the System of Rice Intensification)dan *jajar legowo* digunakan pada sistem PK ini. Budidaya padi organik yang melarang penggunaan bahan kimia akan mendukung pertumbuhan dan perkembangan ikan dan bebek, sehingga dapat meningkatkan hasil panennya. Sementara itu, dengan mengadopsi prinsip-prinsip SRI antara lain dengan penggunaan satu bibit padi muda per lubang tanam dan jarak tanam yang lebih lebar akan mengurangi persaingan antar tanaman. Hal ini akan menghasilkan pertumbuhan akar yang sehat dan kuat yang memungkinkan penyerapan nutrisi secara optimal sehingga tanaman padi juga dapat tumbuh dan berkembang secara maksimal, yang akhirnya akan meningkatkan hasil panen padi.

Konsep pertanian sistem PK ini dikembangkan berdasarkan hasil dari serangkaian uji coba baik jangka pendek maupun jangka panjang yang dilengkapi dengan penelitian aksi secara partisipatif pada lahan-lahan sawah komersial milik petani. Secara detail, hasil penelitian untuk pengembangan sistem PK ini dipaparkan pada bab-bab utama pada buku ini yaitu pada Bab 2, 3, 4, dan 5. Pada bab-bab utama tersebut, analisis hasil panen padi dan stabilitas hasil panennya dihubungkan dengan tingkat keragaman hayatinya. Analisa hasil panen padi pada penelitian ini juga dihubungkan dengan aspek pertanian lain misalkan kondisi cuaca yang bervariasi selama masa penelitian. Penelitian aksi secara patisipatif dengan berbagai pihak yang berkepentingan dilakukan untuk merumuskan langkah-langkah adaptasi terhadap penerapamn sistem PK pada berbagai kondisi sosial dan biofisik yang berbeda. Disamping itu, Bab 1 dan Bab 6 juga dihadirkan untuk memberikan gambaran awal dan refleksi lebih dalam terhadap bab-bab utama.

Bab 1 menjelaskan latar belakang, tujuan dan ruang lingkup penelitian ini. Secara terperinci, tujuan dari penelitian ini dituangkan pada empat pertanyaan penelitian yang disertai dengan pendekatan metodisnya untuk menjawab pertanyaan penelitian tersebut. Bab 2 mencoba untuk menyelidiki pengaruh dari tingkat keragaman unsur-unsur yang digabungkan terhadap hasil panen padi termasuk pendapatan usaha taninya. Hasil penelitian menunjukkan bahwa dengan meningkatkan jumlah keragaman pada lahan sawah yang diuji, hasil panen padi beserta pendapatan dapat meningkat meskipun pada kodisi cuaca ekstrim. Hasil panen padi tertinggi diperoleh pada perlakuan dengan jumlah keragaman paling tinggi. Demikian juga dengan pendapatan bersih diperoleh pada sistem dengan jumlah keragaman komponen yang paling tinggi pula melalui hasil penjualan gabah, ikan, dan itik. Hal ini menunjukkan bagaimana sistem pertanian PK dapat mengurangi dampak buruk perubahan iklim sehingga berkontribusi tidak hanya untuk ketahanan pangan namun juga pada peningkatan sumber pendapatan petani.

Bab 3 membahas tentang hasil panen padi dan stabilitas hasil panen pada tiga sistem budidaya padi, yaitu konvensional, organik, dan PK. Pada bab ini dijelaskan bahwa dengan meningkatkan keragaman hayati dapat pula meningkatkan kemampuan adaptasi dari sistem budidaya padi terhadap berbagai peristiwa cuaca yang bervariasi. Hasil analisa juga menunjukkan bahwa hasil panen padi pada sistem PK memiliki stabilitas yang tinggi, baik untuk stabilitas secara statis maupun dinamis. Hasil panen padi pada sistem PK juga memiliki indeks keandalan (reliability index) yang tertinggi sehingga hasil panen padi dengan sistem PK ini mampu mengungguli hasil panen padi pada kedua sistem monokultur baik konvensional maupun organik.

Selanjutnya, pada Bab 4, mekanisme proses ekologis yang terjadi pada sistem PK yang diuji selama lima musim tanam padi pada lahan sawah milik petani diuraikan secara detail. Hasil pengamatan menunjukkan bahwa dengan peningkatan keragaman hayati, serangan gulma dan hama pada sistem PK terbukti lebih rendah. Hasil analisis perilaku bebek dan komposisi temboloknya yang duiji melalui beberapa uji coba terbukti bahwa itik secara intensif memakan gulma, serangga, siput, dan azolla. Hasil penelitian juga menunjukkan bahwa itik dapat mempercepat siklus hara melalui peristiwa makan dan pengeluaran kotoran (ekskresi) disamping juga melalui gerakannya yang menghancurkan bahan organik pada ekosistem sawah. Secara keseluruhan, dengan penurunan jumlah gulma dan hama serta meningkatnya kandungan hara yang tersedia, hal ini dapat menjelaskan mengapa hasil panen padi pada sistem PK dapat meningkat dan konsisten seiring dengan peningkatan komponen-komponen yang diintegrasikan. Pada Bab 5, studi kasus mengenai langkah-langkah adaptasi sistem PK terhadap beberapa kondisi sosio-biofisik yang berbeda disajikan dengan menggunakan pendekatan sekolah lapang (SL) pertanian yang disederhanakan dan dimodifikasi. Dengan memodifikasi metode SL, umpan balik dari petani terhadap sistem PK dapat diinventarisasi dan di pilih mana yang paling strategis untuk dapat diterapkan sebagai lagkah-langkah adaptasi. Sedangkan penyederhanaan jumlah pertemuan yang hanya ditekankan pada pertemuan untuk pengamatan agroekosistem dengan waktu pertemuan yang juga disesuaikan berdasarkan kesepakatan dengan para petani, maka efesiensi biaya sekolah lapang dapat ditingkatkan.

Berikutnya, pada Bab 6 disimpulkan bahwa pengembangan inovasi baru sistem PK ini dapat meningkatkan hasil panen padi yang lebih stabil sekaligus meningkatkan keragaman pangan sehingga dapat berkontribusi untuk menjaga keamanan pangan dan meningkatkan gizi dan pendapan keluarga tani. Meskipun menawarkan banyak manfaat, pada penerapan sistem PK ini juga memunculkan beberapa dilema. Dilema-dilema tersebut dipaparkan pada Bab 6 dengan sekaligus memberikan strategi untuk mengatasi dilema yang timbul tersebut. Dari uraian diatas, dapat disimpulkan bahwa sistem PK dapat digunakan sebagai salah satu contoh agrobiodiversitas yang mampu memberikan ‘solusi terpadu’ untuk

pemenuhan keamanan pangan, peningkatan keragaman pangan dan sumber pendapatan, dan pemenuhan gizi keluarga serta penyelesaian masalah kelangkaan tenaga kerja dengan tetap menjaga kelestarian lingkungan. Selanjutnya, dari beberapa contoh yang diberikan sebagai langkah-langkah adaptasi sistem PK yang dijabarkan dalam penelitian ini dapat menjadi panduan untuk pelaksanaan program pembangunan pedesaan. Beberapa penelitian lebih lanjut diperlukan pada strategi penurunan kehilangan nitrogen dari system budidaya padi dan manajemen yang lebih baik untuk meningkatkan kemudahan dalam penerapan sistem PK. Selanjutnya, kunci strategis dari penerapan sistem PK ini bergantung pada komunikasi yang baik antar pemangku kepentingan serta kesempatan yang sama dalam mengakses pengetahuan dan pelatihan tentang sistem PK ini

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About the author

Born in a farmer family in Malang, Indonesia, on 20 March 1979, Uma Khumairoh experienced two periods of traditional and modern farming development in her rural community. She saw that traditional farming that manages biodiversity is crucial to protecting food security and the livelihood of full-time smallholder farmer families. This interest led her to study agriculture in Agricultural Faculty, University of Brawijaya (AF-UB), Indonesia for her BSc and specialized herself in plant breeding. She conducted an internship on genetic biodiversity conservation for local Mungbean, and screened those genotypes for their tolerance to the salinity in her BSc thesis. With her ability to maintain high marks while active in a student activity unit during her BSc, she was awarded several scholarships (Phillip Morris, Enhancement of Academic Performance (PPA) and UB thesis fund). She was also awarded as the second fastest BSc graduate. Before graduation, she worked on a coffee plantation in Ijen, East Java in 2002 as a field research assistant. In 2004, she joined a marine and fisheries research project out of UBC Fisheries Centre, University of British Columbia, Canada on Bali straits and National Komodo Park, assisting the fieldwork of its PhD candidate. During this fieldwork, she lived in remote areas with the local communities of fisherman and smallholder farmers, which broadened her knowledge in ecology and natural sciences as well as provided her the opportunity to learn and understand how traditional farming worked for smallholder farmers. This curiosity brought her to join a project with the local NGOs, Mitra Bumi Indonesia and the Institute of Community and Development Studies of East Java (LPKP-Jatim), as a facilitator to develop organic vegetables and rice production with smallholder farmers on East Java. In 2006, she coordinated a project led by LPKP-Jatim on the System of Rice Intensification implementation using participatory experiment and farmer field school (FFS) methods in Malang. In 2008, she was appointed to be the manager of The Community Technology Centre in the same NGO with funding from Microsoft. Having experiences working with smallholder farmers and understanding the constraints in developing organic agriculture in Indonesia, she decided to advance her knowledge by pursuing MSc in Master of Organic Agriculture in Wageningen University in 2009 with financial support from the Ford Foundation. After finished her MSc in 2011, she returned to LPKP-Jatim and expanded her work as the coordinator for community services at the Integrated Organic Farming Systems Research Centre, University of Brawijaya (IORC-UB). During the period of 2011-2013 in IORC-UB, she developed a curriculum for youth on permaculture, organic production, and their implementation in an orphanage, as well as a few Islamic boarding schools. Around the same time, she was also hired by World Education as the senior of the agricultural trainer to train extension officers in Timor Leste to develop FFSs for coffee and vegetable cultivations. She was then awarded a Nuffic fellowship in November 2013 to start her PhD. She was then officially working as a lecturer, a researcher, and the secretary of the International Office in the AF-UB in April 2014. In the same year, her project proposal was granted by the Nestle Kejayan, Indonesia to lead a project in 'a participatory learning to diversify fodder crop production in small dairy farms surrounding the national forest of Konto watershed, Malang, Indonesia'. Simultaneously, in 2015, she was awarded a grant from Nestle foundation, Lausanne, Switzerland to advance her PhD research project. These combined various jobs while pursuing her PhD were not easy, but she was able to manage them successfully, greatly developing her organization and management skills.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Ecological processes underlying performance of complex rice systems and its implementation

Writing of project proposal (4.5 ECTS)

- Improved utilisation of natural resources in complex rice-growing agro-ecosystems

Post-graduate courses (3.3 ECTS)

- Ecological management of rodents, insects, and weeds in rice agro-ecosystems; IRRI, the Philipines (2015)

Laboratory training and working visits (1.2 ECTS)

- N, P, K C Analysis; University of Brawijaya, Indonesia (2014)
- Arthropod, weed identification; University of Brawijaya, Indonesia (2014)

Competence strengthening / skills courses (3.8 ECTS)

- Multimedia; UB, Indonesia (2014)
- Scientific writing; WUR (2016)
- Brain training; WUR (2017)
- Stress identification & management; WUR (2015)

PE&RC Annual meetings, seminars and the PE&RC weekend (0.9 ECTS)

- Final year PE&RC meeting (2016)
- Symposium: drought, plant hydraulic traits and vegetation modelling (2018)

Discussion groups / local seminars / other scientific meetings (8.3 ECTS)

- 2nd SAFE conference; oral presentation; Bali, Indonesia (2014)
- Rural food security symposium; keynote speaker; Kediri, Indonesia (2014)
- 1st International organic conference; organising committee; UB, Malang, Indonesia (2014)
- Symposium & workshop multi-stakeholders complex rice systems; keynote speaker; UB,Malang, Indonesia (2015)
- Wise 1st ; poster presentation; Wageningen; (2016)
- Wise 2nd ; oral presentation; Wageningen (2017)

International symposia, workshops and conferences (11.3 ECTS)

- CBD- COP12; Pyeong Chang; Republic of Korea (2014)
- 5th FSD; oral presentation; France (2015)
- 1st Asian bioculture conference; oral presentation; Ishikawa, Japan (2016)
- 6th Conference satoyama; oral presentation; Siem Riep, Cambodia (2016)
- Satoyama initiative regional workshop; oral presentation; Sabah, Malaysia (2017)
- Menu for change international forum; keynote speaker; Prague, Czech (2018)
- 7th Conference satoyama initiative; oral presentation; Kanazawa, Japan (2018)

Lecturing / Supervision of practicals / tutorials (17.7 ECTS)

- Organic plant production; UB (2014)
- Plant ecology; UB (2014)
- Plant production systems; UB (2014, 2015)
- Agro-ecosystem management; UB (2015)
- Agroforestry; UB (2015)
- MOA master class; WUR (2015, 2018)
- Permaculture; WUR (2017)
- Agrobiodiversity; WUR (2017)
- Organic animal prod; WUR (2017, 2018)
- Introduction to organic production systems; WUR (2018)

Supervision of MSc students

- Experimental analysis of the suitability of ducks, fish and field border plants in complex rice systems in Lima Puluh Kota Regency, Indonesia
- Effects of duck density on suppression of weeds and pests in complex rice systems in Indonesia
- The influence of duck behaviours on weed propagation in complex rice systems in Indonesia
- Evaluation of local rice genotypes under conventional and organic cultivation in Indonesia
- Effects of duck density and foraging frequency on rice production systems in East Java, Indonesia
- Pest and weed suppressive mechanisms in complex rice system at Malang, East Java, Indonesia
- Effects of foraging intensity for the convenience of duck management in complex rice systems in Ciamis, Indonesia
- Understanding practices of complex rice system in East Java, Indonesia

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