

Improving Resource-use Efficiency in Rice-based Systems of Pakistan



Masood Iqbal Awan

Propositions

1. Aerobic rice is a viable option to improve water productivity in regions like Pakistan where water is getting scarcer than land.
(this thesis)
2. Unavailability of well-adapted aerobic varieties of *basmati* rice is a major constraint for expansion of the aerobic rice system in Pakistan.
(this thesis)
3. For the development of a country, eco-efficiency of resource use is at least as important as natural resource abundance.
4. Crop models are often bureaucratic in nature: over-simplified to address a complex problem or over-complicated to resolve a simple problem.
5. Actions designed to improve water use efficiencies must consider trade-offs among the use of water, land, labour, capital, fertiliser and energy.
6. Conducting research is not like catching fish on the beach; it is like searching pearls in the ocean.
7. Pakistan and India need more cricketers and fewer politicians to solve their long-standing conflicts.

Propositions belonging to the PhD thesis:

Improving resource-use efficiency in rice-based systems of Pakistan

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Improving resource-use efficiency in rice-based systems of Pakistan

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Abstract

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Just like in many other parts of the world, diminishing resources of water, labour and energy threaten the sustainability of conventional flooded rice systems in Pakistan. Changing the current production system to non-flooded aerobic rice could considerably increase resource-use efficiencies. However, for subtropical conditions, such as those in South Asia, the non-conventional system is still very much in the development phase. The main objective of this study was to evaluate the aerobic rice system of the Punjab in Pakistan from a biophysical and socio-technological perspective. I employed a combined approach of experimentation and farmer surveys to contribute important information on aerobic rice crop performance, pre-flowering photothermal responses, and farmers' perspective.

Two seasons of field experiments (2009 and 2010) at the research station of the University of Agriculture, Faisalabad–Pakistan tested local (KSK133, IR6, RSP1) and exotic (Apo, IR74371-54-1-1) genotypes against different combinations of irrigation levels (high, moderate, low) and nitrogen rates (0, 170, 220 kg N ha⁻¹). Under aerobic conditions, the water productivity (WP_g; g grain kg⁻¹ total water input) improved significantly, showing a potential water saving of about 20%. However, this improved water productivity was at the cost of declining land productivity, as the actual production per unit area decreased. Grain yield and total aboveground N uptake were mainly limited by irrigation and not by N. The results suggest significant losses of applied N, and indicate that improvements in N use efficiency might be expected if N application is better synchronised with the N-demand of the crop.

Accurate knowledge on rice phenological development is an important feature when the aim is to better match supply and demand for further improvement in resource use efficiencies. A controlled-environment growth chamber study, aimed at estimating pre-flowering photothermal responses, gave a robust set of photoperiod-parameters and demonstrated that all four tested genotypes (KSK133, RSP1, Apo, IR74371-54-1-1) were strongly photoperiod-sensitive. The temperature range in the field experiments was too narrow to achieve convergence to a unique set of optimal temperature response parameters. Yet, sensitivity analysis clearly showed that commonly used standard cardinal temperatures (base, optimum, maximum: 8, 30, 42°C, respectively) overestimated the time to flowering. Data obtained under a wider range of temperatures should result in more accurate estimation of temperature response parameters.

To supplement the basic biophysical research, I conducted farmer surveys (n=215) in three major cropping systems viz. rice-wheat, mixed-cropping and cotton-wheat to understand farmers' perspective about the future prospects of aerobic rice system. Most of the farmers were unaware of aerobic rice technology but expressed their keen interest in experimenting. Farmers perceived aerobic rice as a system to improve resource use efficiency particularly for labour and water but they consider it a knowledge intensive system requiring careful and timely management practices especially for weeds. The unavailability of suitable fine grain aerobic *basmati* varieties was identified as a major constraint for large scale adoption.

Understanding farmers' perspective helped to develop guidelines for the emerging aerobic rice system. The aerobic rice system is a rational approach for improving WP_g and eco-efficiencies of water, labour and energy. Associated risks of crop failure can be reduced by filling the identified knowledge and technological gaps through additional research and adequate training of farmers.

Keywords: Aerobic rice, water productivity, pre-flowering phenology, eco-efficiency, perceptions, transformational technology, food security, resource constraints, Punjab, Pakistan.

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CHAPTER 1

General Introduction

Arable land and water are the two principal natural resources in Pakistan. Arable land is 22 million hectares (Mha), around one-quarter of the total area of the country. About 75% of the arable land is irrigated mainly through the world's largest contiguous gravity flown irrigation network of the Indus River running through nearly the full length of the country (Fig. 1.1). Pakistan's economy still heavily relies on agriculture contributing about 21% to its gross domestic product (GDP) and employing 45% of the work's labour force (GOP, 2012a). Pakistan possesses all the basic elements required for a progressive agriculture – fertile soils, an extensive network of irrigation, appropriate climatic conditions characterised by a high solar radiation throughout the year, and hardworking farmers. This huge potential is articulated by this verse:

“But of his barren acres, Iqbal will not despair: A little rain and harvests shall wave at last, oh Saki” * (National poet-philosopher Allama Iqbal, 1877–1938).

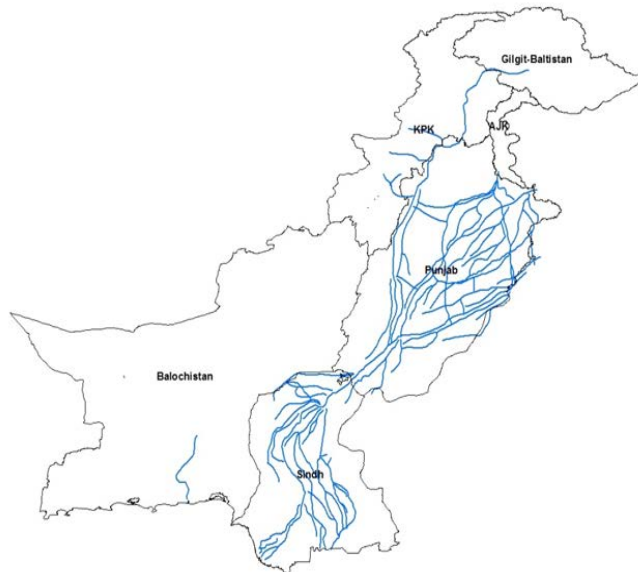


Fig. 1.1. Command area of the Indus basin irrigation system in different provinces of Pakistan.

* English Translation by V.G. Kiernan

Major cash crops are cotton (*Gossypium hirsutum*), sugarcane (*Saccharum officinarum*), wheat (*Triticum aestivum*), maize (*Zea mays*), and rice (*Oryza sativa*). Rice is a highly valued cash crop grown on an area of 2.7 Mha with a total production of about 6 million tonnes (Mt) (Fig. 1.2). Pakistan, just like Thailand, Vietnam, India, and the United States, is among the top five rice exporting countries. These five countries account for 85% of global net trade, of which Pakistan's share is 9% (Wailes and Chavez, 2012).

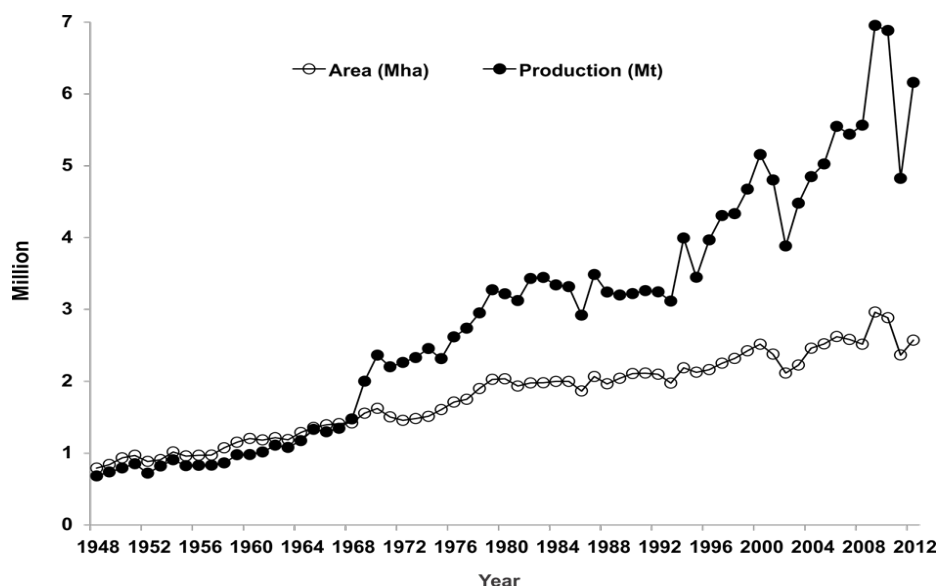


Fig. 1.2. Area and production of rice in Pakistan (1948 – 2012).

Source: Economic Survey of Pakistan 2011/12.

Rice crop grows under diverse climatic conditions. The major rice-growing areas can be categorised into four ecological zones (Fig. 1.3). Zone I consists of the northern high mountainous areas. The climate is subhumid, monsoonal summer type with 750–1,000 mm average annual rainfall. Short duration, cold tolerant rice varieties are recommended for this area to cope with cold injury caused by cold water under low temperature conditions. Zone II is located in the 'Rechna Doab' i.e. land between two rivers– Ravi and Chenab. The climate is semi-arid, subtropical type with 400–700 mm rainfall. The rice growing season is fairly long and suitable for cultivating coarse- (*non-basmati*) as well as fine-grain aromatic (*basmati*) rice varieties. The premium quality *Basmati* rice grows along the 'Kalar tract' which lies in this zone. The Kalar tract is characterised by heavy clay soil with good water holding capacity. Zone III is a large tract of land on the west bank of Indus River. The climate is arid, subtropical

type with 100 mm average annual rainfall. Heat tolerant coarse-grain varieties are grown as the temperature may exceed 50°C in this zone. Zone IV is the Indus delta where the climate is arid tropical marine with no marked seasons, suitable for growing coarse grain varieties (Salim et al., 2003; Bashir et al., 2007). Apart from these major rice growing areas, rice patches are also found in other cropping patterns based on cotton, sugarcane, and maize.

Paddy rice is typically grown by transplanting 30–35 day old rice seedling in continuously flooded conditions with ponding depths of 50–75 mm for most of the growing season, requiring 15 to 25 irrigations. Total water application ranges from 1200 to 1600 mm over a 100–150 day growing period. In general, paddy's gross water requirement is about 1600 mm considering the water required for land preparation (450 mm), evapotranspiration (650 mm), and seasonal losses through seepage and percolation (500 mm) for a fine-textured soil, but a large variation is reported in the total amount applied i.e. 465–3642 mm (Aslam et al., 2002; Ahmad et al., 2007).

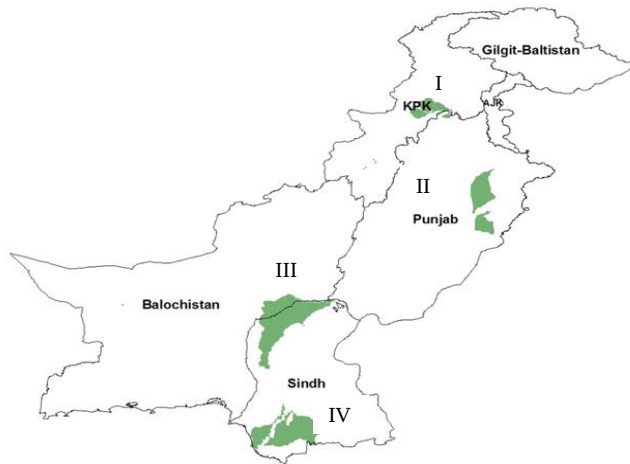


Fig. 1.3. Ecological zones of four main rice growing areas in different provinces of Pakistan.

Pakistan is one of the most water-limited countries with per capita water availability of little over 1000 cubic metres (m^3) and its dependence on a single river system offers little robustness. The system is already running near maximum capacity and there is no additional water that could be injected into it. Inherent complexities of the system and an inadequate knowledge base make it difficult to address the large scale degradation of the resource base due to silting, salinity, pollution, and climate change. Pakistan has only little storage capacity i.e. 150 m^3 per capita relative to the other arid countries such as the United States (5000 m^3) and China (2200 m^3). Institutional failure resulted

in poor governance, distrust, and financial constraints for the implementation of water sector projects. With all these '*sobering facts*', there are some '*hopeful facts*' too. Pakistan has overcome major water challenges in the past and possesses a well-established system of water entitlements. High returns from previous investments in infrastructure and avoiding the trap of subsidising electricity for pumping groundwater are hailed as great achievements. There is also additional scope for increasing productivities per drop of water consumed. Rational and effective use of water will increase total crop production, create job opportunities, and raise income level (GOP, 2007; Briscoe and Qamar, 2009).

There is already a pressing need to identify and adopt measures that will improve water productivity (WP), particularly in '*water-guzzling*' crops like rice. Different water saving technologies have been developed by researchers across the globe including alternate wetting and drying (Bouman and Tuong, 2001), continuous soil saturation (Borrell et al., 1997), system of rice intensification (Stoop et al., 2002), ground cover systems (Lin et al., 2002), and raised bed systems (Choudhury et al., 2007). A fundamentally different approach from these partially aerobic systems is the truly aerobic rice system in which soils are kept aerobic almost throughout the growing season. In aerobic rice systems, rice is cultivated in unpuddled, non-flooded fields under non-saturated (aerobic) soil conditions just like other upland crops such as wheat, maize, and cotton. Aerobic rice is different from the conventional transplanted-flooded rice systems because the crop is direct seeded (instead of being transplanted) and kept under aerobic conditions throughout the growing season. This differs from the more extensively managed 'upland system'; in aerobic systems rice is grown under relatively favourable conditions by supplying external inputs such as fertiliser, irrigation, and herbicides.

Improving *efficiency* i.e. the level of output per unit of input has always been a dominant force shaping agro-ecological systems and human behaviour. For example the hunter-gatherer societies sought improvements in labour efficiency by changing their habitat, diet, or hunting-gathering practices to match food supply patterns (Keating et al., 2013). Emerging global resource constraints have led to a renewed focus on improving the overall eco-efficiencies of agriculture (Keating et al., 2010; Mateo and Ortiz, 2013). Conceptually, *eco-efficiency* is achieving more agricultural outputs in terms of quality as well as quantity with less inputs of land, water, nutrients, energy, labour, or capital, thus covering both the ecological and economic aspects of sustainable agriculture. With this concept including economic and ecological dimensions, Keating et al. (2010) noted that the evolving social and institutional dimensions will determine the extent of further development of eco-efficient agricultural systems.

Aerobic rice could considerably improve current eco-efficiencies in the Pakistani Punjab where water, labour, and energy are becoming increasingly scarce. Efficiency gains in terms of one resource are sometimes at the expense of efficiency losses in terms of another resource. For example, greater water use efficiencies (yield per unit of water) are often associated with lower land use efficiencies (yield per unit of land). In other cases, one efficiency can be increased with little to no efficiency decline for other resources, or even a synergistic effect on other resource use efficiencies. It is therefore important to investigate trade-offs between efficiencies. An optimal system is then a system that maximises resource use efficiency of the most limiting resource (in this case water) while keeping possible efficiency losses for other resources within acceptable limits.

1.1. Challenges in rice-based cropping systems of Pakistan

Rice is grown on irrigated fields (Chapagain and Hoekstra, 2011). Rice-based cropping systems are rice-wheat, rice-berseem, rice-pulses, rice-vegetables and rice-fallow (GOP, 2013). The rice-wheat system, covering an area of 2.2 Mha, is the major cropping system practiced in Pakistani Punjab since 1920. Rice and wheat are two strategic commodities, which make up 90% of total food grain production, thus ensuring food security and providing livelihood to millions of farmers (Timsina and Connor, 2001; Gupta et al., 2004; Erenstein, 2012).

The transplanted-flooded rice system was developed during times of abundant land, water, and labour resources. Drastic increases in yields during the green revolution period (1965–1985) started to stagnate towards the end of twentieth century. With low income generating ability and low conversion efficiencies for the scarce inputs, conventional systems are showing their limitations for resource poor farmers. The villainous stagnation of productivity now threatens the sustainability of intensive systems via the degradation of soil and water resources (Ladha et al., 2003; Erenstein, 2009). Degradation of the resource base is due to conflicting edaphic requirements between rice and succeeding crop, evident from decline in soil organic matter/nutrient availability, increase in soil salinisation, weed infestation, and the build-up of pathogens and pests (Timsina and Connor, 2001; Sahrawat, 2012). Major factors responsible for low values of productivity and meagre resource use efficiencies for general crop production and rice include shortage of water and labour at critical times of crop growth, low fertility status of soils, salinisation, imbalanced use of fertilisers, losses caused by pests and diseases, antiquated farm implements, unexplored potential of suitable germplasm due to slow traditional breeding process, and rising costs of inputs (Khan et al., 2006; Kahlown et al., 2007; Farooq et al., 2008).

Especially in rice-based systems water shortage and low plant population per unit area are the two main hurdles for realising full yield potential because rice is a water- and labour-intensive crop. Although agriculture sector employs 45% of labour force, rice farmers often face the problem of labour shortage during transplanting. Manual transplanting by contractual and unskilled labourers under often extreme climate conditions is an arduous task. Transplanting needs to be completed before the fields dry out, so the contractual labour paid on area basis leaves patches in the field resulting in uneven plantings (Pandey and Velasco, 2005; Baloch et al., 2007). With an inadequate supply of canal water and insufficient rainfall, water shortage is becoming a norm rather than an exception, as all paddy fields in Pakistan are essentially irrigated. Paddy production was badly hit in 2012 by failing rains early in the season and by intense rains and floods late in the season. In addition to water and labour shortage, the worsening energy crisis ensued significant increase in prices of diesel, electricity, and fertilisers, further adding to the cost of production. Most of the rice area is prone to waterlogging and salinity, thus limiting the possibilities of replacing the rice crop with another.

The eco-efficiencies of the conventional rice system in Pakistan are amongst the lowest in the world. Average productivity during the last five years was 2.3 Mg ha^{-1} against a potential yield of $\sim 10 \text{ Mg ha}^{-1}$. Nutrient use efficiencies are 30–45% for N, 20–25% for P, and 80% for K. These values are often below the average estimates of 30–60% for N, 10–35% for P, and 15–65% for K (Zia et al., 2002; Dobermann and Fairhurst, 2000). At the national level water productivity (WP_g) for rice is only $0.16 \text{ (g grain kg}^{-1} \text{ water input through irrigation and rainfall)}$, whereas in the Punjab's rice-wheat system a typical field scale average value of 0.23 g kg^{-1} was reported (Zia et al., 2002; Jehangir et al., 2007; Dahri et al., 2008), which is low in comparison with $\geq 0.40 \text{ g kg}^{-1}$ reported under South Asian conditions (Prasad and Donald, 2011; Kadiyala et al., 2012). Despite all the above-mentioned challenges, favourable price prospects in recent years inspired producers to increase overall rice area mainly in the non-traditional rice belt at the expense of other crops including cotton, the number one cash crop in the country (PARC, 2010; FAO, 2013). Since water availability has developed into the major concern for sustainable rice production, an overview of water resources is presented below.

Pakistan enjoys the world's largest contiguous gravity flown irrigation network consisting of 3 main reservoirs (Tarbela, Mangla and Chashma), 19 barrages, 12 inter-river link canals, 2 siphons across major rivers, 45 main canal commands, and about 107, 000 outlets. Annually about 130 billion cubic metres (BCM) river water is diverted in the canal irrigation networks. Rainfall contributes 16 BCM in the irrigation system and groundwater pumping, as a result of over 900,000 private tubewells, is

about 60 BCM. Hussain et al. (2011) calculated that irrigated agriculture is currently facing a water deficit of 20 BCM which is projected to be 27 BCM in the year 2015. The provincial irrigation department is responsible for management, functioning and maintenance of the entire irrigation network, with the exception of the tertiary canals that are maintained by farmers. Canal water is distributed in a weekly or 10-day rotation system, called *warabandi*, within the watercourse command areas to ensure equitable spreading of water over maximum area.

The water share depends on the size of the landholding of a user and on the water availability in the distribution network. The water distribution system, which is based on a fixed rotation and a crop-based water charge is still common, although discrepancies exist between official- and in practice rules (Hussain, 2007). The supply based irrigation network operates largely in a water-short environment and there is much inequity and unreliability in water distribution at different levels i.e. within a watercourse, along the distributaries, and along the canals (Latif, 2007). The downstream farmers suffer due to lower water supply than authorised due to the conveyance losses, canal breaches due to water theft, and poor maintenance of irrigation infrastructure (Ahmad et al., 2007).

Farmers have to supplement insufficient canal water by groundwater. Canal water is cheap i.e. approximately US\$3.9 ha⁻¹season⁻¹ of about six months but is independent of the quantity of water used for a particular crop. Groundwater pumping is often ≥ 30 times the price of canal water depending on the prevailing energy price and depth of irrigation water (Latif, 2007; Erenstein, 2009). Despite decreasing water availability from canals, judicious use of the scarce canal water remains a secondary concern for farmers due to the prevailing canal water pricing and lack of incentives to enhance WP (Pingali and Shah, 2001; Ahmad et al., 2007). The downstream tail-end farmers use more groundwater than the upstream farmers, which results in deterioration of groundwater quality and land productivity due to salinisation (Hussain et al., 2003; Latif, 2007). Average annual rainfall is under 250 mm, two-thirds of which is concentrated during the monsoon period. The flooded conditions during most of the growing season require water applications of about 1200 to 1600 mm. This has led to extra pumping of low quality groundwater (Ahmad et al., 2007). As a result of this increasing reliance on groundwater, the energy pricing becomes an influential lever for water management (Shah et al., 2009).

1.2. Aerobic rice production as an option: experiences in other parts of the world

Cultivar improvement and better soil-, crop-, and water management practices are among the most important options for increasing the WP of rice. The traditional, low input-responsive, upland cultivars are water stress tolerant, but their yield potential is very low i.e. 1–2 Mg ha⁻¹. The commercial lowland cultivars are high yielding but cannot withstand drought conditions. Aerobic varieties combine some of the yield potential-enhancing traits of high-yielding lowland varieties with adaptations to aerobic soils. In Brazil, the development of improved varieties has led to a rapid spread of a commercial cropping system based on aerobic rice (Pinheiro et al., 2006). The aerobic rice is grown on an area of 250,000 ha in the state of Mato Grosso. A similar development has contributed to the cultivation of around 120,000 ha in the northern China plains (Tuong and Bouman, 2003). In northern China, aerobic rice cultivars yield up to 6–7.5 Mg ha⁻¹ in farmers' fields using flash irrigation in bunded fields (Wang et al., 2002). The new class of upland-adapted cultivars possesses improved lodging resistance, harvest index (HI), and input responsiveness. Breeding efforts are underway to develop suitable germplasm for tropical areas. Zhao et al. (2010) identified 26 genotypes, which had a much higher grain yield (GY) potential and better drought tolerance than the two first generation aerobic rice genotypes (Apo and UPLRi-7). The second generation genotypes, likely to be useful for farmers, were vigorous, early flowering, medium to short duration, had a medium plant height and a relatively high HI. Aerobic rice is suitable for 1) favourable uplands with sufficient rainfall and flat land, 2) rainfed lowlands with coarse-textured well drained soils in undulating fields, and 3) water-short irrigated lowlands. Though aerobic rice technology was pioneered in China and Brazil, the system has also been evaluated in other important rice growing countries. Different studies in East, South, and Southeast Asia support the agronomic feasibility of aerobic rice cultivation promising improved resource use efficiencies. Yet the technology is still in its infancy (Bouman et al., 2005; Pinheiro et al., 2006; IRRI, 2010; Mahajan and Chauhan, 2011; Weerakoon et al., 2011; Kadiyala et al., 2012; Mahajan et al., 2012; Mahajan et al., 2013).

The aerobic rice system is gaining momentum in South Asia as an alternate to the conventional transplanted-flooded rice system (Devkota et al., 2013; Mahajan et al., 2013). Under South Asian conditions, water economy is the main driver behind aerobic rice systems. The conventional transplanted-flooded rice system requires huge quantities of freshwater. The WP_g (g grain kg⁻¹ water input through irrigation and rainfall) values range from 0.20 to 1.25 with an average value of 0.40 (Bouman, 2009). Under aerobic rice systems, the WP_g was projected at 0.89 to 1.05 g grain kg⁻¹ water

by crop models (Aggarwal et al., 2004; Luo et al., 2006; Feng et al., 2007; Xue et al., 2008b). Compared to the transplanted-flooded rice, 50–60% of water can be saved maintaining GY levels at 80% attainable under flooded systems. The GY penalty in Pakistan and India ranged between 7.5–28.5% (Kumar et al., 2011). Together with evapotranspiration, the water required for puddling and losses associated with continuous flooding such as seepage and deep percolation demand a high water application rate in flooded system. Kadiyala et al. (2012) reported that compared to flooded rice system, the WP_g increased but land productivity decreased due to decrease in GY under aerobic rice system in field experiments conducted in India.

Alike water savings, the other major advantage is that aerobic rice systems require less labour because they can be mechanised due to non-flooded conditions and direct seeding. Compared to the conventional transplanted-flooded rice system, total labour requirements can be reduced by 11 to 66%, depending on season, location, and type of direct seeding (Santhi et al., 1998; Rashid et al., 2009). Besides water and labour savings, other incentives include crop intensification, resolving edaphic conflicts between rice and succeeding upland crop, rising interest in conservation agriculture, and environmental sustainability through intercropping. In the Mekong Delta (Vietnam) and Iloilo (the Philippines), direct seeding facilitated double cropping instead of single transplanted crop as a result of labour savings and economic incentives (Pandey et al., 2002). Dry direct seeding on unpuddled fields can avoid deleterious effects of puddling on soil structure and formation of a hardpan, especially relevant to the crucial rice-wheat crop rotation in the context of rising interest in conservation agriculture (Ladha et al., 2009). Intercropping aerobic rice with rubber and oil palm during the immature growth phase (0–3 years) will maximise land utilisation and increase farm incomes according to Sariam and Zainuddin (2007).

Aerobic rice systems, however, require careful management interventions, heavily relying on biocides for managing weeds and nematodes. Essential plant nutrients especially N, P, K, Fe, Zn, and Mn may become deficient under aerobic conditions. Yield decline in monocropped aerobic rice is associated with the interwoven effects of nutrient disorders, allelopathy, and root knot nematodes (George et al., 2002; Pinheiro et al., 2006; Nie et al., 2007; Kreye et al., 2009). Management practices should be developed to enhance resource-use efficiency especially for water and nitrogen (N) which are the most limiting factors. Accurate prediction of the timing of different events in plant development is crucial to facilitate timely resource application, which is crucial for optimising resource use of scarce inputs. Lampayan et al. (2010) evaluated the effects of different amounts and timing of N application on GY of aerobic rice under rainfed conditions in Central Luzon, the Philippines. They reported that under rainfed conditions, GY of about 3.1–4.9 Mg ha⁻¹ can be obtained with

fertiliser rates of 60–150 kg N ha⁻¹. The GY increased with higher applications of N fertilisers. The N losses are generally higher under aerobic system than under flooded system due to nitrification-denitrification processes and possibly as a result of decomposition of soil organic matter (Belder, 2005; Kadiyala et al., 2012; Devkota et al., 2013). The flooded conditions favour production and accumulation of NH₄-N that is readily converted to NO₃-N under aerobic conditions and is prone to losses if it is not readily taken up by the crop (Sahrawat, 2009a; Sahrawat, 2012). Higher N losses under aerobic conditions suggest the need to explore options such as increasing the N dose to compensate for losses, enhancing NO₃-N nutrition, application of N in four splits instead of usually recommended three splits, and studying the interactions between N and water regimes (Kumar et al., 2011; Devkota et al., 2013; Li et al., 2013). In addition to the N losses, nutrient imbalances are reported because with an increase in the soil water tension other nutrients, especially P and K, may be limiting (Mahajan et al., 2012).

The concept of aerobic rice holds promise for farmers facing water shortage in flooded lowlands (Bouman et al., 2005). Assessments of farmers' understandings help in identifying the socio-technological factors that inspire or restrain the process of adoption. Farmer perceptions have a significant positive effect on adoption (Adesina and Baidu-Forson, 1995; Negatu and Parikh, 1999). Kumar et al. (2011) reviewed the key cultivation practices in three countries, namely the US, Sri Lanka, and Malaysia, where more than 90% rice area is under direct seeding. The success of different methods of direct seeding (i.e. dry-, wet-, and water-seeding) was made possible by precise land levelling and water management, adapted-cultivars, even crop establishment, and efficient management of weeds and nutrients. They recommended the development of anticipatory research strategies for regions where direct seeding is likely to be adopted. Similar recommendations were proposed by Mahajan et al. (2013) and Weerakoon et al. (2011) who highlighted the need for development and transfer of location-specific technologies for different agro-ecological regions to enhance resource-use efficiency, net profitability, and sustainable rice production in South Asian regions. Mechanisation of weed control and development of suitable germplasm for direct seeded systems has been emphasised in many studies. Weeds are a major constraint under the aerobic conditions and most of the available cultivars are screened under transplanted-flooded systems (Farooq et al., 2009; Weerakoon et al., 2011; Mahajan et al., 2013).

1.3. Introduction to study area

Punjab is the most populous and agriculturally productive province in Pakistan. It accounts for nearly 67% of the rice area in Pakistan and is responsible for 55% of the total rice production. Rice area is further divided into core- and non-core belts. The core or traditional rice belt consists of (district) Sialkot, Narowal, Gujranwala, Hafizabad, and Sheikhupura. The non-core or non-traditional rice belt consists of (district) Faisalabad, Chiniot, Jhang, Lahore, Kasur, Okara, Sahiwal, Sargodha, and Khushab.

Punjab was transformed into the most productive agricultural land during the *British Raj* following the development of huge irrigation infrastructure in nineteenth century. Geographically it is bordered by Kashmir to the north-east, the Indian states of Punjab and Rajasthan to the east, the Pakistani provinces of Sindh to the south, Balochistan to the southwest, Khyber Pakhtunkhwa to the west and the Capital Territory Islamabad to the north. The word Punjab comes from two Persian words *panj* (five) and *aab* (water), thus known as the land of five rivers – Chenab, Jhelum, Ravi, Beas, and Sutlej – the tributaries of the Indus River (Singh, 2008). Muddy waters of these majestic rivers hold the secrets of the Punjab's classical epics. Along the lush green and scenic banks of Chenab river, Ranjha played enchanting flute for his beloved Heer, in these waters Sassi was thrown as a newborn child by her ominous royal parents, Sohni drowned while swimming to meet her beloved Mahiwal waiting on the other side of river Chenab, and the famous story of Mirza-Sahiban played out in the region between Chenab and Ravi rivers. The Indus Valley Civilisation, one of the world's earliest urban civilisations, also flourished along the banks of the Indus River.

The climate in the rice-wheat agroecological zone is subtropical continental, classified as semi-arid with large seasonal fluctuations in rainfall and temperature. Average annual rainfall is 400 mm, two-thirds of which falls during the monsoon period i.e. June to September. Long and hot summers last from April through September with maximum day temperatures ranging between 21°C and 49 °C. Winters last from December through February with maximum day temperatures ranging between 4°C and 24°C. The climate pattern governs two distinct cropping seasons: *Kharif*, the monsoonal summer season in which the water intensive rice crop is sown and *Rabi*, the drier winter season in which the wheat crop is sown. These two staple crops make this region *granary* of the country (Ahmad et al., 2007; Jehangir et al., 2007).

I conducted field experiments at the research station of the University of Agriculture, Faisalabad and farmer surveys throughout Punjab in three different

cropping systems (Fig. 1.4). The non-traditional rice belt of Punjab province is considered an important target domain for aerobic rice systems.

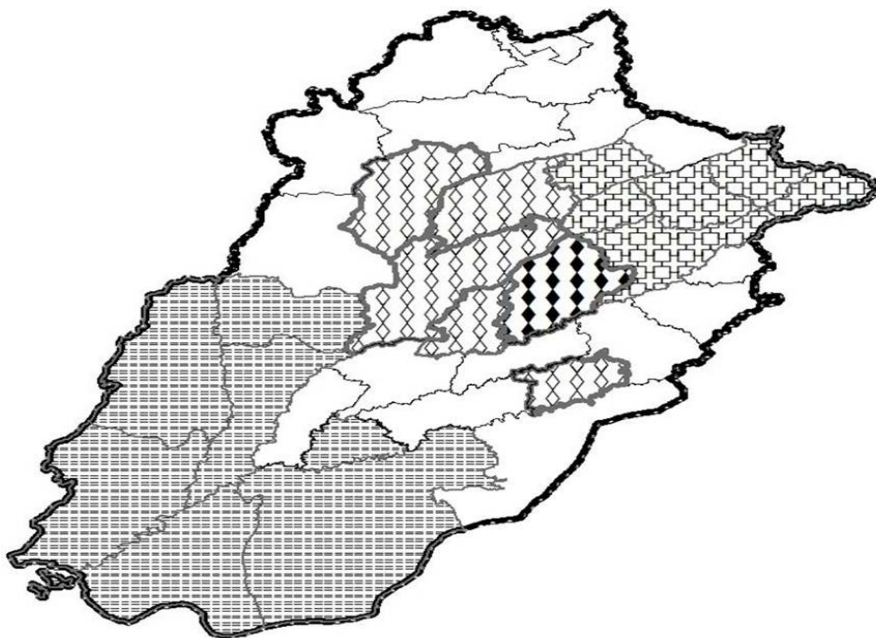


Fig. 1.4. Map of study area showing field experiment site (filled diamonds) and surveyed areas in rice-wheat (squares), mixed-cropping (filled+unfilled diamonds), and cotton-wheat (dashes) cropping system.

1.4. Objectives and approach

In South Asia, aerobic rice is an emerging production system, as it makes better use of the scarce resources of water, labour, and energy. Just like any emerging system it also brings emerging challenges. Agronomic management in combination with technological innovations is required to enhance the resource use efficiencies of precious inputs (water, labour, fertilisers etc.), to cope with the threats posed by climate change, and to address socioeconomic changes such as urbanisation, outmigration of labour, and preference for non-agricultural activities (Ladha et al., 2009).

Considering the complexities and novelty of the aerobic rice system it is important to investigate and optimise its management in well-designed experiments. Optimisation also relies on a better quantitative understanding of rice phenological development, as resource demand is often related to phenology and synchronisation of

supply and demand is key to improving resource use efficiencies. Furthermore, it is important to learn from experiences of farmers who experimented with growing aerobic rice. This study contributes important quantitative information on aerobic rice crop performance and phenology calibration of selected local and exotic genotypes. To complement the basic biophysical research on this topic, I also gathered information on farmer perceptions about the newly proposed system. A thorough review of available literature including peer reviewed articles, research reports, newspaper articles, and personal communication with experts and farmers set the stage for the start of this PhD project. The general objectives of this study were to:

- a) Quantify rice crop performance of selected genotypes in response to different water and N supply rates under aerobic soil conditions
- b) Improve our ability to predict phenology of modern aerobic rice genotypes
- c) Understand and analyse Pakistani farmers' perspective on transformation of transplanted flooded rice to direct seeded aerobic rice

Three different approaches addressed these three objectives. Field experiments covering two rice seasons during 2009–10 addressed the first objective, a detailed controlled-environment growth chamber experiment addressed the second objective and farmer surveys throughout the Punjab province addressed the third objective. Field experiments tested three local genotypes in two seasons (2009/10) against different combinations of water input and N supply rates. Additionally, two exotic genotypes were tested in the second season (2010). Controlled-environment phytotron experiment investigated photoperiod (PP) sensitivity of four genotypes in a reciprocal transfer arrangement under extreme photoperiod conditions. The data obtained from the growth chamber experiment combined with phenological observations from field experiments helped to quantify pre-flowering photothermal responses using an improved rice phenology calibration program (van Oort et al., 2011). Farmer surveys (n=215) generated a data set on farmer perspective about the newly proposed aerobic rice systems. Statistical analyses of the farmer and farm characteristics, level of awareness, interest, farmer perceptions and (in)experiences with aerobic rice helped identifying the emerging challenges in the evolving aerobic rice technology.

In this study a multidisciplinary approach, involving the knowledge of agronomy, physiology, and social sciences was employed to answer the following, overarching research questions:

- 1) Is there a scope to improve WP and N economy by adapting aerobic rice systems?

- 2) How is aerobic rice crop performance of selected genotypes affected by interacting factors of irrigation, N, and genotype (I×N×G)?
- 3) How can we better characterise phenology to be able to improve the timing of resource supply and thus optimise the use efficiency of precious inputs?
- 4) What are the incentives and barriers that might lead to adoption or disadoption of the evolving aerobic rice technology by farmers in Punjab province?
- 5) Based on our findings, what are the prospects for aerobic rice systems in Pakistan?

1.5. Thesis outline

The thesis consists of a General Introduction (Chapter 1), four research papers (Chapter 2–5), and a General Discussion chapter (Chapter 6).

Chapter 2 focuses on water use and rice crop performance of three local and two exotic genotypes in response to different levels of water input under aerobic soil conditions. Implications of findings on phenology, growth, yield, and WP are discussed.

Chapter 3 focuses on N use and rice crop performance of three local genotypes in response to different combinations of water input and N supply rates under aerobic soil conditions. With a specific focus on N response, this chapter elaborates interactions between irrigation, N, and genotype (I×N×G).

Chapter 4 presents a two-step approach to investigate pre-flowering photothermal responses of four modern aerobic rice genotypes. In this chapter, it is explored whether controlled growth chamber experiments improve the photothermal characterisation of rice genotypes.

Chapter 5 details farmer perceptions on transformation of transplanted-flooded rice system to direct seeded aerobic rice system. Based on discussion with farmers, I developed recommendations for the development and transfer of aerobic rice technology in Pakistan.

Chapter 6 summarises the core findings and explores their implications. This chapter concludes with future research directions and main conclusions of the study.

CHAPTER 2

Water use and crop performance of rice (*Oryza sativa* L.) under aerobic conditions in a semi-arid subtropical environment*

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Abstract

Water scarcity challenges the sustainability of conventional rice paddy systems in Pakistan. Changing flooded rice to aerobic rice might be an effective way to improve water productivity (WP) and thus save water. We studied crop performance in relation to different levels of water supply in aerobic rice systems. Three local (KSK133, IR6, RSP1) and two exotic (Apo, IR74371-54-1-1) genotypes were tested in three field experiments during 2009 and 2010. Irrigation levels (high, moderate, low) constituted the main plots and genotypes the sub-plots. Total aboveground dry biomass (TDM) and grain yield (GY) were highest in the high irrigation regime and consistently declined through moderate to low irrigation. TDM (Mg ha⁻¹) ranged from 9.6 to 13.3 and from 5.3 to 12.4 and GY (Mg ha⁻¹) from 3.11 to 5.0 and from 0.79 to 2.41 for the high and low water regime, respectively. The WP_g (g grain kg⁻¹ water) ranged from 0.24 to 0.38 in the high and from 0.11 to 0.26 in the low irrigation treatment. These values are significantly higher than the current national average of 0.16 reported for the conventional system. The lower WP_g at moderate and low water input was due to a reduced reproductive capacity, expressed in a lower panicle number and harvest index (HI). Under limited water supply GY and WP of exotic genotypes were higher than that of local genotypes owing to a high HI. In conclusion, there is great scope for improvement in WP and water saving by a transition towards aerobic rice systems when adapted cultivars and management practices will be introduced in farmer's practice. Particularly in Pakistan, where water scarcity is a greater threat to rice production than land scarcity, aerobic rice systems will offer opportunities to balance production and sustainability. Risk on crop failure can be reduced by providing suitable genotypes, possessing traits of early maturity and ability to maintain reproductive capacity under limited water availability. Crop models can be used to extrapolate our findings on phenology, growth, and WP for a wider range of weather conditions and of irrigation regimes.

Keywords: water productivity, aerobic rice, subtropical, Apo, resource use efficiency, Punjab.

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2.1. INTRODUCTION

Rice (*Oryza sativa* L.), a highly-valued food and cash crop, is sown on an area of 2.7 million hectares (Mha) in Pakistan with a total production of about 6 million tons. In recent years, it has been a major source of foreign exchange earnings due to increase in sown area and total production (GOP, 2012a). Declining water availability is the main threat to sustain production, because all paddy rice in Pakistan is irrigated and the footprint of ground- and surface water, also referred to as blue water, is four times larger than that of rainwater, denoted green water (Chapagain and Hoekstra, 2011). At the same time, irrigated agriculture is facing a water deficit of about 20 billion m³, which is projected to raise to 27 billion m³ in 2015 (GOP, 2007; Hussain et al., 2011). Therefore, there is now a pressing need to identify and adopt measures that will reduce water use by major crops, in particular rice (Kahlowan et al., 2007). Recently, growing rice under aerobic soil conditions, has gained popularity (Bouman et al., 2007a, b). Well managed aerobic rice systems showed grain yield (GY) levels of 4–6 Mg ha⁻¹ in farmer's field conditions (Lafitte et al., 2002; Atlin et al., 2006; Yan et al., 2010), while saving about half of the water that would be required for growing paddy rice (Bouman et al., 2005; Bouman et al., 2007a, b). The target GY for aerobic rice systems is 70–80% of flooded system; the lower GYs can be compensated by using the saved water to irrigate previously un-irrigated area. It is expected that in next few years the cultivation of rice will become possible on 0.4 Mha through direct seeding technology in Pakistan (GOP, 2012b). The aerobic rice system developed for temperate regions of China and Brazil needs further investigation before being introduced in warm tropical and subtropical regions (Prasad and Donald, 2011).

Rice grows in four provinces of Pakistan under diverse climatic conditions but two provinces, Punjab and Sindh, account for nearly 90% of total sown area and production. The conventional system of transplanting 30–35 day old rice seedling in puddled field was developed during times of abundant land, water, and labour resources (Sharif, 2011). Sustainable productivity and improved resource use efficiencies are needed to counterbalance the demands of a rapidly increasing population (~180 million currently) for food and water (Jehangir et al., 2007; Mann et al., 2011).

Changing the conventional production system to aerobic cultivation brings about changes in the soil water regime that in turn induces a change in nutrient dynamics (Belder et al., 2005a), weed infestation (Singh et al., 2008), and timing, severity, or duration of heat/dry spells (de Vries et al., 2011). When put together, all these processes will have serious consequences for crop performance under the new system. Some of the reported consequences are delayed anthesis, reduced biomass production,

panicle sterility, and low harvest index (HI) (Xiaoguang et al., 2005; Castillo et al., 2006; Xue et al., 2008a). Bouman et al. (2005) suggested to analyse the crop performance in terms of yield components such as panicle and grain number, percentage of filled grains, and 1000-grain weight to get an estimate of the sink size. Moreover, this would also give an indication of the stage-specific effects of water stress on crop growth and development in a particular environment. For example, Yan et al. (2010) reported that panicle number was the most limiting factor for GY under aerobic rice systems in the Huai River Basin of China.

Important target domains for aerobic rice systems in Pakistan are the non-traditional rice belt of Punjab province and the whole Sindh province. In the non-traditional rice belt of Punjab, it is difficult to maintain puddling conditions due to water shortage (Mann et al., 2007). Recently, rice area in the non-traditional belt increased by nearly 1 Mha, dominantly planted with *non-basmati* coarse varieties (locally known as *irri* type). Soils in this belt are relatively coarse compared to the typical clayey soils in the traditional rice belt. More than 90% rice area in the Sindh province is occupied by *irri* type varieties which makes it the other important target domain. The coarse grain varieties may show advantage under aerobic rice systems because of their short growth duration and relatively better drought tolerance compared to long duration, fine grain *basmati* type varieties, typically grown in the traditional rice belt of Punjab province (PARC, 2010). In the participatory research trials with aerobic rice systems, conducted by Pakistan Agricultural Research Council (PARC) in collaboration with international research organisations in the target domains, early investigations reported irrigation water savings of 26–32% with GYs comparable or even higher than in the conventional lowland systems of Pakistan (IRRI, 2010; PARC, 2010). There is, however, lack of systematic information regarding genotypic differences for yield performance and water productivity (WP) under different irrigation regimes in the aerobic rice system. In order to provide the necessary quantitative information on yield formation and WP under aerobic rice system, we conducted this study with selected coarse grain genotypes under semiarid conditions of the Punjab province, where aerobic rice is potentially an interesting option for resource poor farmers.

The general objective is to quantify rice crop performance under aerobic conditions to water deficits. The specific objectives of our study were to: 1) compare the performance and WP of selected genotypes under aerobic rice system under three water regimes, and 2) quantify and compare the consequences of potential water input savings for growth, development, and GY. Field experiments were also designed to collect a dataset for modelling studies at the crop and system level.

2.2. MATERIAL AND METHODS

2.2.1. Experimental site and climate

We conducted field experiments at the research station of the University of Agriculture, Faisalabad-Pakistan (31°26' N, 73°06' E, 184.4 m altitude) in 2009 and 2010 covering two rice seasons. The climate of the region is semi-arid and subtropical with an average annual rainfall of about 400 mm. Long and hot summers last from April to September with maximum air temperatures around 50°C and winters last from December to February with minimum air temperatures around 0°C. A meteorological observatory next to the experimental site recorded daily rainfall, maximum and minimum temperatures, radiation, wind speed, and relative humidity (Fig. 2.1). The soil characteristics of the experimental site are Aridisol-fine-silty, mixed, hyperthermic Ustalfic, Haplargid in the USDA classification and Haplic Yermosols in the FAO classification scheme. The ground water table is well below 25 m. At the beginning of seasons in 2009/10, composite soil samples were taken to different depths of 0-100 cm and analysed for various physical and chemical properties (Table 2.1).

2.2.2. Experimental layout, site, and crop husbandry

We conducted three field experiments in 2009/10, all laid-out in a split-plot design with irrigation treatment as main plot factor, and genotype as sub-plot factor in three replicates. Three irrigation treatments i.e. high, moderate, low aimed to create different soil moisture conditions throughout the growing season. When relative soil moisture content (RMC, defined as the moisture content relative to field capacity) dropped to 0.8 (high), 0.6 (moderate), or 0.4 (low), the plots were re-irrigated (~75 mm) (Fig. 2.2a, b). Double bunds separated the plots and plastic sheets installed to a depth of 100 cm prevented seepage. Sub-plot size measured 2.5 × 6 m.

Tropical *indica* type rice genotypes contrasting in origin and growth duration were tested. In the experiments 1 and 2 three local genotypes (KSK133, IR6, and RSP1) were tested in 2009 and 2010. In addition, we conducted experiment 3 in 2010 at the same site next to experiment 2, which evaluated also two 'exotic' aerobic rice genotypes (Apo and IR74371-54-1-1). Local genotype KSK133 (KSK 282 × 4321) is a high yielding, stiff stemmed and extra-long lowland rice variety. This stay-green genotype was released for general cultivation in 2006 by Rice Research Institute, Kala Shah Kaku, Pakistan and recommended for the non-traditional rice belt of Pakistan. It was also used as check variety in direct seeded aerobic rice experiments (Akhter et al., 2007; IRRI, 2010).

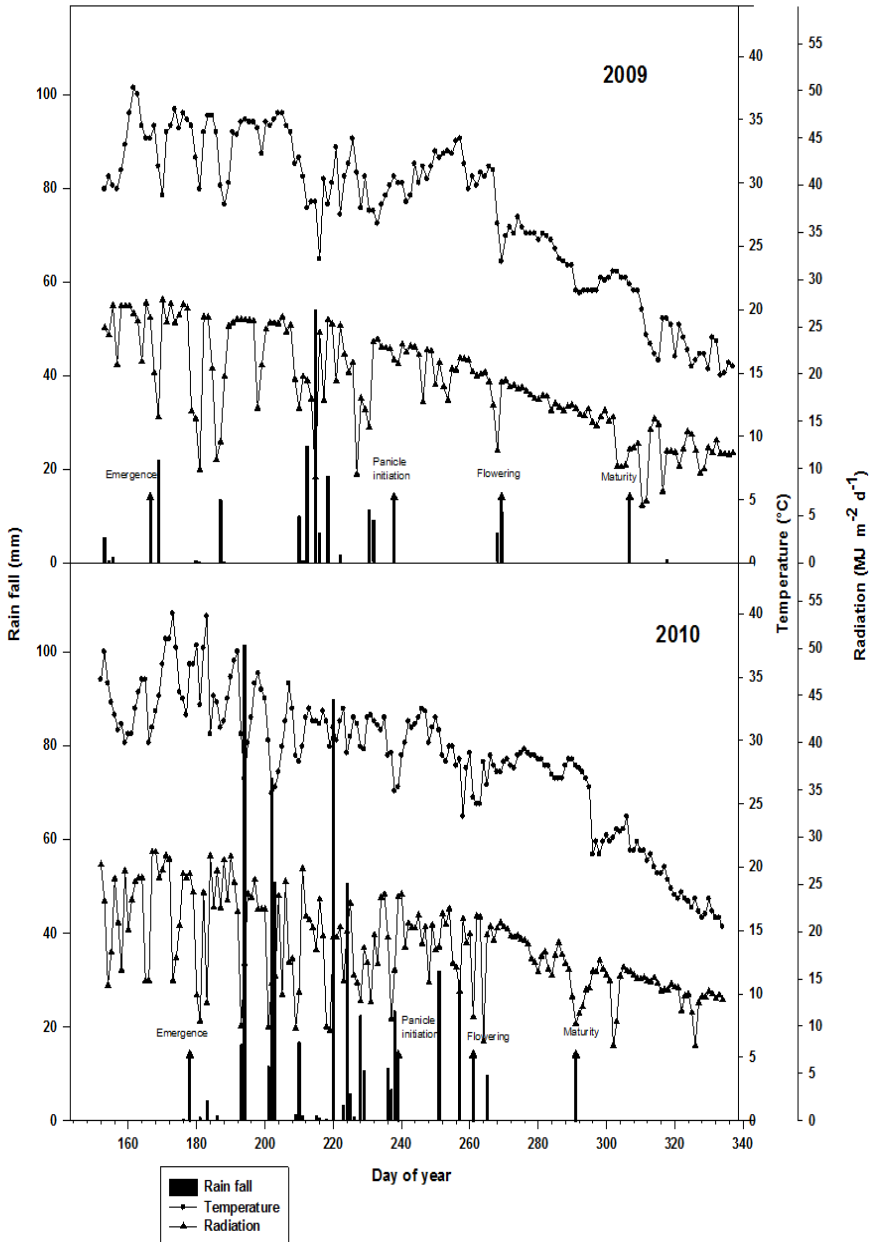


Fig. 2.1. The daily course of rainfall, mean temperature, and radiation in the 2009 (upper) and 2010 seasons (lower). Solid arrows indicate the start of different phenological events for the fastest growing genotype in the high irrigation treatment (RSP1 in 2009 and IR74371-54-1-1 in 2010).

Genotype IR6 was provided by the International Rice Research Institute (IRRI), the Philippines, and released for general cultivation in Pakistan in 1971. It is a popular coarse grain variety among farmers (Bashir et al., 2007). RSP 1 (DM64198) is a mutant of aromatic lowland variety Basmati-385 showing traits of drought tolerance. It is an elite candidate line of the Nuclear Institute for Agriculture and Biology (NIAB)-Pakistan (Akhter et al., 2010). Apo (IR55423-01) is a high yielding improved upland variety, often used as control in aerobic rice experiments and is suitable for tropical conditions (Atlin et al., 2006; Zhao et al., 2010). Genotype IR74371-54-1-1 is an upland line from the Philippines, used in aerobic rice breeding programmes of Asia (Verulkar et al., 2010).

The soil was sandy loam in texture with dull-yellowish brown colour, pH 8.3, bulk density $1.61 \text{ (g cm}^{-3}\text{)}$, organic matter 0.74%, Olsen-P $12.41 \text{ (mg kg}^{-1}\text{)}$, available-K $128 \text{ (mg kg}^{-1}\text{)}$ and electrical conductivity $1.77 \text{ (dS m}^{-1}\text{)}$. The highest value of bulk density (1.71) was found at 20–40 cm, indicating a compacted zone in the second layer. The high pH value represents typical calcareous nature of the soil. Total soil N and organic matter were mostly accumulated near the soil surface and decreased with increasing soil depth (Table 2.1).

To avoid confounding effects of soil fertility on evaluating genotypic performance, we applied the recommended amounts of macro- and micronutrients for farmers. Recommended amount of nitrogen (N) i.e. 170 kg N ha^{-1} applied as urea was side-dressed in three equal splits at the time of emergence, tillering, and panicle initiation (PI). Phosphorus (60 kg P ha^{-1}), potassium (80 kg K ha^{-1}), zinc ($12.5 \text{ kg Zn ha}^{-1}$), and boron (2 kg B ha^{-1}) were applied basal in the form of single super phosphate, muriate of potash, zinc sulphate, and borax, respectively. The pre-soaked and fungicide treated seeds of all genotypes were direct seeded at 75 kg ha^{-1} with the help of a single row hand drill at 3 cm depth, in rows 22.5 cm apart. The crops were sown on July 4, 2009 and June 17, 2010, except that the RSP1 genotype was sown one week later in 2010 i.e. June 25, 2010. Before starting tillage operations to prepare a seed bed, the field was fully irrigated (locally called as *rouni*). At proper soil moisture conditions, the soil was pulverised through mould board plough and stubbles and weeds were incorporated. A fine seedbed was prepared by three to four cultivations followed by planking. The plots were kept weed free by hand weeding and a combination of pre- and post-emergence herbicides. Appropriate pesticides were used as to manage insect pests and diseases.

Table 2.1. Physical and chemical properties of composite soil samples from the main experimental plots.

Soil profile	Soil Texture		BD ^a	Porosity	pH	OM ^b	Total N	NO ₃ -N	NH ₄ -N	Olsen-P	Available-K	EC ^c
Depth (-cm)	Sand (%)	Silt (%)	Clay (%)	(%)		(%)	(%)	(mg kg ⁻¹)	(mg kg ⁻¹)	(mg kg ⁻¹)	(mg kg ⁻¹)	(dS m ⁻¹)
0-20	63.5	24.7	11.8	45.3	8.2	1.23	0.08	8.97	54.48	12.41	128	1.77
20-40	57.1	29	13.9	35.8	8.6	0.9	0.06	8.97	48.21	-	-	-
40-60	59.5	28.7	11.8	41.9	8.4	0.57	0.04	11.86	37.72	-	-	-
60-80	55	31.1	13.9	37.7	8.3	0.52	0.03	10.23	46.16	-	-	-
80-100	52.9	35.4	11.8	35.8	8.2	0.5	0.03	7.81	39.51	-	-	-

^a Bulk density; ^b organic matter; ^c electrical conductivity.

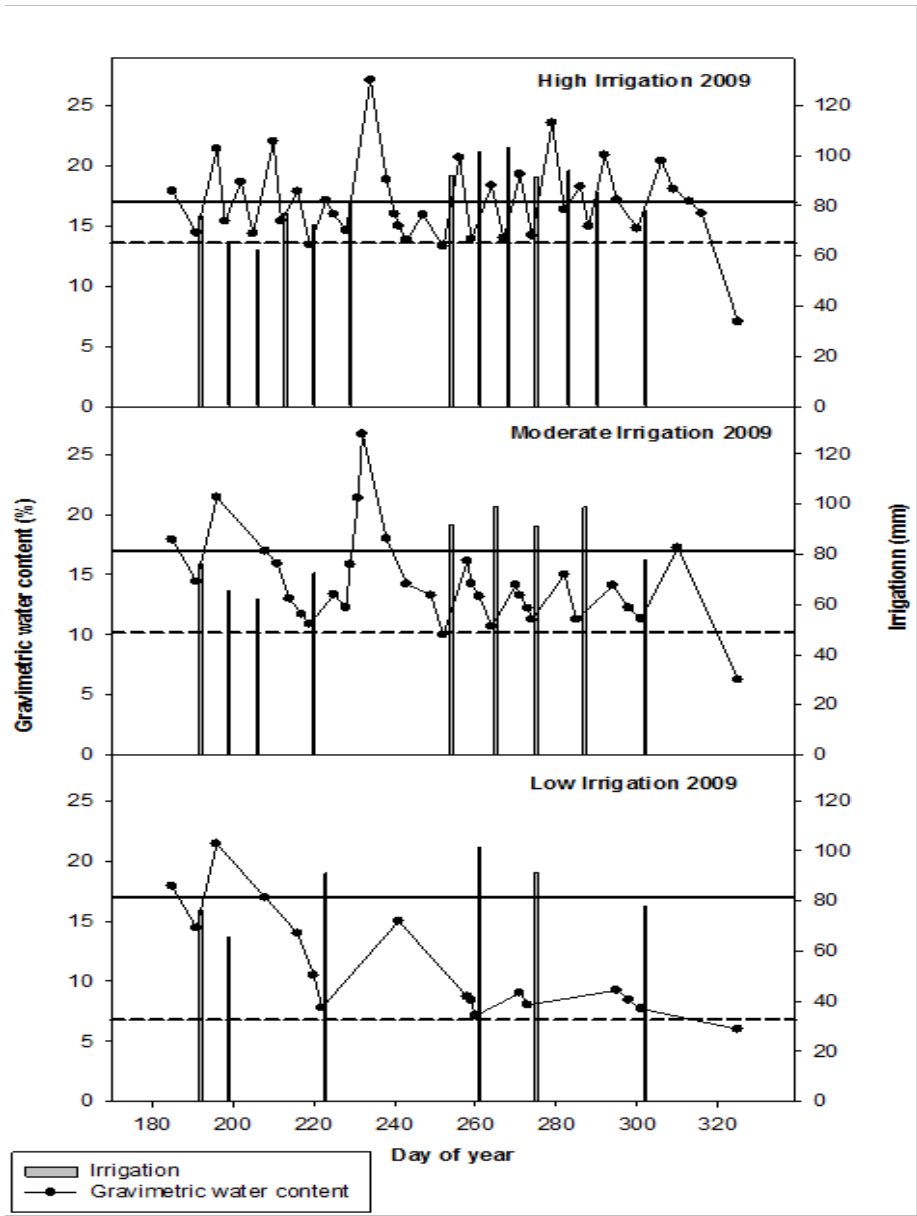


Fig. 2.2a. Gravimetric water content of three water regimes during 2009 season. Horizontal solid line indicates the gravimetric water content at field capacity and horizontal dashed line indicates the gravimetric water content at 80% field capacity (high), gravimetric water content at 60% field capacity (moderate), and gravimetric water content at 40% field capacity (low). Vertical bars indicate irrigation time and amount. Irrigation input was 1080 (high), 736 (moderate), 503 (low). Rainfall was 198 mm.

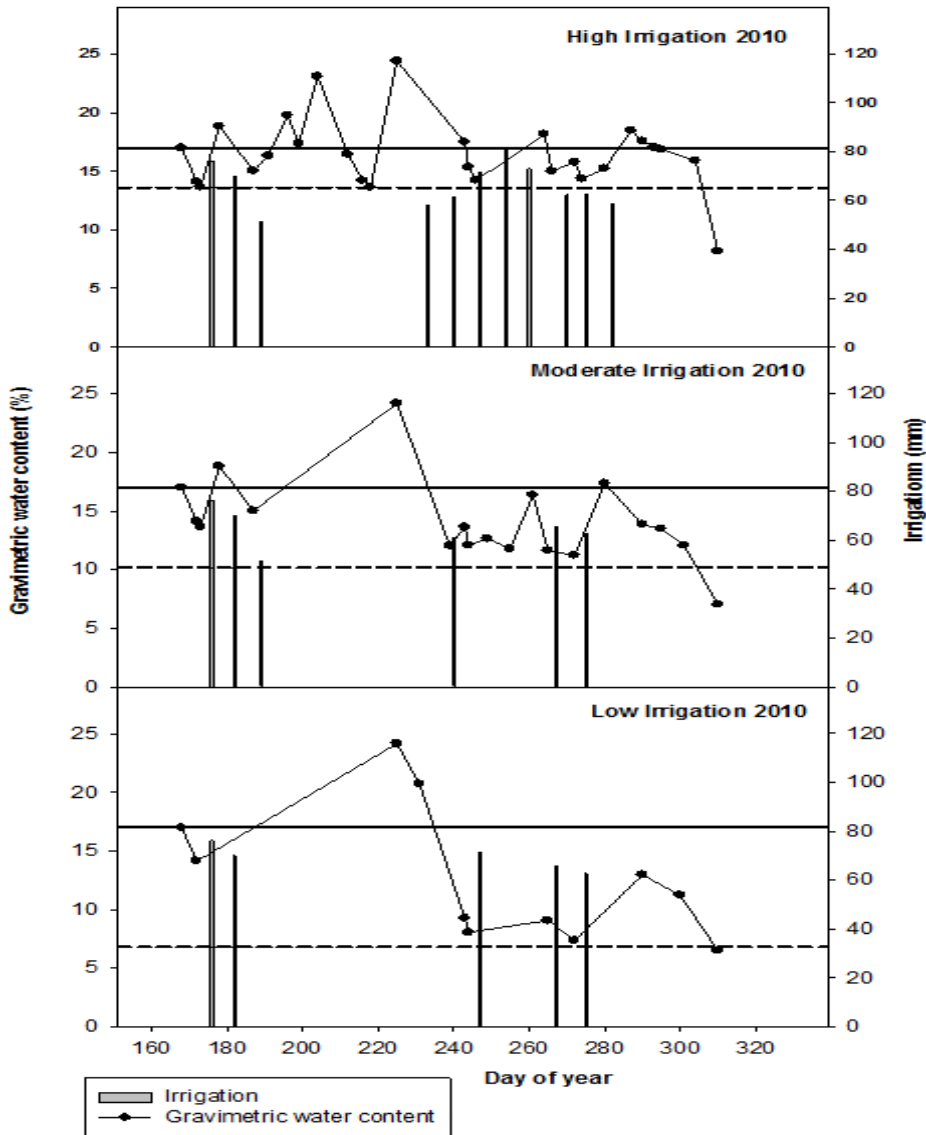


Fig. 2.2b. Gravimetric water content of three water regimes during 2010 season. Horizontal solid line indicates the gravimetric water content at field capacity and horizontal dashed line indicates the gravimetric water content at 80% field capacity (high), gravimetric water content at 60% field capacity (moderate), and gravimetric water content at 40% field capacity (low). Vertical bars indicate irrigation time and amount.

Irrigation input was 726 (high), 387 (moderate), 346 (low). Rainfall was 592 mm.

2.2.3. Field observations, measurements, and calculations

To monitor soil moisture content, we regularly collected composite soil samples from the root zone (0–300 mm) and oven-dried the material at 105°C for 24 h to determine gravimetric soil moisture content. Crop developmental stages recorded in the field were emergence, PI (visual verification of the panicle primordia development), flowering, grain filling, and physiological maturity at 50% values (Fig. 2.1). At five key developmental stages i.e. active tillering, PI, flowering, grain filling, and physiological maturity we cut a row of 1 m at ground level in each sub-plot and separated the sampled plants into green leaves, dead leaves, stem (including leaf sheath), and panicle (if any). The separated fractions of biomass were oven dried at 70°C for three days before weighing. A central area of 3 m² in each sub-plot was harvested to estimate grain and total aboveground dry biomass (TDM). The grain moisture content was determined immediately after threshing and GY was expressed at the standard 14% moisture content. HI was calculated as the ratio of GY to TDM at maturity. The panicle number m⁻², number of spikelets per panicle, spikelet fertility, and 1000-grain weight (g) were determined from 0.5 m row. Spikelet fertility was calculated by separating filled and unfilled grains in tap water. Rooting depth was measured by excavating roots with a shovel. Water productivity (WP_g or WP_b, g kg⁻¹) was calculated as the GY or TDM divided by total water input through rainfall and irrigation.

2.2.4. Statistical analysis

We analysed the field data of all three experiments by analysis of variance (ANOVA) using generalised linear model procedure (GLM) of SAS 9.2 for Windows (SAS Institute, Cary, NC). The effects of irrigation, genotype, and their interaction on growth, development, GY, yield components, and water responses were established by using the following model:

$$Y_{ijk} = \mu + I_i + G_j + B_k + I_i * G_j + \varepsilon_{ijk}$$

where Y_{ijk} is dependent variable subjected to the i^{th} irrigation treatment and j^{th} genotype in the k^{th} block; $i=1-3$; $j=1-3$ (experiments 1 and 2), $j=1-2$ (experiment 3); $k=1-3$; μ = overall mean; I = Irrigation effect, G = Genotype effect, B = Block effect; ε_{ijk} = General Error Term. Tukey's test was used to test whether I , G , and the interaction term $I * G$ significantly affected dependent variables Y_{ijk} . Differences were considered significant at $P \leq 0.05$ and data were analysed separately for each experiment.

2.3. RESULTS

2.3.1. Weather and field hydrology

Typical monsoon type climate prevailed during crop growth seasons in 2009 and 2010 (Fig. 2.1). The rainfall, concentrated in July–September, was more frequent and three times higher in 2010 (600 mm) than in 2009 (200 mm). This resulted in a dry growing season in the first year and a wet season in the second year. The uncertainty in rainfall is typical for the semi-arid conditions of the region. More than 85% of rainfall occurred during the vegetative phase in both seasons, i.e. before panicle initiation (PI). Mean daily radiation was slightly higher and more fluctuating in 2009 (18.8 vs. $18.2 \text{ MJ m}^{-2} \text{ d}^{-1}$) than in 2010 due to the lower rainfall frequency and associated lower cloudiness in 2009. Mean air temperature was fairly similar between two seasons i.e. 27.7°C in 2009 vs. 28.3°C in 2010. The mean daily minimum air temperature ranged from 10.5°C in November to 27.9°C in July, while maximum air temperature ranged from 25.7°C in November to 40.1°C in June.

The relative soil moisture content (RMC) was initially equal as all treatments uniformly received the first two irrigations to support crop establishment. The relative soil moisture content in the high irrigation treatment (0.8 RMC) remained close to field capacity and varied between 0.8 to 1.0, whereas, in moderate (0.6 RMC) and low (0.4 RMC) treatments it remained well below field capacity. In 2010, however, the difference in soil moisture content between moderate and low irrigation treatments was less than in 2009. In both years the amount of total water applied through irrigation and rainfall in the high treatment was comparable (1278 and 1318 mm), but the amount of water applied in the low treatment of 2010 (938 mm) was comparable to the moderate treatments in 2009 and 2010 (934 and 979 mm). In 2009, the low treatment received significantly lower amount of total water than any of the other treatments (701 mm). The amount of water input through irrigation and rainfall in the respective irrigation treatments in both years is presented in Figs. 2a, b and 4. Due to the high rainfall in 2010, the irrigation water input in all treatments was considerably lower in 2010 compared with 2009 in all irrigation treatments i.e. high (–67%), moderate (–53%), low (–69%), respectively. Still total water input (rainfall+irrigation) in 2010 was higher than in 2009. All genotypes received irrigation at the same time in respective irrigation treatments. In 2010, the respective irrigation treatments of experiments 2 and 3 received the same amount of water at the same time. The irrigation was stopped about two weeks prior to maturity in all treatments. Less variation in soil moisture content between three irrigation treatments at harvest indicated that the soil was freely draining.

2.3.2. Growth and development

2.3.2.1. Number of days to flowering and maturity

Duration from emergence to flowering was significantly affected by irrigation, genotype, and their interaction in 2009 (Table 2.2). The dates of successive phenological events are shown in Fig. 2.1 for earliest flowering genotype in the high irrigation treatment (RSP1 in 2009 and IR74371-54-1-1 in 2010).

Table 2.2. Analysis of variance for days to flowering (DF), total aboveground dry biomass (TDM, Mg ha⁻¹), grain yield (GY, Mg ha⁻¹), harvest index (HI), panicle number m⁻² (PN), spikelets per panicle (SP), spikelet fertility (SF, %), thousand-grain weight (1000-GW, g), water productivity based on TDM (WP_b, g aboveground biomass kg⁻¹) and GY (WP_g, g grain kg⁻¹) across three local rice genotypes.

Experiment 1 (2009^b)

SOV ^a	DF	TDM	GY	HI	PN	SP	SF	1000-GW	WP _b	WP _g
I	***	***	***	***	***	NS	***	***	NS	***
G	***	NS	NS	NS	NS	NS	*	**	*	NS
I x G	***	NS	*	NS	NS	NS	NS	NS	NS	*
C.V. ^c	0.5	10.5	14.9	11.9	19.5	4.9	5.7	4.1	9.8	14.6

Experiment 2 (2010^b)

SOV ^a	DF	TDM	GY	HI	PN	SP	SF	1000-GW	WP _b	WP _g
I	NS	**	***	***	*	NS	***	**	*	**
G	***	NS	**	*	NS	NS	NS	NS	*	**
I x G	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C.V. ^c	-	19.8	15.6	12.3	23.3	3.3	9.2	5.8	19.9	15.4

^a I: irrigation treatment (high, moderate, low), G: genotype (KSK133, IR6, RSP1); ^b levels of significance indicated: NS = not significant, *significant at P≤0.05, **significant at P≤0.01, ***significant at P≤0.001; ^c coefficient of variation.

Differences in flowering date were largest between high and moderate or low irrigation treatments, but negligible between moderate and low treatments in 2009

(Table 2.3). Under high irrigation, genotype RSP1 flowered 7 to 8 days (d) earlier than KSK133 and IR6. Under moderate and low irrigation, flowering was delayed by 10 to 11 d for RSP1 and 5 to 6 d for KSK133 and IR6. Irrigation did not affect the time to flowering in 2010 as only slight differences in RMC due to irrigation treatments appeared early in the season due to more rainfall. The duration from flowering to maturity, the reproductive phase, remained unaffected by the irrigation regimes or genotype i.e. a mean value of 32 d. The duration of this phase is mainly determined by temperature.

Table 2.3. The number of days to flowering for three genotypes under different water regimes in the 2009 and 2010 seasons.

Year	Genotype	High	Moderate	Low
2009	KSK133	93.0b	98.3ef	99.3fg
	IR6	94.7c	100.3g	99.7fg
	RSP1	86.3a	97.3de	96.3d
2010	KSK133	92.0b	92.0b	92.0b
	IR6	93.0b	93.0b	93.0b
	RSP1	89.0a	89.0a	89.0a

Statistically significant differences ($P \leq 0.05$) are indicated by different lower-case letters within/ between columns and rows for mean values of the interaction between irrigation and genotypes in each year.

2.3.2.2. Aboveground biomass

The TDM was significantly affected by the irrigation regime (I) in both years, but not by genotype (G) and the $I \times G$ interaction (Table 2.2). Under high irrigation, TDM continued to increase during the reproductive phase to achieve the highest value - about 10.7 Mg ha^{-1} at maturity, especially for genotype RSP1 (Fig 2.3). Differences in TDM were small among three irrigation regimes at tillering i.e. 53–55 days after sowing (DAS) and at panicle initiation (PI) i.e. 69–87 DAS. In moderate and low irrigation treatments, the rate of TDM accumulation decreased after PI stage in 2009 due to frequent drought spells. In 2009, TDM at flowering and maturity was significantly different among irrigation treatments ($P \leq 0.01$) but non-significant among genotypes. In 2010, TDM at maturity was significantly different among irrigation treatments ($P \leq 0.01$). These differences were the result of a decline in TDM growth after flowering in the moderate and low irrigation regimes. Rooting depth was limited to 0.20–0.25 m.

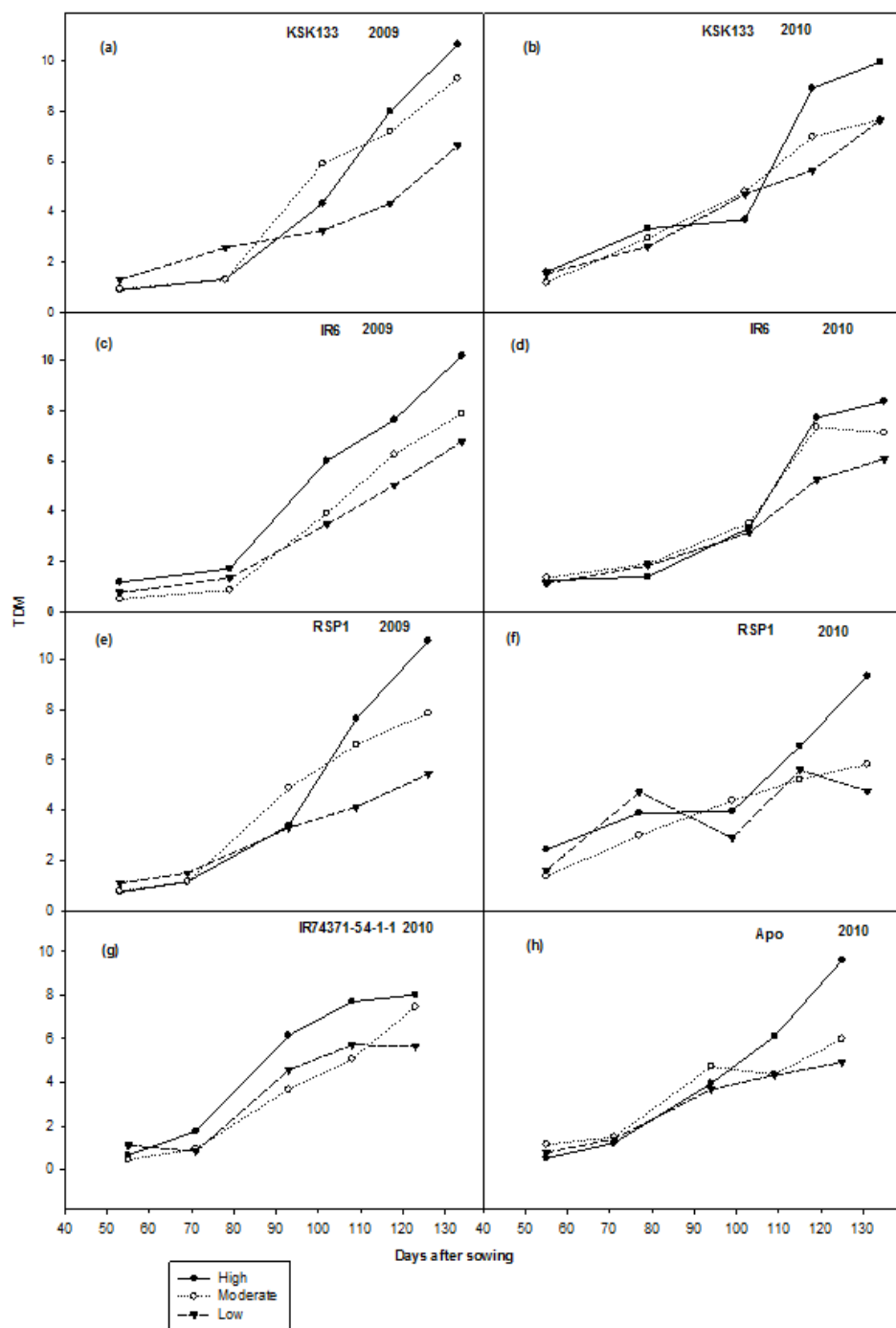


Fig. 2.3. Total aboveground dry biomass (TDM Mg ha^{-1}) of five genotypes at different growth stages and soil water regimes in the 2009 and 2010 seasons.

2.3.3. Grain yield and yield components

The GY was highest under high irrigation and strongly declined for all genotypes under moderate to low irrigation regimes (Table 2.4). Differences in GY among irrigation treatments were significant ($P \leq 0.001$) in both years. However, the interaction between irrigation and genotype was only significant in 2009 (Table 2.2). Under high irrigation, KSK133 achieved a much higher (about 1 Mg ha⁻¹) GY than RSP1 and IR6, whereas under moderate irrigation GYs of all three genotypes were comparable (Table 2.4). The locally adapted genotype KSK133 outyielded IR6 and RSP1 under high irrigation with GYs of 4.11 and 5.0 Mg ha⁻¹ in 2009 and 2010, respectively. The higher GYs of all genotypes under low and high irrigation in 2010 were a consequence of more rainfall during the pre-flowering phase. The availability of extra water enhanced crop growth and panicle and spikelet development.

Harvest index (HI), ranging from 0.15 to 0.39, was significantly ($P \leq 0.001$) higher when more irrigation was applied in both years (Table 2.4). Differences between genotypes were different in 2010 only ($P \leq 0.05$). Under high and moderate irrigation, HI was higher in 2010 than in 2009, whereas it was comparable under low irrigation. The lowest HI value (0.15) was found for RSP1; thus this relatively early genotype was most sensitive to drought. The panicle number varied between 190–400 m⁻² depending on the irrigation treatment. High irrigation resulted in more panicles than moderate or low irrigation (Table 2.5). The number of spikelets per panicle was unaffected by irrigation, genotype or their interaction; however, water stress under moderate and low irrigation significantly decreased the grain filling percentage. Spikelet fertility was higher under high irrigation than in the moderate or low treatments, indicating the strong effect of drought stress around flowering. Reproductive capacity of genotypes was statistically different in 2009 only. IR6 had a lower percentage of filled grains compared to KSK133 and RSP1 (Table 2.5). Averaged across all irrigation treatments, IR6 had the lowest value of spikelet fertility in both years, which indicates its lower adaptability to the semi-arid growing conditions. Thousand-grain weight (g) was highest under high irrigation and significantly reduced by drought in both years. Differences between genotypes were small, ranging from 21.0 to 22.8 g, but differed significantly in 2009 only (Table 2.5).

2.3.4. Water productivity (WP)

As the amount of water input in the respective irrigation treatments was similar for all the genotypes tested, the differences in WP between genotypes result from differences in TDM or GY. The WP with respect to TDM (WP_b, g biomass kg⁻¹ water)

Table 2.4. Total aboveground dry biomass (TDM, Mg ha⁻¹), grain yield (GY, Mg ha⁻¹) and harvest index (HI) of three local genotypes under three water regimes in the 2009 and 2010 seasons.

Year	Genotype	TDM ^a			GY ^a			HI ^a		
		High	Moderate	Low	High	Moderate	Low	High	Moderate	Low
2009	KSK133	12.85a	9.27bc	6.16de	4.11a	1.85c	1.15dc	0.32a	0.20de	0.19de
	IR6	10.67ab	7.86cd	6.92de	3.11b	1.81c	1.50dc	0.29abc	0.23cd	0.22de
	RSP1	10.80ab	7.89cd	5.31e	3.39ab	1.93c	0.79d	0.31ab	0.24bcd	0.15e
2010	KSK133	13.33a	12.56a	11.00a	5.00a	3.24bcd	2.41cde	0.38a	0.26bc	0.22bcd
	IR6	9.56a	8.33a	8.56a	3.72abc	2.53cde	1.72e	0.39a	0.30ab	0.20cd
	RSP1	10.89a	9.67a	12.44a	4.14ab	2.00de	1.84e	0.38a	0.21bcd	0.15d

^a Statistically significant differences ($P \leq 0.05$) are indicated by different lower-case letters within/between columns and rows for mean values of the interaction between irrigation and genotypes in each year for each parameter.

ranged from 0.73 to 1.33 (Fig. 2.4). In 2009, WP_b was comparable among irrigation treatments, whereas in 2010 WP_b increased consistently in all genotypes as the total water input reduced in moderate and low irrigation treatments. WP of genotypes was different in both years, but the interaction between genotype and irrigation was non-significant (Table 2.2). KSK133 obtained the highest WP_b in 2010 i.e. 1.33 g kg^{-1} . The WP with respect to GY (WP_g , g grain kg^{-1} water) ranged from 0.11 to 0.38 (Fig. 2.4). Decreasing water input significantly reduced WP_g in both years.

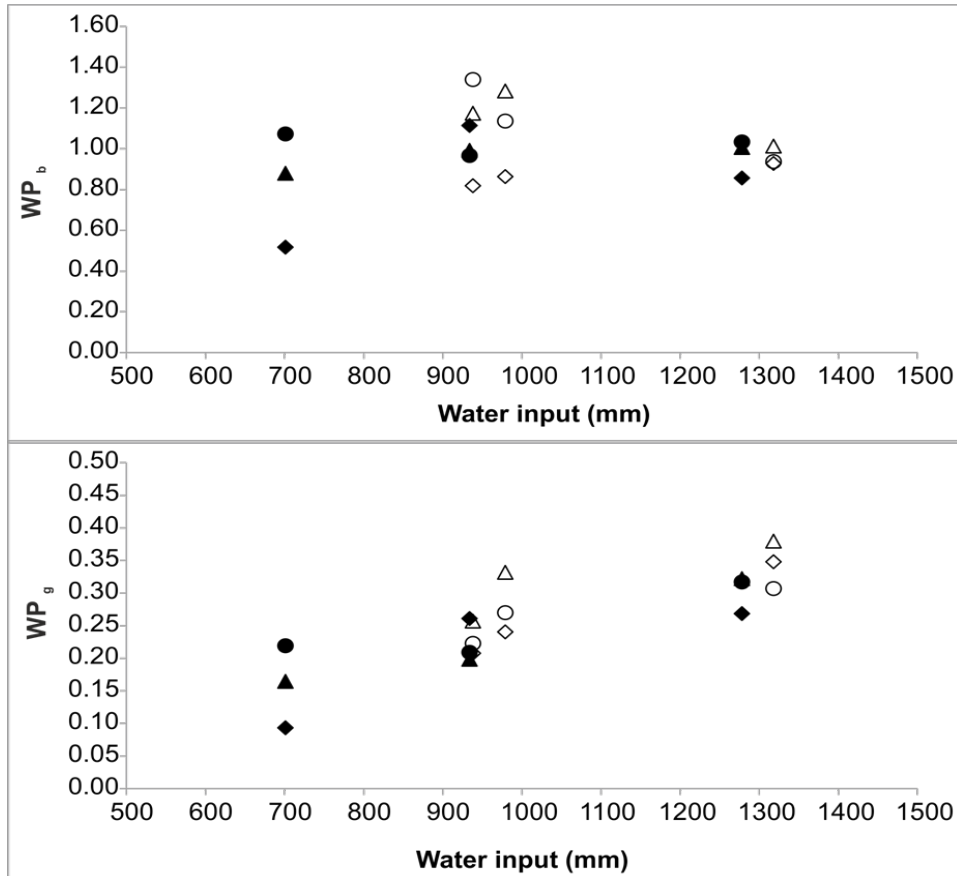


Fig. 2.4. Water productivity (above) with respect to total aboveground dry biomass (WP_b , g aboveground biomass kg^{-1} water) and water productivity (below) with respect to grain yield (WP_g , g grain kg^{-1} water) of three genotypes under three soil water regimes. Closed symbols represent 2009 and open symbols represent 2010; quadrangles for KSK133, triangles for IR6, and circles for RSP1. Water input (mm) = Irrigation+Rainfall. Irrigation (mm)= 1080 (high), 736 (moderate), 503 (low) in 2009 and 726 (high), 387 (moderate), 346 (low) in 2010. Rainfall (mm) = 198 in 2009 and 592 in 2010.

Genotypes were different in 2010 and irrigation interacted with genotype in 2009 (Table 2.2). In the high water input treatment, KSK133 obtained the highest WP_g in both years i.e. 0.32 in 2009 and 0.38 in 2010. In moderate water input treatment, WP_g was comparable among three genotypes in 2009, whereas in low water input, IR6 maintained WP_g but in case of KSK133 and RSP1, it dropped further. In general, WP_g was higher in 2010 than in 2009 due to better growing conditions.

Table 2.5. Yield components for three irrigation treatments and three local genotypes during the 2009 and 2010 seasons.

Year	Yield component	Irrigation treatment ^a			Genotype ^a		
		High	Moderate	Low	KSK133	IR6	RSP1
2009	Panicle number m^{-2}	363a	220b	190b	271	232	280
	Spikelets per panicle	129	128	133	134	127	128
	Spikelet fertility (%)	74a	62b	54c	65a	59b	66a
	1000-grain weight (g)	23.4a	21.3b	20.5b	21.3b	21.1b	22.8a
2010	Panicle number m^{-2}	400a	312b	258b	329	349	292
	Spikelets per panicle	130	128	129	131	128	129
	Spikelet fertility (%)	79a	67b	54c	67	65	68
	1000-grain weight (g)	23.4a	21.3b	20.7b	21.5ab	21.0b	22.7a

^a Statistically significant differences ($P \leq 0.05$) within a row are indicated by different lower-case letters for mean values of the main effects of irrigation and genotype. Means with no letters indicate non-significance.

2.3.5. Cultivar performance

In 2010, we conducted an additional experiment in which we tested two drought tolerant exotic genotypes (Apo and IR74371-54-1-1) that are commonly used in aerobic rice breeding programmes, in addition to the three locally grown genotypes (KSK133, IR6, RSP1). Irrigation affected most of the traits, except for days to flowering, TDM, and panicle number m^{-2} ; genotypes and their interaction with irrigation was non-significant (Table 2.6). Apo and IR74371-54-1-1 showed a faster development rate with shorter durations between growth stages than the three local genotypes. Apo took 115 d and IR74371-54-1-1 took 113 d to maturity. Similar to the local genotypes in 2010, number of days to flowering was unaffected by the irrigation treatment. GYs and other variables for the two genotypes are shown in Table 2.7.

Table 2.6. Analysis of variance for days to flowering (DF), total aboveground dry biomass (TDM, Mg ha⁻¹), grain yield (GY, Mg ha⁻¹), harvest index (HI), panicle number m⁻² (PN), thousand-grain weight (1000-GW, g), water productivity based on TDM (WP_b, g aboveground biomass kg⁻¹) and GY (WP_g, g grain kg⁻¹) across two improved exotic genotypes.

SOV ^{a,b}	DF	TDM	GY	HI	PN	1000-GW	WP _b	WP _g
I	NS	NS	**	*	NS	*	*	*
G	NS	NS	NS	NS	NS	NS	NS	NS
I x G	NS	NS	NS	NS	NS	NS	NS	NS

^a I: irrigation treatment (high, moderate, low), G: genotype (Apo, IR74371-54-1-1); ^b levels of significance indicated: NS = not significant, *significant at P≤0.05, **significant at P≤0.01.

Table 2.7. Mean values for days to flowering (DF), total aboveground dry biomass (TDM, Mg ha⁻¹), grain yield (GY, Mg ha⁻¹), harvest index (HI), panicle number (PN, m⁻²), thousand-grain weight (1000-GW, g), water productivity based on TDM (WP_b, g aboveground biomass kg⁻¹) and GY (WP_g, g grain kg⁻¹) for three irrigation treatments across Apo and IR74371-54-1-1, the two improved exotic genotypes used in this study.

Parameter	High	Moderate	Low
DF	84	84	84
TDM	11.11	10.72	9.89
GY	4.34a	3.57b	2.64c
HI	41a	32b	27b
PN	367	346	307
1000-GW	23.9a	21.1b	20.9b
WP _b	0.81b	1.13a	1.05ab
WP _g	0.33ab	0.36a	0.28b

Statistically significant differences (P≤0.05) within a row are indicated by different lower-case letters for mean values of the main effects of irrigation. Means with no letters indicate non-significance.

Since these were not significantly different between the two genotypes (Table 2.6), we present for each irrigation treatment only the average of the two genotypes (Table 2.7). GYs declined in moderate or low irrigation treatments (Table 2.7). The GY in the high irrigation treatment was, however, lower than the GY of local genotype KSK133 in the high irrigation treatment of 2010 i.e. 5.0 Mg ha⁻¹. In moderate and low irrigation treatments, however, a comparison of exotic genotypes with the local ones showed that

the short duration genotypes achieved higher GYs of 3–4 Mg ha⁻¹ in moderate and 2.5–2.77 in low treatment which is significantly higher than the local genotypes under similar circumstances (Table 2.7). This is largely due to exotic genotypes maintaining higher HI and higher panicle number. Under the highest irrigation treatment, Apo and IR74371-54-1-1 had comparable GY and WP as against the local genotypes but under stress conditions i.e. moderate and low these two genotypes performed better than the local genotypes.

2.4. DISCUSSION

2.4.1. Experimental set-up

We set out to investigate the performance of aerobic rice in the field under a wide range of available soil water conditions. Hence, we conducted experiments on a light textured soil (58% sand content) with a deep water table i.e. below 25 m. A coarse soil texture and deep groundwater table minimises the chances of capillary rise to root zone. Rainfall during vegetative growth, however, made it difficult to maintain water stress in moderate and low irrigation treatments in 2010. Relatively small differences between moderate and low treatments are reflected in similar crop performance. Field experiments on water saving often experience ‘uninvited sources of variation’ such as rainfall and shallow groundwater tables (Belder et al., 2004) but also represent the true agro-environmental conditions. Experimental site has a high pH and low supplies of the available nutrients. Rice soils of Pakistan are generally characterised by a high pH due to calcareousness and a deficiency of nutrients (Zia, 1990; Zia et al., 1994; Sarwar et al., 2008). The experiments tested three local genotypes over two seasons (2009 and 2010). For a comparison to the local genotypes, we included two exotic aerobic rice genotypes in 2010, all of which were *non-basmati* coarse grain genotypes. To extrapolate our findings, we collected the required (soil, climate, and crop) input parameters for running the APSIM-Oryza model, a new functionality developed in the APSIM modelling framework to simulate rice production systems under alternating submergence and non-submergence conditions. Implications of this study for the crop modelling are discussed in the section 2.4.4.2.

2.4.2. Crop performance and traits

2.4.2.1. Phenology

Among the genotypes, the differences in number of days to flowering and growth duration confirmed their contrasting phonological characteristics. Irrigation and

genotype had a significant effect on crop performance and interacted for GY, WP_g, and days to flowering in 2009, which might be explained by distinct differences among irrigation treatments and a higher water stress compared to 2010.

Keeping in mind the shorter duration of RSP1 in 2009, this genotype was sown one week later in 2010 to synchronise flowering with the other genotypes and avoid confounding effects of rainfall. This worked well as we limited the difference in flowering date to less than one week. Differences in number of days to flowering between two years are explained by higher rainfall and more water availability in 2010 than in 2009. The role of water stress in delaying rice crop development is well documented (Fukai, 1999; Saini et al., 1999; Lafitte and Courtois, 2002). High transpiration demands due to a large canopy in dry season are the main reason for delayed flowering. These results are in line with those of Xiaoguang et al. (2005) and Castillo et al. (2006).

Days to flowering increased under drought. Genotype IR6 that normally matures in 116 d (Bashir et al., 2007), took 124 d which is consistent with 125 d reported by Ali et al. (2007) under direct seeding system. Similarly KSK133 that normally matures in 105 d according to Akhter et al. (2007), took 125 d. The extension of duration is critical in relation to water use, as the crop needs additional water for an extended period, and also in relation to management, as the harvesting will occur during possibly unfavourable conditions (Dunn and Gaydon, 2011). The aerobic rice system is advantageous as it saves time, water and labour required for puddling and transplanting. The conventional system needs 200–300 mm water for puddling and subsequent land preparation, one month prior to transplanting (Jehangir et al., 2007; Chapagain and Hoekstra, 2010). These advantages may be off-set if the crop duration extends. Modern aerobic rice genotypes Apo and IR74371-54-1-1 performed better than local genotypes in terms of GY and WP under limited water supply. This resulted from a shorter duration and higher HI, showing their potential to adapt to aerobic conditions. Short duration might have enabled these genotypes to use the available water effectively.

2.4.2.2. Crop growth

Crops produced similar amounts of TDM up to the tillering stage in 2009 and up to flowering stage in 2010, after which TDM production was reduced in the moderate and low irrigation treatments. The reduction in TDM accumulation in response to drought was reported in other studies with aerobic rice (Bouman et al., 2005; Peng et al., 2006). The high GY resulted from a high HI but not necessarily from more TDM. This is in line with Laza et al. (2003) who reported that HI is more important than

TDM production under sub-optimum growing conditions. Effective translocation of TDM accumulated before flowering stage to the grains and high TDM production during ripening stage are required for achieving high GY.

2.4.2.3. Grain yield and yield components

Averaged over two years, the difference in GY between high and moderate or low irrigation treatments was strongly associated with the differences in values of panicle number and HI. The period around anthesis is most sensitive to drought resulting in high sterility and low HI. A high value of HI in the high treatment resulted from more water availability around flowering (Bouman et al., 2006). HI dropped drastically as we increased the water stress level which is consistent with the findings of Belder et al. (2004) and Xue et al. (2008a). The higher TDM did not result in a higher HI, which may be explained by the 'haying-off effect' (Debaeke and Aboudrare, 2004).

2.4.3. Water productivity and water use

Compared to the conventional system, WP improved as water use declined. Among three irrigation treatments, WP_b was comparable (2009) or increased significantly (2010) as water input declined in moderate and low treatments. The final TDM decreased in response to water deficit but this did not affect WP_b negatively unlike WP_g . We achieved the highest values of WP_g with high treatment ranging 0.24–0.32 in 2009 and 0.28–0.38 in 2010. These values are significantly higher than the values (in the conventional flooded system) of 0.16 at the national level and also higher than a typical field scale average of 0.23 reported for the rice-wheat system by Jehangir et al. (2007). In moderate and low treatments, the GY dropped proportionally more than the amount of water saved, resulting in a decreased WP_g . Sink size and the dry matter partitioning seem to considerably be affected by final GY and hence WP_g . Highest values of WP_g were accompanied by highest values of final TDM, HI, panicle number, spikelet fertility, and 1000-grain weight. Yan et al. (2010) found that panicle number was the main limiting factor for yield formation due to a low tiller emergence frequency and a low fraction of productive tillers. WP_g of major crops in Pakistan is among the lowest in the world i.e. 0.78 (maize), 0.54 (wheat), 0.16 (rice) (Dahri et al., 2008). WP_g was limited by sink capacity that is typically the case under warm (sub-)tropical conditions (Bouman and Tuong, 2001; Bouman et al., 2005) unlike temperate conditions where WP_g values of 0.6–0.8 were reported (Xiaoguang et al., 2005). In the hot and dry climate of Sahel, de Vries et al. (2010) found that an irrigation regime that

starts as conventional flooded and changes to alternate wetting-drying (AWD) around PI stage gave higher WP_g than either fully flooded or AWD.

Water use declined compared to the conventional system. Total water input (I+R) in the high treatment (1278–1318 mm) was less than gross water requirements of 1600 mm for paddy rice in Pakistan. Depending on the soil type and rainfall, the average amount of water applied as irrigation (excluding rainfall) varies from 465 mm to 3642 mm, with a mean value of 1309 mm. About 33% farmers in Punjab, however, apply irrigation water in excess of 1600 mm (Bhatti and Kijne, 1992; Aslam et al., 2002). The total water input in the high irrigation treatment was comparable with irrigation input of 1410 mm observed in a light-textured soil under aerobic rice system by Mann et al. (2011). Based on our results, we conclude that further optimisation of irrigation amount is possible and holds the promise for both higher GY and higher WP_g .

2.4.4. Implications of the study

2.4.4.1. General

Decreasing availability of irrigation water is a major concern for agriculture worldwide (Rijsberman, 2006). In light of the water shortage for irrigated lowlands of South Asia and in particular Pakistan i.e. a water-stressed country with per capita water availability of 1100 m³, the current practices must transition towards a water saving agriculture like aerobic rice cultivation. We explored the effect of different irrigation regimes under aerobic rice system that can help designing the viable adaptation options for rice farmers. Our results suggest that there is a great scope for improvements in WP and water saving by replacing some of the conventional paddy systems with aerobic rice systems. GYs of tested genotypes are within the target yield of 4–6 Mg ha⁻¹ for aerobic rice, but still far below their reported yield potential (~10 Mg ha⁻¹) (Muhammed, 1985) and earlier reported values under aerobic rice system (~7 Mg ha⁻¹ for KSK133). So producing more rice per unit area with less water is only partially possible, but some of the saved water can be used to irrigate previously un-irrigated area (Bouman and Tuong, 2001) or farmers might sell the saved water. Our analysis suggests that further optimisation is possible by increasing water input relative to the levels applied in this study.

Aerobic rice has in comparison with flooded rice a higher WP and lower GY per unit land. Where water is scarcer than land and demands for rice remains large, the aerobic rice system is in this respect an attractive option. Still, WP of rice is lower than WP of other arable crops and one might think if the challenge is to cope with water scarcity, then why continue growing rice at all? There are a number of reasons for this.

People are used to eating rice and this will not easily change. Farmers are skilled at growing rice, it is part of the culture. And finally many areas are more suitable for rice than for other crops. Pakistan has about 8 Mha cultivable waste land (GOP, 2012a). With a high population growth rate, water is getting scarcer than land. Logically, if Pakistan opts to restrict rice cultivation, it would demand major changes in crop culture, marketing, dietary preferences, and the additional water reservoirs. Most rice areas are saline and prone to waterlogging, limiting the choice of replacing rice (Dahri et al., 2008). In this scenario, transformation of conventional systems to aerobic rice system seems a realistic option. The on-going breeding efforts for aerobic rice should focus on improved HI, high panicle number, high spikelet fertility, and screening on drought and salt tolerant germplasm. Rooting depth in our study was limited to 0.20–0.25 m, which hinders water uptake from the deeper layers. The conventional varieties are bred under flooded system and possess low values of root biomass. Genotypes with a vigorous and deeper root systems will better adapt to aerobic rice systems. Since the crop duration has direct implications for resource use and the sowing window, aerobic rice genotypes should be early-maturing. The extended duration under aerobic rice systems is probably one of the reasons for failure of long duration *basmati* genotypes under limited irrigation regimes.

2.4.4.2. Crop modelling

Empirical studies can only ever evaluate a small sub-set of all possible $G \times M \times E$ combinations. Crop growth modelling could help in extrapolating results of field experiments and exploring options for studying resource use efficiency and addressing crop management issues (Zhang et al., 2007). Results and dataset of this study can be used to extrapolate our findings for the resource-limited rice production systems in the region. The APSIM-Oryza model can be used to capture the effects of water dynamics in relation to management issues such as irrigation and fertilisation. Our work suggests that one important issue in such simulations should be accurate simulation of phenology and genotype-specific delay in flowering as a function of drought stress. Another important component should be the accurate modelling of how yield components (panicle number, sterility) are affected by drought. A model component able to simulate ‘haying-off’ will be an important tool for optimisation in a changing climate scenario under the water-limited environments. We recommend more experiments seeking to maintain soil moisture at contents higher than 80% on different soil types in combination with modelling exercises to find out the trade-offs between GY, resource use efficiency, and water saving.

2.5. CONCLUSIONS

Pakistan is one of the leading rice exporting countries and thus contributes to global food security. Looming water crisis, however, necessitates the implementation of new water saving practices such as aerobic rice cultivation to sustain area and production of rice. The aerobic rice is being tested and up-scaled in two major rice producing provinces of Pakistan. We conducted field experiments in the non-traditional rice belt of Punjab province, which is an important target domain for aerobic rice. Our study contributes important quantitative information on phenology, growth, GY, yield components, and WP of candidate coarse grain genotypes and supports the agronomic feasibility of aerobic rice system in subtropical regions. Reduced water input decreased the GY but increased WP, suggesting the need to optimise resource use and develop suitable varieties for aerobic rice system. We recommend more experiments, seeking to maintain relative soil moisture content at higher levels than 80% on different soil types. This should be combined with a modelling study to find the optimum water supply and economic analysis of water saving and GY. Adapted genotypes showed to be better able to withstand conditions of lower water availability, clearly lowering the risk of obtaining low GY. Breeding should utilize this genetic material to develop local genotypes adapted for aerobic soil conditions. Further development and dissemination of technology calls for addressing issues related to irrigation infrastructure, water pricing, availability of quality herbicides, a sound production technology package, and an understanding of farmer perspective.

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CHAPTER 3

Nitrogen use and crop performance of rice (*Oryza sativa* L.) under aerobic conditions in a semi-arid subtropical environment*

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Abstract

Aerobic rice is gaining in popularity across South Asia, mainly because it saves water and labour. Under warm (sub)tropical conditions of this region, this non-conventional system aimed at improved resource use efficiency, is still in the development phase. We tested crop performance and nitrogen (N) uptake of three local genotypes in relation to different water and N supply rates under aerobic conditions at the research station of the University of Agriculture, Faisalabad–Pakistan. In field experiments during 2009–2010, covering two rice seasons, three irrigation levels (high, moderate, low), three N rates (0, 170, 220 kg N ha⁻¹), and three genotypes (KSK133, IR6, RSP1), crop performance and total N uptake (TNU) were strongly influenced by irrigation and differed between genotypes. At the highest level of irrigation, genotype KSK133 performed better than RSP1 and IR6, resulting in an accumulated aboveground biomass of 13 Mg ha⁻¹ and a grain yield of 5 Mg ha⁻¹. The TNU ranged from 34 to 126 kg ha⁻¹ in 2009 and from 52 to 123 kg ha⁻¹ in 2010. For all genotypes, we observed a strong positive correlation between TNU and grain yield. Surprisingly, N application rate did not influence TNU, but the high irrigation regime increased TNU. The limited response to N application suggests significant losses of the applied N. This highlights the need for careful N management in aerobic rice systems; N-application should match with the periods of sufficient soil moisture availability and the greatest crop N demand.

Keywords: N uptake, water × N × G, aerobic rice, Pakistan.

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3.1. INTRODUCTION

In Asia, the agricultural sector withdraws 90% of developed freshwater resources; of this more than 50% is used to irrigate rice (Barker et al., 1998; Maclean et al., 2002; Molden et al., 2007). Tuong and Bouman (2003) calculated that about 15–20 million ha of irrigated (flooded) rice area might be affected by water scarcity by 2025. The looming water crisis threatens the sustainability of the conventional flooded rice system, especially in countries like Pakistan where the entire rice production area is essentially irrigated. An alternative to the conventional system is ‘aerobic rice production’ which entails the growing of a rice crop in non-flooded, unpuddled soil by supplementary irrigation and external inputs. The system of aerobic rice, primarily developed for temperate conditions, needs detailed investigation before being introduced in warm tropical and subtropical regions like South Asia (Prasad and Donald, 2011). Adjustment of the system for (sub-)tropical regions involves the identification or development of appropriate varieties, optimisation of management practices, and quantification of yield potential and resource use efficiencies (Belder et al., 2005a).

Reducing water inputs will reduce actual yields, given the sensitivity of rice crops to water limitation during critical developmental stages. In rice, leaf expansion stops completely when root-zone soil water pressure potential exceeds 50 kPa (Tuong and Bouman, 2003; Wopereis et al., 1996). Water stress may result in delayed flowering, reduce biomass production as a result of reduced transpiration, increase panicle sterility, lower harvest index (HI), and ultimately impact on grain yield (GY) (Castillo et al., 2006; Xiaoguang et al., 2005; Xue et al., 2008b). Lafitte and Courtois (2002) observed large genotype $\times$ water interaction for GYs of upland rice.

Nitrogen (N), the most limiting factor next to water, plays a key role in improving crop performance by promoting leaf area, biomass growth, yield, and by reducing evaporative losses (Sinclair, 1990; Yoshida, 1981). Kato et al. (2007) reported that deep-rooting cultivars accumulated more N and produced more biomass under intermittent drought stress. Limited information is available on the effects of nutrient supply on plant growth and GY of aerobic rice (Nie et al., 2008). The dominant form of N under aerobic soil conditions is nitrate (NO_3) leading to lower ammonia (NH_3) volatilisation losses, the predominate source of N losses in flooded rice systems (Sahrawat, 2009a, b; Vlek and Craswell, 1981). Yet, alternate wetting and drying (AWD) of the soil can lead to increased ammonification of N from decomposing dead organic matter (during aerobic conditions), followed by ammonia losses (under anaerobic conditions, after irrigation). When the soil dries again, ammonification is followed by nitrification-denitrification processes, thus increasing N_2 and N_2O losses

(Frolking et al., 2004; Yue et al., 2005; Zou et al., 2005). Aerobic rice may lead to higher N uptake and biomass growth, but may also result in higher N losses if more N is available in the system than can be taken up by crop and living microbial biomass (Belder, 2005; Belder et al., 2005a). In case of upland rice, yield response to N varied owing to variations in N recovery and internal N use efficiency, which again was strongly affected by water supply (Kondo et al., 2005).

Important characteristics for developing new elite varieties for water-saving production systems are input responsiveness and plant characteristics such as deep root system, high N uptake, and GY stability under different water regimes (Lafitte et al., 2002; Kato et al., 2006; Kato et al., 2007). Aerobic varieties combine some of the yield potential-enhancing traits of lowland high-yield varieties with adaptation to aerobic soils. This new class of upland-adapted cultivars with improved lodging resistance, HI, and input responsiveness has been developed by breeding programmes in China, Brazil, and the Philippines (Atlin et al., 2006; Wang et al., 2002). In South Asian countries such as Pakistan, India, Bangladesh, and Nepal, the development of suitable aerobic varieties is so far generally restricted to screening the available germplasm (IRRI, 2010; Prasad and Donald, 2011).

Aerobic rice is an emerging production system in South Asia. In aerobic rice systems, most of the studies focused on either water or N use (Bouman et al., 2007b; Bueno et al., 2010; Cui et al., 2008; Mahajan et al., 2012; Xiaoguang et al., 2005; Zhang et al., 2009). There are some reports on irrigation×N interactions (Belder et al., 2005a, b; Xue et al., 2008b), but studies on the interactive effects of irrigation×N×genotype (I×N×G) are scarce. The existing studies suggested inconsistent results. For example in some cases, a significant water×N was found (Mahajan et al. 2012; Kadiyala et al. (2012), whereas in others it was non-significant (Belder et al. 2004; Haefele et al. 2008; Zhang et al. 2009). Some studies suggested a positive response to the applied N fertiliser (e.g. Zhang et al. 2009; Lampayan et al. 2010; Mahajan et al. 2012) whereas others suggested a poor response (e.g. Kreye et al. 2009; Xue et al. 2008b). There are different reasons for these inconsistencies including differences in environment such as shallow or low ground water table, rainfall patterns, over-fertilisation of the previous crop, unresponsive genotypes, and limitations of growth factors other than N. Therefore it is important to evaluate the crop performance under newly proposed productions systems in response to varying levels of scarce inputs for target environments, where the aim is to improve resource use efficiencies.

We conducted our study in a semi-arid subtropical region which is considered an important target domain for the dissemination of aerobic rice systems. Nitrogen use of aerobic rice in this environment, with varieties relevant for this environment, has to

date not been investigated. A review of literature suggested that most of the studies on water saving rice cultivation in Pakistan focused on comparing the flooded and aerobic cultures, and in most cases for the fine grain *basmati* genotypes (IRRI, 2010; PARC, 2010; Mann et al. 2011; Sarwar et al. 2013). However, coarse grain genotypes are considered suitable candidate for these new water production systems because of their shorter growth duration and relatively better drought tolerance compared to *basmati* genotypes. Studies on the interactive effects of irrigation and N for suitable genotypes, as reported in this paper, are essential to contribute important quantitative information for further development of the aerobic rice technology in the light of possible risk factors, which have not been systematically investigated before. To our knowledge this is the first study to report on irrigation×N×genotype interaction under the sole aerobic rice system for three important coarse grain genotypes (KSK133, IR6, RSP1).

The specific objective of our study was to analyse GY of selected genotypes under different water and N supply rates.

3.2. MATERIAL AND METHODS

3.2.1. Experimental site, layout, and crop husbandry

We conducted field experiments at research station of the University of Agriculture, Faisalabad–Pakistan (31°26' N, 73°06' E, 184 m altitude) in 2009 and 2010 covering two rice seasons. The soil at the experimental site was a sandy loam. The soil belongs to the Lyallpur soil series i.e. Aridisol-fine-silty, mixed, hyperthermic Ustalfic, Haplargid in USDA classification and Haplic Yermosols in the FAO classification scheme, with a dull-yellowish brown colour (10 YR 5/3). Table 3.1 presents the main physical and chemical soil properties determined at the start of each growing season before seeding.

Field experiment set up was as a three-factor split-split-plot design with three replicates. The main factor, irrigation, consisted of three treatments i.e. high, moderate, and low. Irrigation treatments were imposed to create distinct water conditions during the growing season with relative water content (RMC, defined as the soil moisture content (MC) relative to field capacity (FC) i.e. $RMC = MC/FC$) as the criterion for re-irrigation. The procedure followed to determine field capacity was: 1) wetting-up the soil profile by applying a full irrigation to saturate the soil, 2) covering an area of about 4 m × 4 m with a plastic sheet to prevent evaporation before sampling, 3) measuring the soil moisture content each 24 h until the changes were very small, at which point the soil moisture content was considered to be at field capacity. The soil moisture content was determined gravimetrically.

Table 3.1. Physical and chemical properties of the soil at 0–100 cm depth.

Properties ^a	Units	Depth (-cm)				
		0-20	20-40	40-60	60-80	80-100
Sand	(%)	63.5	57.1	59.5	55	52.9
Silt	(%)	24.7	29	28.7	31.1	35.4
Clay	(%)	11.8	13.9	11.8	13.9	11.8
Bulk density	(g cm ⁻³)	1.45	1.7	1.54	1.65	1.7
pH		8.2	8.6	8.4	8.3	8.2
Organic matter	(%)	1.23	0.90	0.57	0.52	0.50

^a Average values of two years (2009–10).

The sub-factor, nitrogen (N), consisted of three treatments i.e. 0, 170, and 220 kg N ha⁻¹. The N dose of 170 kg N ha⁻¹ is recommended application rate for tested genotypes in our study area. Fertiliser N was applied in three equal splits at emergence, active tillering, and panicle initiation (PI) stages in the respective sub-plots. Double bunds and plastic sheets installed to a depth of 1 m prevented lateral flows of water and N across the adjacent treatment plots. The third factor, genotype, constituted the sub-sub-plots (2.5 m × 6 m). We tested three local tropical *indica* type rice genotypes: KSK133, IR6, and RSP 1. KSK133 (KSK 282 × 4321) is a high yielding, stiff stemmed, and extra-long lowland rice variety. This stay-green and water stress tolerant genotype is recommended for the non-traditional rice belt of Pakistan. The genotype was released in 2006 for general cultivation by Rice Research Institute, Kala Shah Kaku, Pakistan. It was also used as check variety in direct-seeded aerobic rice experiments in an international collaborative research programme on water saving rice cultivation (Akhter et al., 2007; IRRI, 2010). IR6 is an introduction from International Rice Research Institute (IRRI), the Philippines. It is a popular coarse grain variety among farmers. It was released in 1971 for general cultivation in Pakistan (Bashir et al., 2007). RSP 1 (DM64198) is a mutant of aromatic lowland classic variety Basmati-385. It is an elite candidate line of the Nuclear Institute for Agriculture and Biology, Pakistan, showing traits of water stress tolerance (Akhter et al., 2010).

Phosphorus (60 kg P ha⁻¹), potassium (80 kg K ha⁻¹) zinc (12.5 kg Zn ha⁻¹), and boron (2 kg B ha⁻¹) were applied basal in the form of single super phosphate, muriate of potash, zinc sulphate, and borax, respectively. The pre-soaked and fungicide treated seeds of all genotypes were direct seeded at 75 kg ha⁻¹ with the help of a single row hand drill at 3 cm depth, in rows 22.5 cm apart. In 2009, all rice genotypes were sown on July 4. In 2010 KSK133 and IR6 were sown on June 17, whereas RSP1 was sown

one week later due to its noted shorter growth duration in 2009. The purpose of this delayed planting was to synchronise flowering of the three genotypes. Before primary tillage operations, the experimental field was fully irrigated (locally referred to as *rouni*). At proper soil moisture conditions, the soil was pulverised through mould board plough and stubbles and weeds were incorporated. A fine seedbed was prepared by three to four cultivations followed by planking. Hand weeding and a combination of pre- and post-emergence herbicides kept the plots weed free. Appropriate pesticides were used as needed to manage insect pests and diseases (PARC, 2010).

3.2.2. Measurements and calculations

To monitor soil moisture content during crop growth season in the main plots, we collected composite soil samples from the root zone (0-300 mm) with the help of an auger. The tested genotypes have a shallow root system, which was confirmed by measurements on root length at the time of harvesting. The roots were mainly concentrated in 200-250 mm. When RMC dropped to 80% (high), 60% (moderate), and 40% (low) of field capacity in the root zone, we re-irrigated (~75 mm) the respective irrigation plots. Dynamics of soil moisture contents in three irrigation treatments, frequency of soil sampling, and the amount of applied irrigation water are shown in Fig. 2.2a-b (*chapter 2*). The frequency of soil sampling was more in the high irrigation treatment compared to the moderate and low treatments. A cut-throat flume (90 cm × 20 cm) was installed in the main water channel of the experimental field to measure the discharge rate ($\text{m}^3 \text{s}^{-1}$) of the stream (Hansen et al., 1980).

The amount of water input in different irrigation treatments and growing seasons is shown in Table 3.2. We cut a row of 1 m at ground level in each sub-plot and separated the sampled plants into green leaves, dead leaves, stem (including leaf sheath), and panicle (if any). The separated fractions of biomass were oven dried at 70°C for three days before weighing. The dried sub-samples of the green leaves, stem, and grain were finely ground to determine the N content using micro-Kjeldahl method following digestion in a $\text{H}_2\text{SO}_4\text{-H}_2\text{O}_2$ solution (AOAC, 1984). Total aboveground nitrogen uptake (TNU) was calculated as the product of N concentration and dry biomass of the discerned plant organs (Ladha et al., 2005). A pre-determined central area of 3 m² in each sub-plot was harvested to estimate GY and total aboveground dry biomass (TDM) at maturity. The grain moisture content was determined immediately after threshing and GY was expressed at the standard 14% moisture content. The HI was calculated as the ratio of GY to TDM.

Table 3.2. Total water input (irrigation + rainfall; mm) per year and irrigation treatment.

Year	Irrigation treatment	Irrigation (mm)	Rainfall (mm)	Total water input (mm)
2009	High	1080	198	1278
	Moderate	736	198	934
	Low	503	198	701
2010	High	726	592	1318
	Moderate	387	592	979
	Low	346	592	938

3.2.3. Data analysis

We analysed the field data by analysis of variance (ANOVA) using generalised linear model procedure (GLM) of SAS 9.2 for Windows (SAS Institute, Cary, NC). The effects of irrigation, N, genotype and their interactions on the TDM, GY, HI, and TNU were established by using the following model:

$$Y_{ijkl} = \mu + I_i + N_j + G_k + B_l + I_i * N_j + I_i * G_k + N_j * G_k + I_i * N_j * G_k + \varepsilon_{ijkl}$$

where Y_{ijk} is dependent variable subjected to the i^{th} level of irrigation, j^{th} level of N, and k^{th} genotype in the l^{th} block ; I = Irrigation effect, N = Nitrogen effect, G = Genotype effect, B = Block effect; ε_{ijkl} = General Error Term. Tukey's test was used to test whether I, N, G, and the interactions significantly affected dependent variable Y_{ijkl} . Differences were considered significant at $P \leq 0.05$ and data were analysed separately for two years (2009/10).

3.3. RESULTS

Our field experiments were designed to quantify crop performance in terms of TDM, GY, HI, and TNU as affected by combinations of irrigation and N-fertilisation rate. We also tested for differences between three selected local genotypes in response to these input combinations.

3.3.1. Season 2009

Table 3.3 summarises the seasonal results of the analysis of variance (ANOVA). For TDM, GY, and HI we found significant three-way interactions between irrigation, N, and genotype ($I \times N \times G$).

Table 3.3. Analysis of variance for total aboveground dry biomass (TDM, kg ha⁻¹), grain yield (GY, kg ha⁻¹), harvest index (HI), total aboveground nitrogen uptake (TNU, kg ha⁻¹) across three local genotypes, three N rates, and three irrigation levels in two years.

SOV ^a	2009				2010			
	TDM	GY	HI	TNU	TDM	GY	HI	TNU
I	***	***	***	***	NS	***	***	***
N	*	*	NS	NS	NS	**	***	NS
G	***	***	NS	***	***	***	NS	*
I×N	***	**	NS	**	NS	**	**	NS
I×G	***	***	**	***	*	*	NS	NS
N×G	**	NS	NS	NS	*	**	NS	*
I×N×G	**	*	*	*	NS	NS	*	NS
C.V. ^b	9.8	15.6	13.5	11.9	16.3	16.6	11.8	19.2

^a I: irrigation treatment (high, moderate, low), N: nitrogen rate (0, 170, 220 kg ha⁻¹); levels of significance indicated: NS = not significant, *significant at $P \leq 0.05$, **significant at $P \leq 0.01$, ***significant at $P \leq 0.001$; ^b coefficient of variation.

Due to large number of treatment combinations, it is inappropriate to discuss each interaction individually; here we focus on the most relevant ones. However, all data are presented in figures. The general trend was that the TDM accumulation increased in response to increasing water input but at a given combination of irrigation and genotype, differences were less visible between the three N rates for all three tested genotypes (Fig. 3.1). The G–N–I (genotype–N–irrigation) treatment combination of KSK133–220–high recorded the highest TDM and did not differ significantly from some other treatment combinations (i.e. KSK133–0/170–high, KSK133–0–moderate, and IR6/RSP1–170–high; TDM range 10.4–13.3 Mg ha⁻¹). The treatment combination of KSK133–0–low recorded the lowest TDM and did not differ significantly from some other treatment combinations (i.e. KSK133–170–low, IR6–0/220–low, IR6–220–moderate, and RSP1–0/170–low; TDM range 3.6–6.3 Mg ha⁻¹). We also measured the dry biomass of leaf (LDM), stem (SDM), and panicle (PDM) (data not shown). In the high N treatment, LDM, especially the dead leaf, was significantly higher compared to the zero N/recommended treatments but SDM and PDM were comparable across genotypes and irrigation treatments. Among genotypes, KSK133 had higher PDM and SDM compared to RSP1 and IR6, whereas LDM was comparable across N and irrigation treatments.

GY responses largely mirrored the TDM results, with the exception of the response to water limitations in the moderate and low irrigation treatments, where GY was disproportionally lower than TDM. Again, we did not find a strong response to N application. Only genotype IR6 under the high irrigation treatment had significantly higher GY at recommended and high N compared to the zero N treatment. The

treatment combination of KSK133–170–high achieved the highest GY, which was statistically in the same group as some other treatment combinations (i.e. KSK133–0/220–high, KSK133–0–moderate, and IR6/RSP1–170–high; GY range 3.11–4.11 Mg ha⁻¹). The treatment combination of KSK133–0–low achieved the lowest GY, which statistically did not differ from some other treatment combinations (i.e. KSK133–170/220–low, IR6–220–moderate, and IR6/RSP1–0/170/220–low; GY range 0.65–1.54 Mg ha⁻¹).

The HI reflects how much TDM was converted to the economically desired component i.e. GY. We found that HI was mainly dependent on irrigation not on N or genotype; the highest HI occurred in treatment combination of KSK133–170–high, which did not differ significantly from quite a number of other treatment combinations (i.e. KSK133–0/220–high, KSK133–0–moderate, IR6–170/220–high, IR6–170/220–moderate, IR6–0–low, RSP1–0/170/220–high, and RSP1–0/170–moderate; HI range 0.23–0.32). The lowest HI occurred in treatment combination of RSP1–0/170–low, which did not differ significantly from quite a number of other treatment combinations (i.e. KSK133–0/170/220–low, KSK133–170/220–moderate, IR6–0–high, IR6–170/220–low, and RSP1–220–moderate/low; HI range 0.15–0.23).

3.3.2. Season 2010

For TDM, we found significant N×G and I×G interactions (Table 3.3). KSK133 responded positively to both N-fertilisation and irrigation, whereas RSP1 and IR6 did not show a clear pattern (Fig. 3.2). Across three N rates, KSK133 accumulated the highest TDM (10–13 Mg ha⁻¹), which was comparable with RSP1 (10–12 Mg ha⁻¹) but consistently higher than for IR6 (8–10 Mg ha⁻¹) in all three irrigation treatments. We observed a similar trend across three irrigation treatments between genotypes and N rates. KSK133 had higher values for PDM and SDM than of RSP1 and IR6. Across genotypes and irrigation treatments, SDM was higher and PDM lower in the high N treatment compared to the zero N/recommended N treatments (data not shown).

For GY, we found a two-way interaction between all three main factors i.e. I×N, N×G, and I×G. For all tested genotypes, the highest GYs were obtained at the high irrigation treatment. Compared to 2009, the difference in the total amount of water input (hence soil moisture content) between moderate and low irrigation treatments was small (Table 3.2). This was reflected by comparable GYs for the moderate and low irrigation treatments. KSK133 had significantly higher GY (4.54 Mg ha⁻¹) than RSP1 (3.74 Mg ha⁻¹) and IR6 (3.41 Mg ha⁻¹) at the high irrigation treatment. Again, response to N-fertilisation was limited to a few treatment combinations.

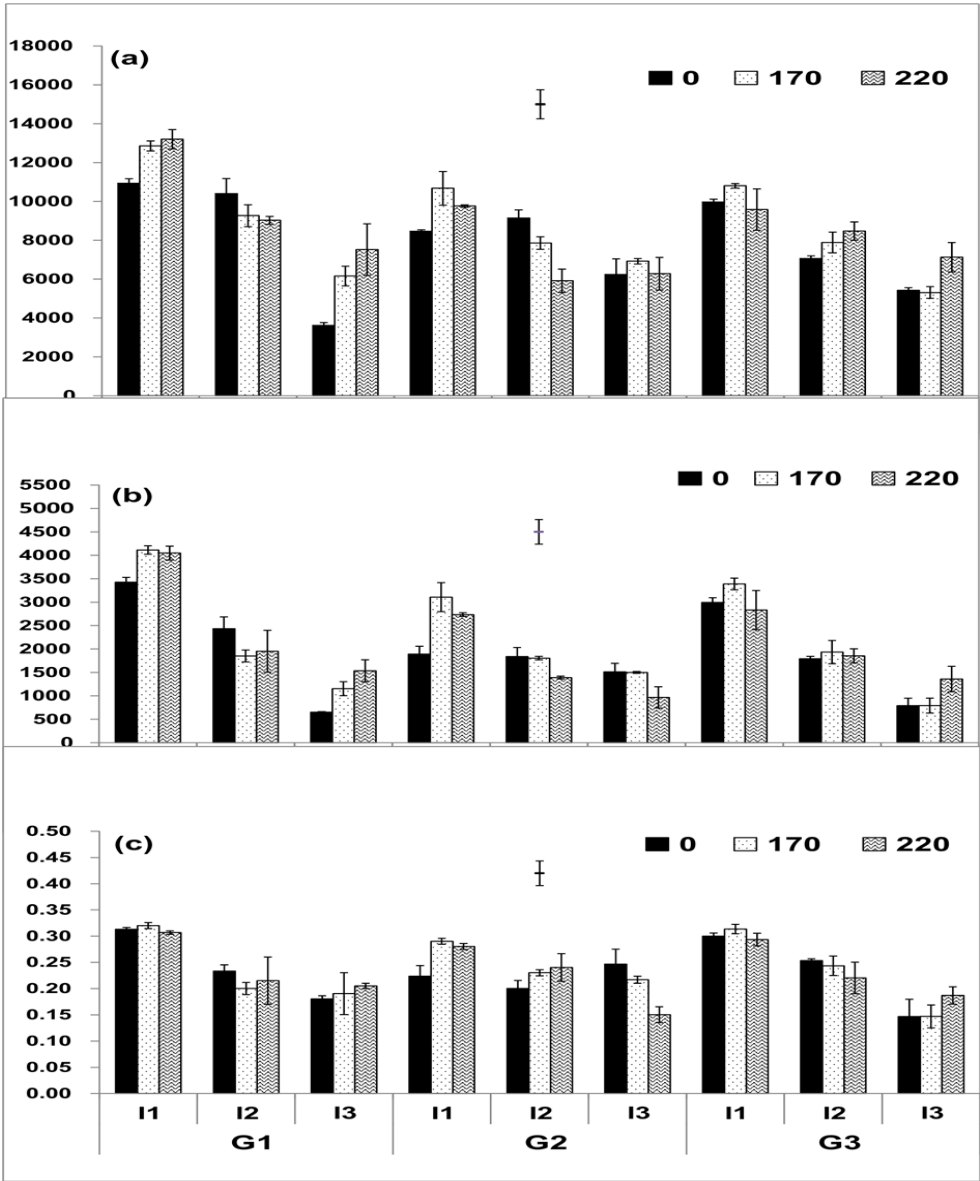


Fig. 3.1. Total aboveground dry biomass (TDM kg ha⁻¹; a), grain yield (GY kg ha⁻¹; b), and harvest index (HI; c) of three genotypes under three irrigation treatments and three N rates in 2009. Genotypes: G1 (KSK133), G2 (IR6), G3 (RSP1); Irrigation treatments: I1 (High), I2 (Moderate), I3 (Low), N rates: Zero N (0 kg N ha⁻¹), Recommended (170 kg N ha⁻¹), High (220 kg N ha⁻¹). Error bars within a vertical column indicate standard error of difference of means for each I×N×G combination, whereas, error bars above the columns indicates average standard error of difference of means.

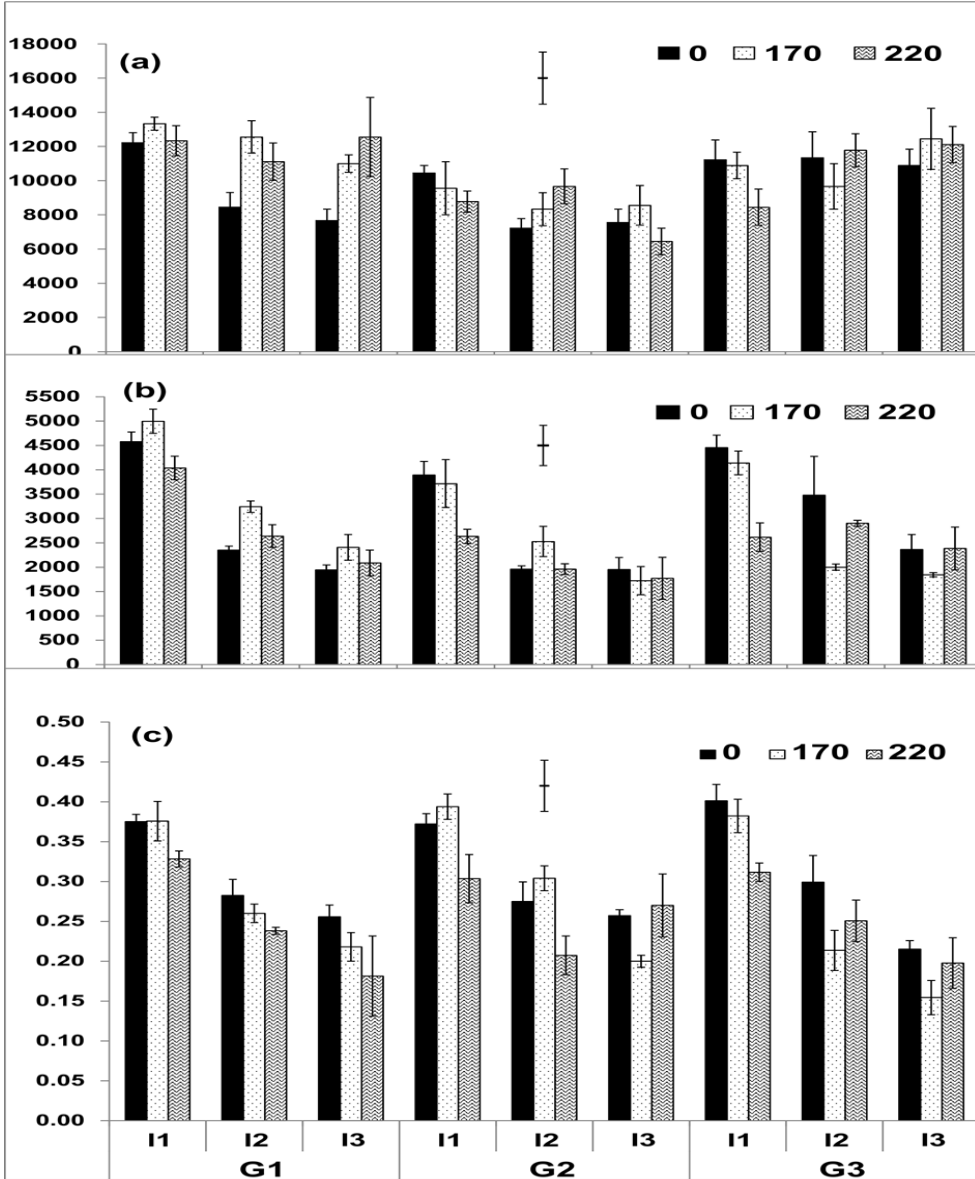


Fig. 3.2. Total aboveground dry biomass (TDM kg ha⁻¹; a), grain yield (GY kg ha⁻¹; b), and harvest index (HI; c) of three genotypes under three irrigation treatments and three N rates in in 2010. Genotypes: G1 (KSK133), G2 (IR6), G3 (RSP1); Irrigation treatments: I1 (High), I2 (Moderate), I3 (Low), N rates: Zero N (0 kg N ha⁻¹), Recommended (170 kg N ha⁻¹), High (220 kg N ha⁻¹). Error bars within a vertical column indicate standard error of difference of means for each I×N×G combination, whereas, error bars above the columns indicates average standard error of difference of means.

At high irrigation, high N treatment had significantly lower GY (3.10 Mg ha^{-1}) than zero N (4.31 Mg ha^{-1}) or recommended (4.29 Mg ha^{-1}) treatment. As in 2009, we found a significant $I \times N \times G$ interaction for HI. In general, irrigation increased HI, and differences between genotypes were marginal. N-fertilisation frequently resulted in a lower HI. Compared to 2009, HI was generally higher, especially in moderate and low irrigation treatments due to better growing conditions resulting from higher rainfall. The highest HI occurred in treatment combination of RSP1–0–high, which did not differ significantly from quite a number of other treatment combinations (i.e. KSK133–0/170/220–high, KSK133–0–moderate, IR6–0/170/220–high, IR6–170–moderate, IR6–0–low, RSP1–170/220–high, and RSP1–0–moderate; HI range 0.28–0.40). The lowest HI occurred in treatment combination of RSP1–170–low, which differed from some other treatment combinations (i.e. KSK133–170/220–moderate, KSK133–0/170/220–low, IR6–0/220–moderate, IR6–0/170/220–low, RSP1–170/220–moderate, RSP1–0/220–low; HI range 0.15–0.27).

3.3.3. Total N uptake (TNU)

In both years, TNU remained unaffected by N application rate, yet we observed significant effects of irrigation and genotype (Table 3.3). Additionally, we observed a significant 3-way $I \times N \times G$ interaction for TNU in 2009 (in 2010 we only observed a $N \times G$ interaction) (Fig. 3.3). The differences in TNU resemble the differences in TDM as N content of the different fractions of biomass remained unaffected by any of the three factors. The values of N content were generally above the critical deficiency levels of <2.5% at tillering and <2% at flowering stage for leaf and 0.6–0.8% (Table 3.4) at maturity for straw (Dobermann and Fairhurst, 2000). In both years, irrigation had a significant, positive effect on TNU. In 2009, the treatment combinations of KSK133–220–high resulted in the highest TNU, which was statistically in the same group as few other treatment combinations (i.e. KSK133–0/170–high, KSK133–0–moderate, IR6–170–high, IR6–0–moderate, and RSP1–0/170–high; TNU range $93.5\text{--}126.1 \text{ kg ha}^{-1}$).

Table 3.4. Nitrogen (N) content of green leaf, stem, and grain of rice plants under three irrigation regimes and three N rates averaged over two years (2009–10).

Treatment ^a	%N at tillering	%N at flowering		%N at maturity	
	green leaf	green leaf	green leaf	stem	grain
Low irrigation					
0 kg N ha ⁻¹	2.59	2.28	1.22	1.05	1.18
170 kg N ha ⁻¹	2.65	2.21	1.23	1.02	1.27
220 kg N ha ⁻¹	2.40	2.33	1.18	1.00	1.22
Moderate irrigation					
0 kg N ha ⁻¹	2.61	2.29	1.27	1.10	1.28
170 kg N ha ⁻¹	2.52	2.29	1.11	1.05	1.16
220 kg N ha ⁻¹	2.35	2.23	1.22	1.00	1.18
High irrigation					
0 kg N ha ⁻¹	2.53	2.10	1.21	1.05	1.29
170 kg N ha ⁻¹	2.70	2.23	1.18	0.97	1.34
220 kg N ha ⁻¹	2.61	2.17	1.19	0.95	1.22

^a None of the values were significantly different remaining unaffected by irrigation level or N rates.

The treatment combination of KSK133–0–low resulted the lowest TNU, which was statistically in the same group as few other treatment combinations (i.e. KSK133–170/220–low, IR6–0/170/220–low, RSP1–170–moderate, and RSP1–0/170/220–low; TNU range 34.2–67.1 kg ha⁻¹). In 2010, we found N×G interaction; KSK133 had highest values of TNU (97 kg ha⁻¹) in recommended N treatment, which was statistically different from IR6 in zero N and high N treatments and from RSP1 in recommended and high treatments. In both years, we found strong positive correlations between TNU and GY for all three genotypes (Table 3.5).

3.4. DISCUSSION

3.4.1. Major findings

We found that water deficit was the main factor affecting aerobic rice performance in terms of TDM, GY, HI, and TNU. The response varied between the three genotypes. The absence of a clear and consistent response to N characterises our experimental results.

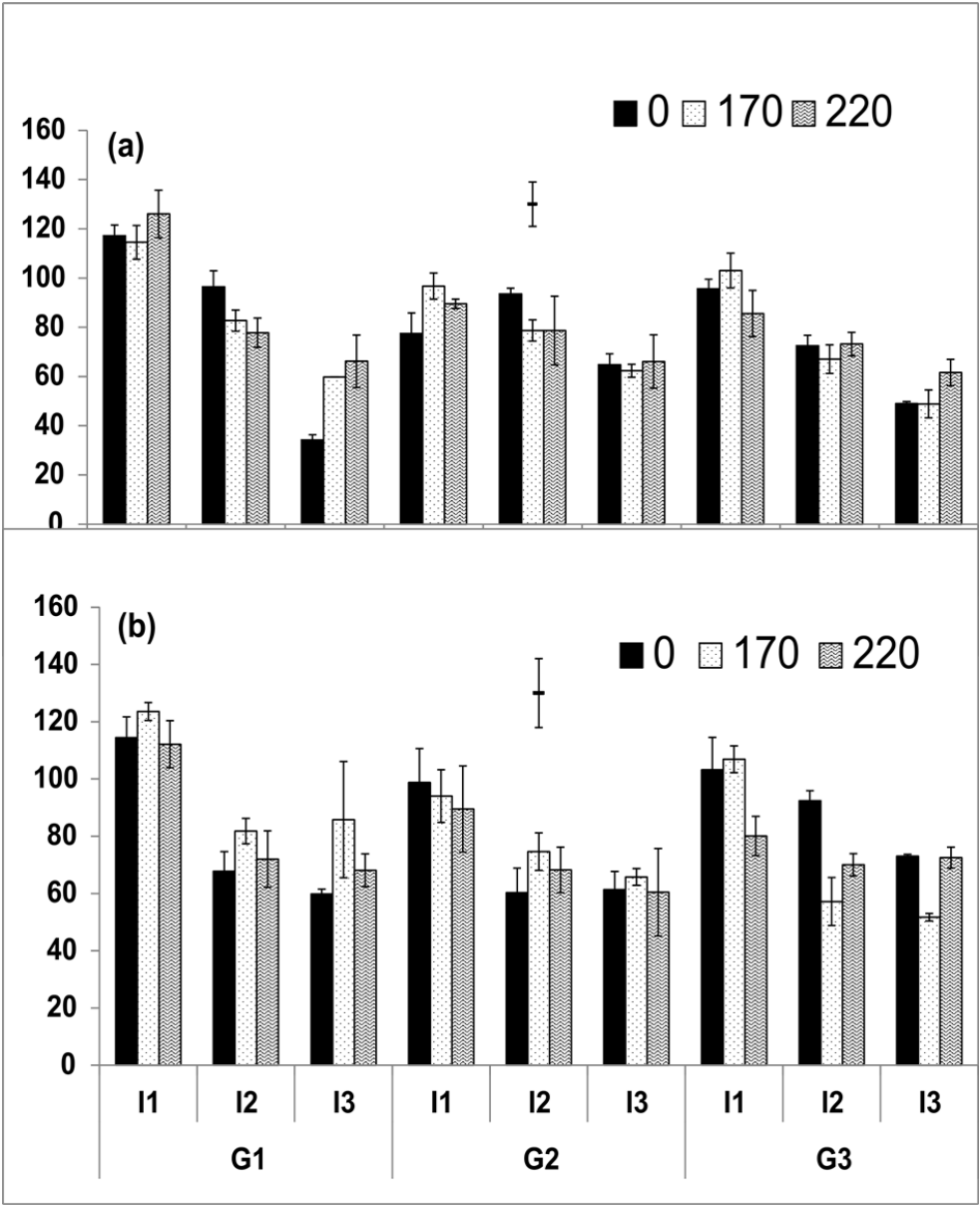


Fig. 3.3. Total N uptake (TNU kg ha⁻¹) of three genotypes under three irrigation treatments and three N rates in 2009 (a) and 2010 (b). Genotypes: G1 (KSK133), G2 (IR6), G3 (RSP1); Irrigation treatments: I1 (High), I2 (Moderate), I3 (Low), N rates: Zero N (0 kg N ha⁻¹), Recommended (170 kg N ha⁻¹), High (220 kg N ha⁻¹). Error bars within a vertical column indicate standard error of difference of means for each I×N×G combination, whereas, error bar above the columns indicates average standard error of difference of means.

Significant two- and three-way interactions between irrigation, N, and genotype reported here are partially in line with Mahajan et al. (2012) and Kadiyala et al. (2012) who also found significant water $\times$ N interactions for traits such as GY and TNU. In contrast, when comparing alternately submerged-non submerged systems with continuous submergence in terms of crop performance and water use at different N levels, Belder et al. (2004) did not find a significant water $\times$ N interaction for GY, TDM, and water productivity. This absence of interaction was attributed to shallow groundwater tables in the studied areas of China and the Philippines. In our experiment higher rainfall in 2010 resulted in higher GY and less pronounced differences between moderate and low irrigation regimes than in 2009. Genotype KSK133 accumulated the highest TDM. This difference was the consequence of differences in PDM and SDM but not in LDM. It shows that KSK133 had higher sink capacity during the reproductive stage than RSP1 and IR6. High yielding genotypes, in a particular environment, are characterised by a high TDM and ability to maintain HI (Ying et al., 1998).

Final GY depends on TDM accumulation and its partitioning towards the grains. Genotype IR6 accumulated the least TDM and produced the least GY, which indicates its unsuitability to adapt aerobic conditions. In our study, TNU was limited by reduced TDM formation under water saving regimes not by available N. Differences in GY and TNU were mainly due to the differences in irrigation and this is a clear consequence of the reduced mass flow, reduced transpiration, and reduced TDM production under water limitations. The limited response of GY to N application and the fact that N concentrations in the crop organs were in normal ranges suggests a high indigenous soil N supply. We were unable to confirm whether this was due to a high initial mineral N content or within season N supply from decomposing organic matter. We can confirm that a significant amount of the high N doses that we applied were not taken up by the crop. N supplied may have been temporarily immobilised by soil microbes or it could be lost through percolation or lost to air as N_2 , N_2O and NH_3 . Temporal immobilisation is unlikely, as soil organic matter was low (0.50–1.23%, Table 3.1) and is probably already saturated with N (hence the high indigenous soil N supply). Percolation losses are unlikely to be large as water supply in our experiments was limited. The process of AWD is known to stimulate decomposition of soil organic matter and nitrification-denitrification processes. Although we have insufficient experimental data to quantify the complete N (and hence energy) balance, we hypothesise that atmospheric N losses are a major factor in the overall N balance. This should be tested in future experiments.

Table 3.5. Grain yield (GY kg ha⁻¹) response to total N uptake (TNU kg ha⁻¹) of three genotypes averaged over two years (2009-10).

Treatment	KSK133			IR6			RSPI	
	GY	TNU ^a		GY	TNU ^a		GY	TNU ^a
Low irrigation	0 kg N ha ⁻¹	1298	47.0	1733	63.1		1576	61.1
	170 kg N ha ⁻¹	1780	72.8 (15%)	1612	64.0 (1%)		1318	50.3 (-6%)
	220 kg N ha ⁻¹	1811	67.2 (9%)	1369	63.3 (0%)		1871	67.1 (3%)
Moderate irrigation	0 kg N ha ⁻¹	2392	82.1	1900	76.9		2635	82.4
	170 kg N ha ⁻¹	2547	82.3 (0%)	2167	76.7 (0%)		1967	62.1 (-12%)
	220 kg N ha ⁻¹	2295	74.9 (-3%)	1674	73.4 (-2%)		2377	71.6 (-5%)
High irrigation	0 kg N ha ⁻¹	4004	115.8	2892	88.1		3725	99.4
	170 kg N ha ⁻¹	4555	119.1 (2%)	3412	95.4 (4%)		3765	105.0 (3%)
	220 kg N ha ⁻¹	4043	119.1 (1%)	2683	89.5 (1%)		2725	82.8 (-8%)

^a in parentheses are the values of N recovery of N (%) calculated as difference in N-uptake between fertilised and unfertilised plot per unit of N fertiliser applied.

3.4.2. Implications

The intensified rice-wheat systems of Pakistan and India in the Indo-Gangetic plains are becoming unprofitable and unsustainable. Practices based on the principles of eco-efficient agriculture are required to enhance productivity of the Indo-Gangetic plains (Balasubramanian et al., 2013). Eco-efficient agriculture is about efficient use of resources in a sustainable way, which can be achieved by altering crop management or land use. Eco-efficiency, however, is not a magic bullet to solve all the problems regarding water scarcity issue and there are certain risk factors associated with a practice or technology. Eco-efficient use of water and N is of prime importance in agriculture (Keating et al., 2010). The direct-seeded aerobic rice is an emerging production system in South Asia, aimed at increasing the overall eco-efficiencies of rice-based cropping systems, in particular the rational use of water (Keating et al., 2010). In aerobic rice system, risk is that water and labour savings might happen at the cost of N losses and possible soil organic matter depletion. Water saving aerobic rice and AWD systems can improve water use efficiency and increase irrigated crop area. However our results and also those of (limited) other studies (Belder et al., 2005a; Kadiyala et al., 2012; Mahajan et al., 2012) suggest that this system might result in high N losses and possibly depletion of the soil organic N resource, which is largely preserved under anaerobic conditions (Larson and Clapp, 1984). Even if the decomposition is slow, anaerobic soils normally mineralise higher amounts of N as less is immobilised compared to aerobic soils (De Datta, 1987). Soil infertility problems under aerobic conditions are a consequence of the depletion of soil organic matter and N as well as to the unavailability of micronutrients such as Mn, Fe, and Zn in calcareous soils resulting in nutrient disorders and imbalances. The flooded conditions favour production and accumulation of $\text{NH}_4\text{-N}$ that is readily converted to $\text{NO}_3\text{-N}$ under aerobic conditions and is prone to losses (Sahrawat, 2009a, b; Sahrawat, 2012). According to Belder et al. (2005a), the amount of unaccounted N was higher under aerobic conditions than under flooded conditions. Thus, while the system undisputedly saves water, labour, and energy and uses these three inputs more efficiently, the system has higher N losses than the conventional flooded system (Devkota et al., 2013).

In our study area, water is considered more limiting than N fertiliser. Hence we consider it a promising alternative technology despite the high N losses, but it is clear that reducing N losses from aerobic rice systems should be an important topic for further research and improvement of the technology. The key questions appear to be how N losses can be reduced and how depletion of soil organic N can be reduced. One

approach might be adding large quantities of compost and crop residues to the soil to compensate for reductions in indigenous supply, as advocated by the so-called 'systems of rice intensification'. However, this would also increase labour demand for composting and incorporation of the compost. The main aim of adding composts to rice fields is to increase available N and to balance the immobilisation and mineralisation of N found in the soil (Kumazawa, 1984).

In order to improve eco-efficiencies of both water and N, it is therefore necessary to follow an integrated crop management approach and educate farmers about resource conservation technologies such as laser land levelling, designing suitable crop rotations by introducing a short duration green manure crop after wheat harvesting, incorporation of crop residues instead of burning, deep rooted cultivars, and maintaining an optimum level of water and required macro- and micro-nutrients are some of the strategies proposed to get an optimal response to applied N (Balasubramanian et al., 2013; Keating et al., 2013; Keating et al., 2010; Ladha et al., 2005). Other promising approaches could be to promote $\text{NO}_3\text{-N}$ rather than $\text{NH}_4\text{-N}$ as a source of fertiliser and apply N in four splits instead of generally recommended three splits (Devkota et al., 2013; Li et al., 2013; Qian et al., 2004).

3.5. CONCLUSIONS

In South Asia, the emerging aerobic rice systems promise improved resource use efficiencies for the scarce water, labour, and energy inputs. Our study showed that transformation of transplanted-flooded rice to direct-seeded aerobic rice system can have a significant impact on N dynamics resulting in high N losses. We also found that irrigation management is critical to avoid secondary stresses, e.g. N limitations. The significant losses of applied N in our study warrant further investigation and careful design of nutrient management strategies in keeping careful attention to water availability and crop demand. We suggest more experiments on water saving under different combinations of N amounts and better understanding of the fate of applied N through quantification of N balance. Among tested genotypes, KSK133, unlike IR6, was able to perform adequately under aerobic conditions. We recommend including KSK133 in the on-going aerobic rice breeding programmes, because of its ability to maintain GY under aerobic conditions. The developing technology of aerobic rice will benefit from development of adapted varieties and optimisation of crucial irrigation and fertiliser inputs.

CHAPTER 4

A two-step approach to quantify photothermal effects on pre-flowering rice phenology*

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Abstract

Decreasing water availability for rice based systems resulted in the introduction of water saving production systems such as aerobic rice and alternate wetting-drying technology. To further improve resource use efficiency in these systems, water management should be attuned to critical growth stages, requiring accurate prediction of crop phenology. Photoperiod-sensitivity of aerobic rice genotypes complicates the estimation of the parameters characterising phenological development and hence impairs predictions. To overcome this complication, we followed a two-step approach: 1) the photoperiod response was determined in growth chambers, through a reciprocal transfer experiment with variable day length, conducted at a fixed temperature, and consecutively, 2) the temperature response was studied by combining the obtained photoperiod parameters with data from field experiments. All four aerobic rice genotypes tested exhibited strong photoperiod-sensitivity. Durations of basic vegetative phase (BVP) i.e. when plants are still insensitive to photoperiod, photoperiod-sensitive phase (PSP), and post-PSP (PPP) varied among genotypes. The temperature response of the genotypes was explored by combining phenological observations in the reciprocal transfer experiment with observations in two field experiments. The temperature range in the field experiments was too narrow to obtain convergence to a unique set of temperature response parameters, regardless whether a bilinear or a beta model was used. Sensitivity analysis however provided clear arguments in support of the recent doubts on the validity of a commonly used set of cardinal temperatures for rice phenology. Using standard cardinal temperatures overestimated the rate of development at temperatures below 31°C. This finding stresses the need for experiments on rice phenology under a wider range of temperatures.

Keywords: Aerobic rice, photothermal response, flowering, phenology parameterization, reciprocal transfer experiment.

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4.1. INTRODUCTION

Within crops resource accumulation and the efficiencies of their use are strongly coupled to the timing and interplay of plant growth and development. Understanding phenological chronology is important for fine-tuning genotype selection and adjusting sowing dates (Vergara and Chang, 1985; Fukai, 1999). Accurate prediction of critical growth stages is also crucial for designing appropriate crop management. The timing of resource application is particularly important when these resources are scarce. Temperature and photoperiod (PP) are the two principal factors controlling pre-flowering development of plants. Studies on photothermal responses thus facilitate the selection of adapted genotypes for target environments as well as the optimisation of crop management in order to minimise the adverse consequences of seasonal constraints (Collinson, 1992; Fischer et al., 2003). For rice crops careful genotype selection and scheduling of resource application is essential for the success of water saving systems such as aerobic rice and alternative wetting-drying technology (Lafitte and Courtois, 2002; Belder et al., 2005a; Xiaoguang et al., 2005).

Rice (*Oryza sativa* L.) is a short-day plant and the degree of PP-sensitivity varies among genotypes. Since the 1960s, IRRI has been breeding for less PP-sensitive genotypes, thus allowing these genotypes to be grown in multiple cropping systems. IR8, a less PP-sensitive genotype developed in 1966 showed a wider adaptability and stable growth duration compared with the traditional genotypes (Vergara and Chang, 1985; Prasad et al., 2001). In the higher latitudes of Japan and Northeast China, early maturing *japonica* PP-insensitive genotypes allow for growing rice under adverse conditions i.e. short and cool summers under long days of more than 15 h (Okumoto et al., 1996; Wei et al., 2008). However, PP-sensitivity may have advantages as a safety mechanism when exact planting dates are not followed. Within a wide range of sowing dates, a PP-sensitive genotype would still flower and mature at the same time. The synchronised maturation of crop might help prevent the ripening of the crop to occur under unfavourable conditions (Vergara and Chang, 1985; Prasad et al., 2001). For that reason, PP-sensitivity is an important trait that can be used in breeding programmes that target improved crop performance in resource-limited environments (Poonyarit et al., 1989; Li et al., 1995; Fischer et al., 2003). Long duration, PP-sensitive genotypes can better withstand unfavourable conditions such as early drought, transplanting shock and low soil fertility (Vergara and Chang, 1985; Fukai, 1999).

Phenology calibration from field observations is especially difficult in case of PP-sensitive genotypes (van Oort et al., 2011). The two main problems are: a) finding the start and end of the PP-responsive period, and b) disentangling photoperiod and

temperature effects. Temperature and photoperiod are correlated; during summer daylength (photoperiod) is generally longer and temperatures are higher. The question arises: if a delay in flowering is observed during summer, is this due to the longer daylength, temperatures above the optimum temperature for development, or both? Often this question can simply not be answered from field experiments. To disentangle both effects, we applied a two-step approach. Firstly, the photoperiod parameters were estimated in a PP-controlled reciprocal transfer experiment at constant temperature. In a second step these photoperiod parameters were used to study the temperature response under field conditions. The temperature response calibration problem becomes relatively simple when default values for cardinal temperatures can be assumed. In that case the only remaining parameters to be estimated are the temperature sums needed to complete the consecutive development stages. For rice, commonly used cardinal temperatures are 8, 30 and 42°C for the base, optimum and maximum temperature, respectively (Matthews et al., 1995; Bouman et al., 2001). However, two recent studies (Zhang et al., 2008; van Oort et al., 2011) questioned the validity of these commonly used default parameters and showed that these could lead to bias in simulated phenology.

The objectives of this paper were therefore to (1) present a two-step approach for estimating the photothermal phenology of rice genotypes, (2) apply this approach to four modern aerobic rice genotypes and (3) study the validity of a set of standard cardinal temperatures commonly used for simulating rice phenology.

4.2. MATERIAL AND METHODS

In this section we first outline the set of equations used to describe the photothermal response to pre-flowering rice phenology (section 4.2.1). In section 4.2.2 the phytotron study for determining PP-sensitivity is presented, whereas the details regarding the field experiments on temperature sensitivity are outlined in section 4.2.3. Both sections start with a description of the experimental set-up, followed by an outline of the procedures for parameter estimation.

4.2.1. Development stages and equations

Rice development can be partitioned into two main phases: the pre-flowering phase from emergence ($\theta=0$) to flowering ($\theta=1$) and the grain filling phase from flowering to maturity ($\theta=2$). The pre-flowering phase can be further dissected into three sub-phases: the basic vegetative phase (BVP, $0<\theta<\theta_1$), the PP-sensitive phase (PSP, $\theta_1<\theta<\theta_2$) and the post-PSP phase (PPP, $\theta_2<\theta<1$). In the above θ (-) is the development

stage with values of zero at emergence, 1 at flowering and 2 at maturity. Parameters θ_1 and θ_2 mark the start and the end of PSP, respectively. Durations of BVP, PSP, and PPP are expressed in days (d) and the value of θ increases daily with development rate (DR; d⁻¹). Equation 1 is used for obtaining development rate in the pre-flowering phases:

$$DR(T,P) = \begin{cases} g(T)/f_o & \theta \leq \theta_1 \text{ or } \theta \geq \theta_2 \\ g(T) * r(P)/f_o & \theta_1 < \theta < \theta_2 \end{cases} \quad (1)$$

In this equation, $g(T)$ and $r(P)$ are unit less temperature- and PP-response functions respectively, and f_o is duration (in days) from emergence to flowering under optimal temperature and optimal day length. Equation 1 is a simplified version of the equation used by Yin et al. (1997a, b) in which the photoperiod sensitive (PSP) and non-photoperiod sensitive (BVP and PPP) phases are distinguished, but a single function $g(T)$ is used for temperature effect and no distinction is made between the effects of day and night temperature. Function $r(P)$ represents the photoperiod response function.

In our two step approach, we first estimated the values of θ_1 and θ_2 and selected the most appropriate photoperiod response function $r(P)$ for each genotype separately. For the shape of $r(P)$ four functions were considered:

$$r(P) = \begin{cases} 1 \text{ for } P \leq P_o \\ 1 - \delta(P - P_o) \text{ for } P > P_o \end{cases} \quad (2)$$

$$r(P) = \left[\left(\frac{P - P_b}{P_o - P_b} \right) \left(\frac{P_c - P}{P_c - P_o} \right)^{\frac{P_c - P_o}{P_o - P_b}} \right]^\beta \quad (3)$$

$$r(P) = \begin{cases} 1 \text{ for } P \leq P_o \\ \frac{1}{1 + \gamma(P - P_o)} \text{ for } P > P_o \end{cases} \quad (4)$$

$$r(P) = \begin{cases} 1 \text{ for } P \leq P_o \\ \exp(k(P - P_o)) \text{ for } P > P_o \end{cases} \quad (5)$$

Yin et al. (1997c) analysed a large data-set of cultivars and found a large genotypic variation in the PP-sensitivity parameters, whereas, the genotypic variation in optimum photoperiod (P_o) was relatively small. The estimated value of P_o was very close to the widely used value i.e. 10 h d⁻¹ (Vergara and Chang, 1985). In this study, the P_o was therefore fixed to 10h d⁻¹ as this also helped to reduce the number of parameters to be estimated.

The PP-sensitivity parameters δ , β , γ and k were estimated such that $r(10)=1$ and the best fit through the three data points (10, 12.5 and 15h d⁻¹) was obtained. Note that equation 2 shows a linear response; whereas the response is non-linear in equations 3, 4 and 5 (see the Results section for the shape of these equations fitted to experimental data). Equation 3 is the beta function where P_b and P_c are the base and ceiling photoperiods, set to 0 and 24h d⁻¹, respectively (Yin and Kropff, 1996).

From the first step we derived, for each genotype, the values of θ_1 and θ_2 and the $r(P)$ function and its parameters. With these parameters fixed, we moved to step 2 where we estimated the remaining temperature parameters and f_o (d). Temperature response was assumed to be the same for all developmental phases. First a bilinear temperature response model was used (eq. 6):

$$g(T_h) = \begin{cases} \frac{T_h - TBD}{TOD - TBD} & TBD < T_h < TOD \\ \frac{TMD - T_h}{TMD - TOD} & TOD < T_h < TMD \end{cases} \quad (6)$$

where TBD (°C) is the base temperature, TOD (°C) the optimum and TMD (°C) the maximum temperature and T_h the hourly temperature. We included the bilinear temperature model (6) because it is the most commonly used approach in existing crop growth models like ORYZA2000 (Matthews et al., 1995; van Oort et al., 2011; Bouman et al., 2001). Also we estimated parameters for the (bell shaped) beta function (Yin et al., 1995):

$$g(T_h) = \left[\left(\frac{T_h - TBD}{TOD - TBD} \right)^{\frac{TOD - TBD}{TMD - TOD}} \left(\frac{TMD - T_h}{TMD - TOD} \right)^{\frac{TMD - T_h}{TMD - TOD}} \right]^{BETA} \quad (7)$$

where the shape of the bell function is defined by parameter BETA (Yin et al., 1995). For both temperature functions the daily temperature driven development rates were calculated as the average of 24h hourly development rates. Hourly temperatures were calculated based on daily maximum (T_{max}) and daily minimum (T_{min}) temperatures (Matthews et al., 1995):

$$T_h = \frac{T_{max} + T_{min}}{2} + \frac{T_{max} - T_{min}}{2} \cos(0.2618(h - 14)) \quad (8)$$

In the following sections we describe the experiments and the procedures for estimating the parameters in equations 1-7.

4.2.2. Step 1: Photoperiod sensitivity

4.2.2.1. Plant material

We investigated the phenological responses of four tropical *indica* type rice genotypes. The genotypes were selected on the basis of contrasting origins. KSK133 (KSK 282 × 4321) is a high yielding, stiff stemmed and extra-long lowland rice variety that stays green at the time of maturity. It was released for general cultivation in 2006 by Rice Research Institute, Kala Shah Kaku, Pakistan, and recommended for the non-traditional rice belt of Pakistan. It was also used as check variety in direct seeded aerobic rice experiments (Akhter et al., 2007; IRRI, 2010). RSP1 (DM64198) is a mutant of aromatic lowland genotype Basmati-385, showing traits of drought tolerance. It is an elite candidate line of the Nuclear Institute for Agriculture and Biology (NIAB)-Pakistan (Akhter et al., 2010). Apo (IR55423-01) is a high yielding improved upland variety of the Philippines, often used as control in aerobic rice experiments and is suitable for tropical conditions (Atlin et al., 2006; Zhao et al., 2007). IR74371-54-1-1 is an upland line from the Philippines, used in aerobic rice breeding programmes of Asia (Verulkar et al., 2010).

4.2.2.2. Environmental conditions

The experiment was conducted in phytotrons of Wageningen University and Research Centre, the Netherlands. We used three climate chambers to establish short (SD), intermediate (ID) and long (LD) day length treatments of 10, 12.5, and 15h d⁻¹, respectively. Photoperiod treatments were chosen to cover a broad range of principal rice growing environments. Reciprocal transfers of plants occurred between SD and LD chambers keeping ID chamber as the non-transfer chamber. Each growth chamber had an area of 3.5 × 2.5 m². Plants in all chambers received uniformly distributed artificial assimilation light during 10h d⁻¹ provided by a combination of incandescent HPI/Son-t and fluorescent TL lamps (Philips Master TLD 58/840 reflex new generation, R/FR +/- 3). The photosynthetically active radiation (PAR) provided by the assimilation light was 520±20 µmol.m⁻².s⁻¹ at pot level i.e. 1.1 m above the floor. In the ID and LD chambers, day length extending light of about 18 µmol.m⁻².s⁻¹ was supplied. This value is well above the threshold level of 10 µmol.m⁻².s⁻¹ for full PP-response of rice plants (Yin et al., 1997c). The ratio of red: far-red light (660 nm: 730

nm) established by these day length extending lights was 2.3, which is higher than that of natural daylight (1.2), but close to the values (2.5–5) reported for greenhouse and growth chamber lightings (Black et al., 2005). Little is known about possible effects of this ratio on development, but the scarce literature availability suggests that it has no effect (Black et al., 2005). The chamber settings for dark periods were: SD 18.00-08.00h, ID 19.15-06.45h, LD 20.30-05.30h. The temperature was set to 26°C and maintained constant in order to avoid confounding effects of different sensitivity to temperature during day and night. We recorded soil temperature and the temperature at 10 cm height with thermocouple psychrometers to check whether there was a temperature gradient between and within the chambers. These measurements revealed that the chambers had uniform conditions. Relative humidity was maintained at a constant value of 70%.

4.2.2.3. Plant husbandry

Four sterilised seeds of respective genotypes were sown at a depth of 2 cm in each pot (3.5 L, 22 cm in diameter) and later thinned to two plants at two-leaf stage. The pots were filled with mixed soil (12-14-24 g NPK per 0.81 kg), supplying 340, 173, 565 mg NPK per pot. Additionally, we applied 210, 52, 85 mg NPK per pot to supply a total of 550, 225, 650 mg NPK per pot. The nutrient solution (pH 6, EC 2.3) was prepared by dissolving nutrient salt-plant-prod (27-15-12% N-P₂O₅-K₂O) in water. Irrigation water was applied twice a day to each pot with drainage holes at the base. Plants were supported with two plastic rings fixed above the pot with a wooden stick in the middle to prevent intermingling of plants. Daily observations were made to record flowering dates. Flowering was defined as the moment when 50% of the florets of the first panicle had flowered (Yin et al., 1997c). Observations were made on the two plants per pot separately. The experiment was terminated after 162 DAE, the moment that even all the plants in the LD chamber had flowered.

In the reciprocal transfer chambers (SD and LD) the pot experiment was laid-out in split plot design in two replications, with transfer date as main factor and variety as sub-factor. Transfer of plants between SD and LD chambers occurred at 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 days after emergence (DAE). Once a pot was transferred, it remained in the new chamber thereafter. In addition, there were 16 non-transfer pots (4 per each genotype) exposed to continuous short- or long-day length as control treatments. In each chamber the 96 experimental pots were surrounded by 32 border pots. In the non-transfer chamber (ID) the same number of pots was installed, meaning that each genotype was represented by 24 pots. This relatively high number was used to get an indication of the variation in flowering date within genotypes.

4.2.2.4. Parameter estimation

Data on number of days from emergence to flowering (f) observed in reciprocal transfer chambers were used to estimate the duration of BVP (d), PSP under short day conditions (PSP_{10} ; d), PSP under long day conditions (PSP_{15} ; d), and PPP (d). We used an iterative procedure of the PROC NLIN of the Statistical Analysis System Institute (SAS Inc.) which allows to combine data sets from reciprocal transfers (SD to LD and vice versa) into one single analysis (Yin et al., 1997c; Yin et al., 2005; Yin, 2008). From the estimated durations of the pre-flowering development phases, we calculated f_{op} (the minimum number of days to flowering at 26°C and the optimum PP), θ_1 and θ_2 , following Yin et al. (2005) as:

$$f_{op} = BVP + PSP_{10} + PPP \quad (9)$$

$$\theta_1 = BVP/f_{op} \quad (10)$$

$$\theta_2 = (BVP + PSP_{10})/f_{op} \quad (11)$$

The duration of the PSP during the 12.5h d^{-1} daylength treatment was calculated as the observed duration to flowering at 12.5h d^{-1} ($f_{obs;12.5}$) minus the BVP and PPP from above:

$$PSP_{12.5} = f_{obs;12.5} - BVP - PPP \quad (12)$$

Based on earlier research (Yin et al., 1997a,b) it was assumed that a photoperiod of 10h d^{-1} , which corresponds to our short day treatment (SD), is the optimum day length for development and consequently $r(10)$ was set to one. Accordingly, $r(P)$ for the other two treatments was calculated as:

$$r(P) = PSP_{10}/PSP_p \quad (13)$$

A non-linear optimisation procedure using the Solver in MS Excel was used to obtain the PP-sensitivity parameters δ , β , γ and k for equations 2, 3, 4 and 5, by minimising the error between simulated and observed $r(P)$ values at 12.5 and 15h d^{-1} . The goodness of fit (R^2) and maximum error of the three equations was calculated for each genotype.

4.2.3. Step 2: Temperature sensitivity

Based on the previous section (4.2.2.4), we fixed for each genotype θ_1 , θ_2 , and the $r(P)$ function that gave the best fit. With those parameters fixed, the remaining temperature response was calibrated, combining the phytotron experiments with field data.

4.2.3.1. Field experiments

Field experiments were conducted in 2009 and 2010 at the research station of the University of Agriculture, Faisalabad (UAF)–Pakistan (31°26' N, 73°06' E, 184.4 m altitude). The climate of region is semi-arid and sub-tropical. The experiments were originally designed to quantify water and nitrogen (N) use efficiencies under aerobic rice system and were laid-out in split-split plot arrangement. Irrigation levels (High, Moderate, and Low) constituted the main plots, N rates (0, 170, 220 kg ha⁻¹) the sub-plots and aerobic rice genotypes the sub-sub-plots. The dates of sowing, emergence, panicle initiation, flowering, and physiological maturity were based on observations in two neighbouring rows and recorded at 50% value i.e. by counting the minimum number of days taken by half of the plants to reach a phenological stage (Table 4.1). Phenological observations from the treatments at the highest N and water supply levels were used for the current analysis. Experiments were conducted in the period of June to November. Meteorological observatory of the university situated less than 1 km of the experimental site recorded daily rainfall (mm), maximum and minimum temperatures (°C), sunshine hours, wind speed (km h⁻¹) and relative humidity (%) (Table 4.2). Astronomical day length during the period from emergence to flowering was 11.3–13.9h, or 12.2–14.8h if 0.9h of twilight per day is added as in the ORYZA2000 model (Bouman et al., 2001), thus well within the photoperiod range considered in step 1. Average temperature during this period was 31°C in 2009 and 30°C in 2010, in both years 90% of daily temperatures from emergence to flowering were in the range of 26–35°C. Towards the end of the growing seasons it cooled down to average daily temperatures around 18–26°C. Genotypes KSK133 and RSP1 were grown in both years, whereas genotypes Apo and IR74371-54-1-1 were only grown in 2010.

4.2.3.2. Parameter estimation

From the field experiments, astronomic day length was calculated with standard equations (Goudriaan and Van Laar, 1994; Bouman et al., 2001). In all situations, two

calibrations were made, one with photoperiod similar to the calculated astronomical day length, and a second one in which the photoperiod was extended with 0.9h d^{-1} of twilight. Before parameter calibration we checked, for both the bilinear (eq. 6) and beta-model (eq. 7), how well days to flowering for all four genotypes in the field experiment could be simulated when using the standard cardinal temperatures for rice phenological development: TBD=8°C, TOD=30°C and TMD=42°C (Bouman et al., 2001). Additionally for the beta model, it was assumed that BETA=1 (Yin et al., 2005).

With TBD, TOD and TMD (and BETA) fixed the $g(26)$ -values for the bilinear model and the beta-model could be determined (0.82 and 0.92, respectively). Accordingly, these values combined with the minimum duration to flowering at 26°C (f_{op}) obtained in the reciprocal transfer experiment, were used to calculate the minimum duration to flowering at optimal temperature (30°C) and daylength (10h d^{-1}) as:

$$f_o = g(26)f_{op} \quad (14)$$

With this, all parameters needed for equation 1 were fixed and the duration to flowering for the six data-points in the field experiments (KSK133 and RSP1 in 2009, 2010, Apo and IR74371-54-1-1 in 2010) were simulated and compared with observed durations in the field. This exploration was followed by parameter calibration for the temperature response of the genotypes that were grown in both 2009 and 2010. For the bilinear model TBD, TOD and TMD were systematically varied: TBD: 1-20°C (step 1°C), TOD: 26-40°C (step 1°C), TMD: 40-90°C (step 10°C). For the beta model TOD and BETA were varied, whereas TBD and TMD were kept at their standard value: TBD: 8°C, TMD: 42°C, TOD: 28-38°C (step 0.5°C), BETA: 0.5-10.0 (step 0.5). For any such fixed set of parameters the value of f_o was iteratively estimated by minimising the error between simulated and observed duration to flowering. The goodness of fit obtained with each parameter set was calculated as:

$$RMSE_f = \sqrt{\frac{1}{n-1} \sum_i (f_{obs,i} - f_{sim,i})^2} \quad (15)$$

where f stands for number of days from emergence to flowering. $RMSE_f$ (d) is the root mean square error calculated based on the phenological observations on plants that remained in the same growth chamber throughout the experiment ($i = 1$ to 3) and in the two years of field experimentation ($i = 4$ to 5), with $f_{obs,i}$ the observed and $f_{sim,i}$ the simulated duration from emergence to flowering in days. From all simulated parameter

sets we selected, for both 0h twilight and 0.9h twilight, the five sets with the lowest $RMSE_f$ values.

Table 4.1. Phenological development (measured at 50% value) and growth duration of genotypes.

Year	Variety	S ^a	E ^b	PI ^c	F ^d	M ^e	Duration ^f
2009	KSK133	Jul-04	Jul-12	Sep 18-29	Oct 12-20	Nov 14-21	125-132
	RSP1	Jul-04	Jul-12	Sep 9-26	Oct 5-17	Nov 5-19	116-130
2010	KSK133	Jun-17	Jun-27	Sep-04	Sep-27	Oct 29	124
	RSP1	Jun-25	Jul-05	Sep-10	Oct-02	Nov 3	121
	Apo	Jun-17	Jun-27	Aug-27	Sep-19	Oct-20	115
	IR74371-54-1-1	Jun-17	Jun-27	Aug-27	Sep-18	Oct-18	113

^aSowing; ^b emergence; ^c panicle initiation; ^d flowering; ^e maturity; duration is in days.

Table 4.2. Mean monthly weather data of rice growth seasons 2009 and 2010.

Year		Tmax	Tmin	Avg.	RH ^a	R ^b	SS ^c	WS ^d
		°C			%	mm	h	km h ⁻¹
2009	July	38.0	27.9	32.9	59.0	43.5	9.0	7.5
	August	36.6	27.6	32.1	65.8	116	8.4	8.2
	September	36.3	24.4	30.3	61.0	20.6	9.2	6.0
	October	32.7	17.1	24.9	57.9	17.5	8.9	3.7
	November	25.7	10.8	18.2	64.7	0.7	6.3	3.3
	Avg.	33.8	21.5	27.7	61.7	198.3 (Total)	8.3	5.8
2010	June	40.1	27.7	33.9	40.0	1	9.4	8.0
	July	36.0	27.9	31.9	63.6	277.8	9.0	8.1
	August	34.9	26.1	30.5	74.6	226.6	6.0	6.5
	September	33.9	23.3	28.6	66.8	86.5	7.9	5.7
	October	32.9	19.7	26.3	59.6	0	7.6	3.3
	November	27.1	10.5	18.8	62.3	0	8.5	2.6
	Avg.	34.2	22.5	28.3	61.1	591.9 (Total)	8.1	5.7

^a relative humidity; ^b rainfall monthly total; ^c sunshine; ^d wind speed.

4.3. RESULTS

4.3.1. Photoperiod sensitivity

Observations showed that with an increase in day length from 10 to 12.5 and 15h d⁻¹, the number of days to flowering (*f*) steadily increased (Fig. 4.1). This demonstrates that all four genotypes were sensitive to photoperiod. In the 12.5h d⁻¹ chamber the maximum difference in *f* within each genotype was 15–18 d with a standard deviation of 3.5–4.6 d.

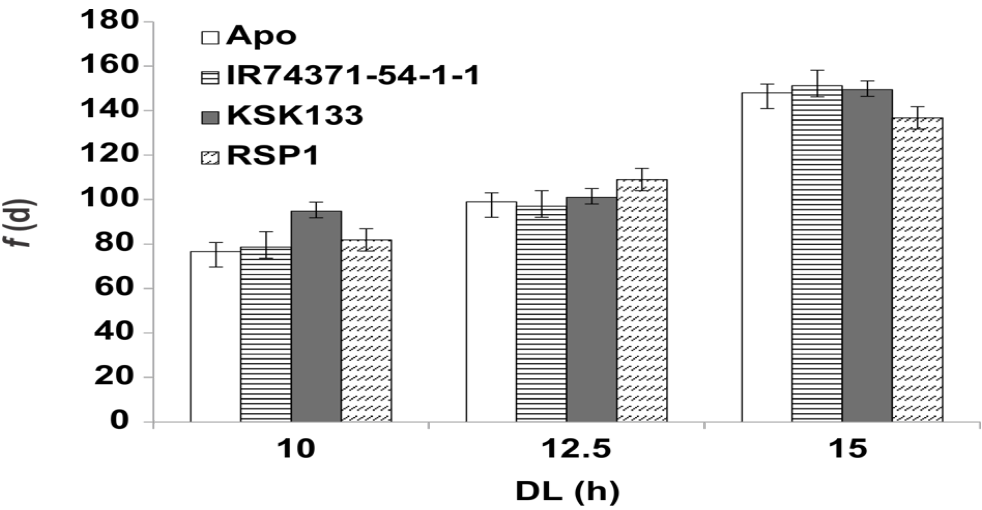


Fig. 4.1. Days from emergence to flowering (*f*) of four rice genotypes at three different day lengths (DL) in the phytotron chambers at 26°C. Error bars show minimum and maximum observed values.

The relation between *f* and days from emergence to transfer (Transfer DAE) of the four genotypes is illustrated in Fig. 4.2a-d. For all genotypes, plants flowered following a pattern described by Yin et al. (1997c) i.e. until a certain transfer date *f* was constant, after which a linear increase (transfer from LD to SD) or a linear decrease (transfer from SD to LD) in *f* was observed. Except for pots transferred during the PSP, variation in *f* of transferred pots of the same genotype was generally small (i.e. <2 d in 90% observations and never exceeding 7 d) (Fig. 4.2a-d). Analysis of these patterns resulted in estimates of the length of three successive phases, i.e. BVP, PSP and PPP (Table 4.3). The length of the BVP varied between 25 (Apo) and 39 d (KSK133). The length of PSP₁₀ was shortest in RSP1 (13 d) and longest in

KSK133 (23 d). The PSP₁₅, obtained under LD conditions, took 68 and 78 d for RSP1 and KSK133, respectively, compared to 93 and 91 d for Apo and IR74371-54-1-1.

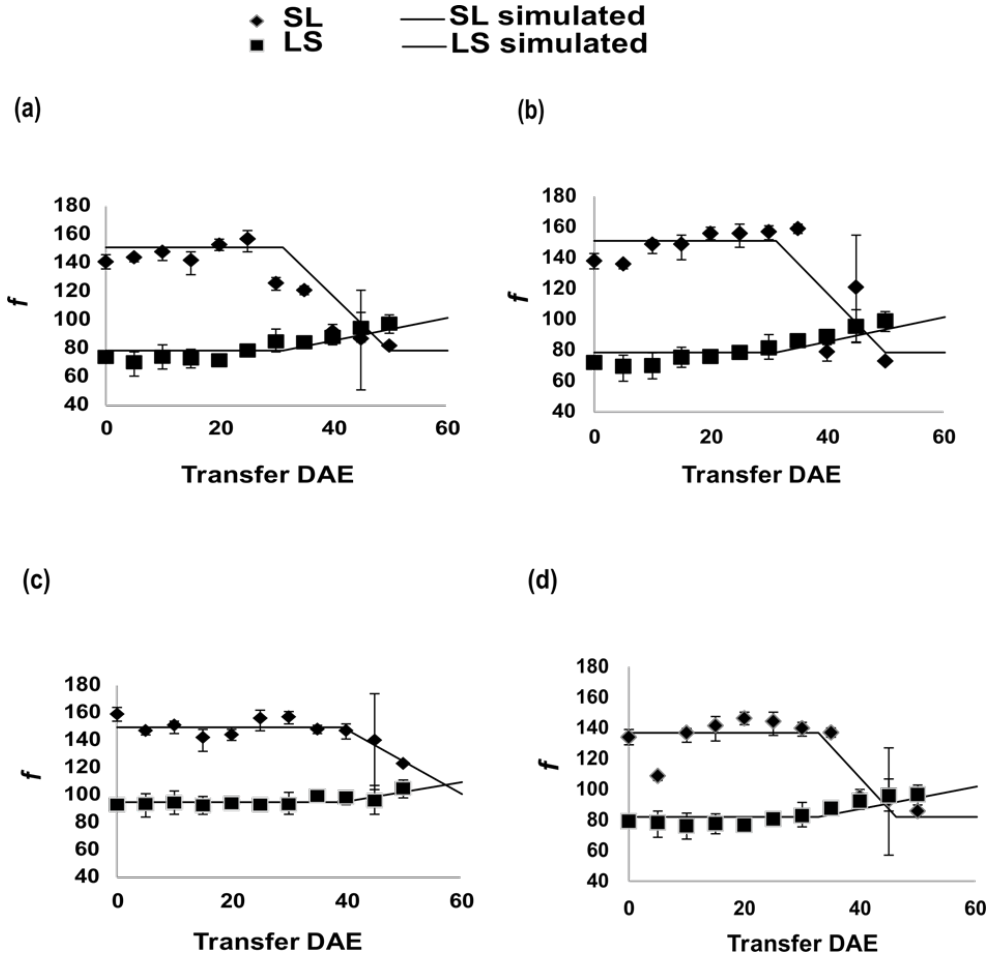


Fig. 4.2a-d. Days from emergence to flowering (f) for Apo (a), IR74371-54-1-1 (b), KSK133 (c) and RSP1 (d) transferred from short day to long day (SL) or long day to short day (LS) at various times after emergence (Transfer DAE). Error bars show minimum and maximum observed values. The solid lines indicate the fitted relations for transfers from SL to LS and LS to SL.

The extension of the PSP under long day conditions was thus considerably longer with Apo and IR74371-54-1-1 (71 and 73 d, respectively) than with the local

genotypes RSP1 and KSK133 (55 d). In contrast, the PPP only differed 7 d, and ranged from 29 d (IR74371-54-1-1) to 36 d (RSP1).

The PP-response parameters (f_{op} , θ_1 and θ_2) were derived from the length of the various phases, using equations 9–11. The f_{op} , an estimate of earliness of a genotype, was quite similar for Apo (77 d), IR74371-54-1-1 (79 d) and RSP1 (82 d). For KSK133 a considerably longer f_{op} (94 d) was observed. The relation between $r(P)$ and photoperiod, shown in Fig. 4.3 for optimised functions (bold parameters in Table 4.3), showed a similar pattern for Apo and IR74371-54-1-1 (eq. 5, exponential function), for KSK133 photoperiod response was best described by a beta function (eq. 3) and photoperiod response of RSP1 was best described by an inverse function (eq. 2).

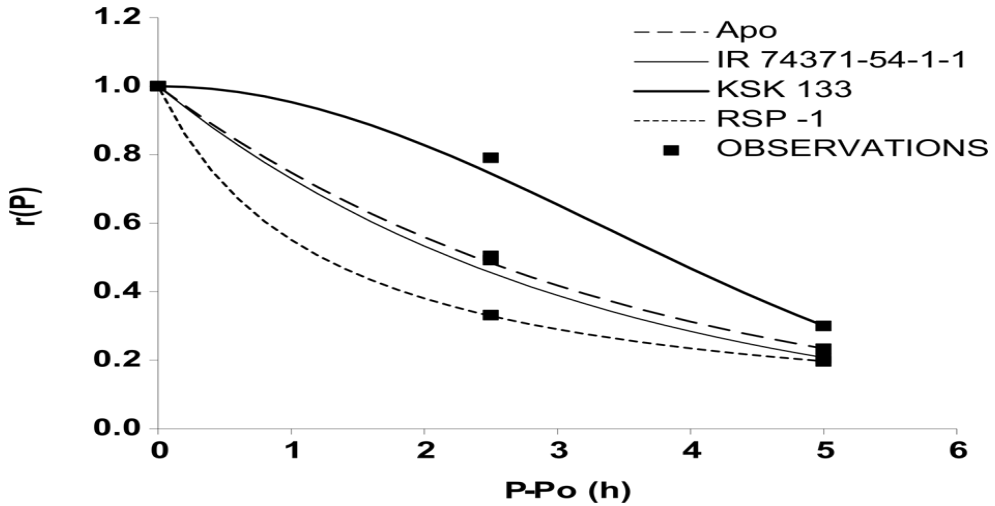


Fig. 4.3. The optimum photoperiod functions $r(P)$ for observed and fitted curves of four rice genotypes. For photoperiods shorter than P_o $r(P)$ is set to 1.

The $r(P)$ functions that gave the best fit were:

For Apo

$$r(P) = \begin{cases} 1 & \text{for } P \leq P_o \\ \exp(-0.291(P - P_o)) & \text{for } P > P_o \end{cases}$$

For IR74371-54-1-1

$$r(P) = \begin{cases} 1 & \text{for } P \leq P_o \\ \exp(-0.315(P - P_o)) & \text{for } P > P_o \end{cases}$$

For KSK133

$$r(P) = \left[\left(\frac{P - P_b}{P_o - P_b} \right) \left(\frac{P_c - P}{P_c - P_o} \right)^{\frac{P_c - P_o}{P_o - P_b} 5.640} \right]$$

For RSP1

$$r(P) = \begin{cases} 1 & \text{for } P \leq P_o \\ 1 - 0.815(P - P_o) & \text{for } P > P_o \end{cases}$$

Inspection of observed $r(P)$ values for KSK133 in Fig. 4.3. suggests that for KSK133 a linear $r(P)$ function (eq. 2) with higher value for P_o could also have given an accurate fit through the three data points.

4.3.2. Temperature sensitivity

When standard cardinal temperatures were used, the duration of the period from emergence to flowering in the field was considerably overestimated for all four genotypes. For the bilinear model, this was in the order of 20 to 35 d when calculated with 0h twilight (Fig. 4.4a) and even more when 0.9h of twilight was added. Also with default values for the beta temperature model the duration to flowering was severely overestimated, by 17 to 29 d (Fig. 4.4b). Subsequent optimisation of cardinal temperatures for genotypes KSK133 and RSP1 identified parameter sets that reduced the errors to 2 d or less for all five data points of the two genotypes. No clear convergence to a unique optimal parameter set was observed. A wide range of parameter sets resulted in similarly accurate predictions. This indicates that a much broader environmental temperature range must be sampled to improve and generalise parameter estimation and hence predictions. Despite this apparent lack of parameter convergence, all near-optimal parameter sets had one thing in common: they all simulated slower development below around 31°C. This is seen in Figs. 4.5 and 4.6 where below 31°C the optimised curves are all below the default curve indicating a slower development in this temperature range. Additionally, for the bilinear model, the part of the optimised curve above 31°C was mostly found above the default curve, indicating a faster development. This was the case for both genotypes, regardless of twilight. For clarity of presentation, only the results of KSK133 with twilight are shown, but all of the selected parameter sets showed the same pattern.

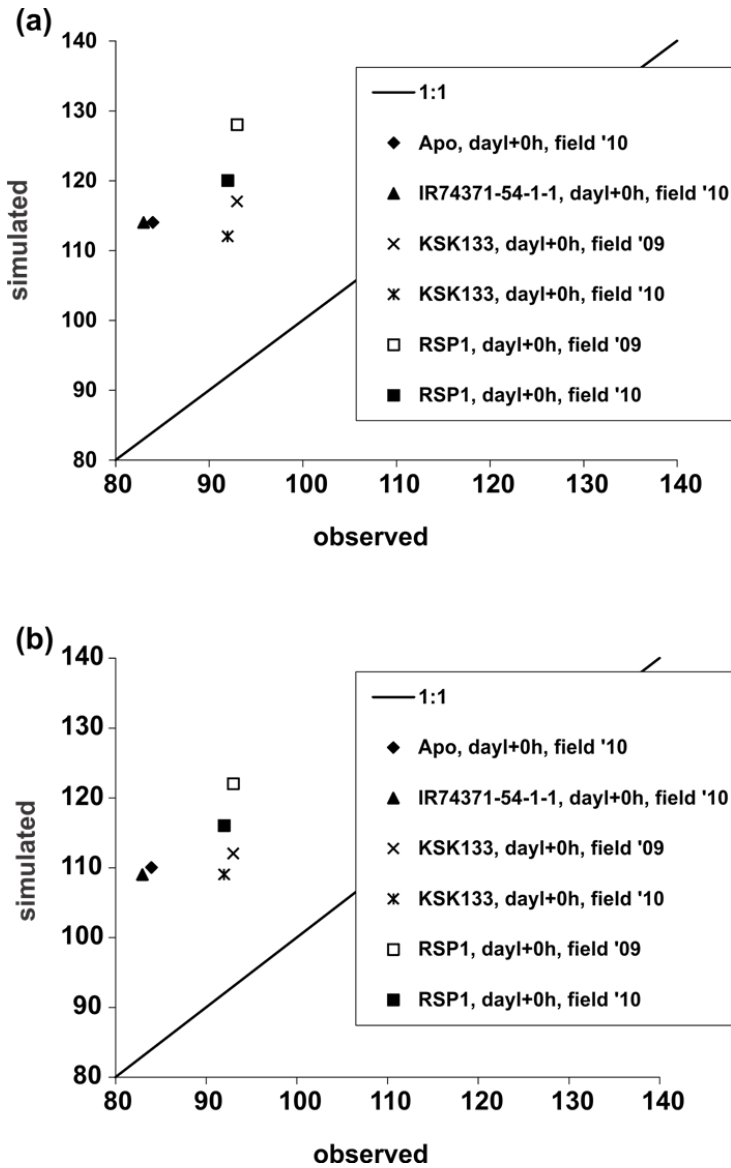


Fig. 4.4a-b. Simulated duration to flowering under field conditions with (a) TBD=8°C, TOD=30°C, TMD=42°C, 0h of twilight and f_o calculated as in equation 13, (b) TBD=8°C, TOD=30°C, TMD=42°C, BETA=1, 0 hours of twilight and f_o calculated as in equation 14.

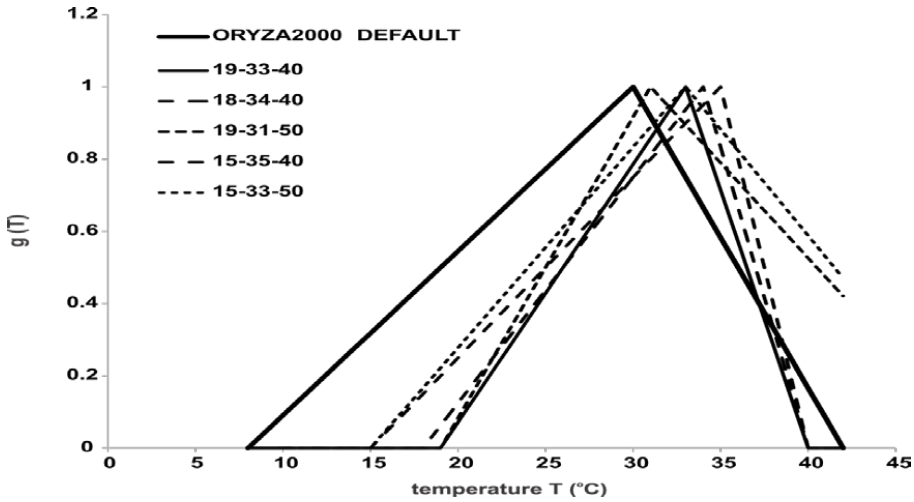


Fig. 4.5. Standard and optimised bilinear temperature response functions for genotype KSK133. Curve names: twilight-TBD-TOD-TMD. The figure shows the 5 best curves obtained with 0.9h twilight and a similar pattern was observed without twilight. About 90% of the daily average temperatures in the field were within the range of 26–35°C.

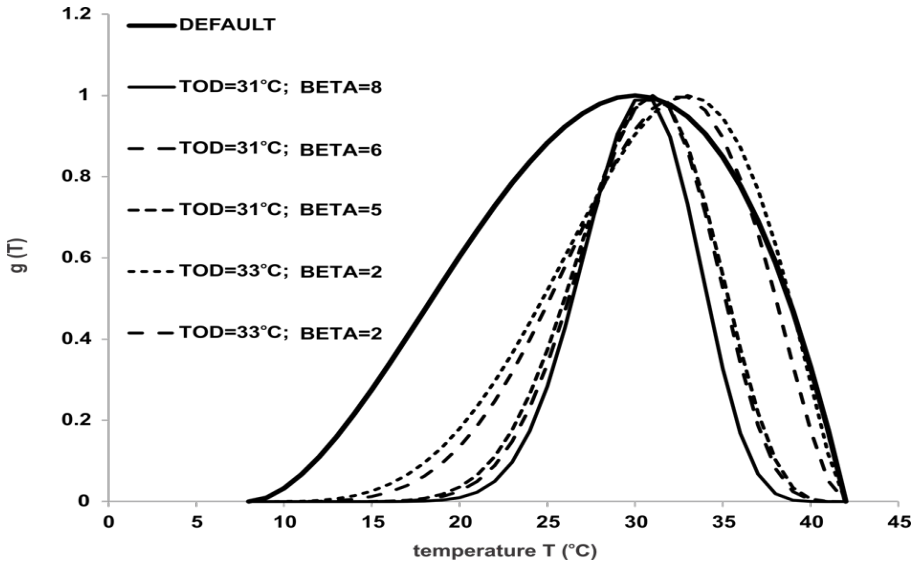


Fig. 4.6. Optimised beta temperature response functions for genotype KSK133. The figure shows the 5 best curves obtained with 0.9h twilight and a similar pattern was observed without twilight. About 90% of the daily average temperatures in the field were within the range of 26–35°C.

Table 4.3. Photoperiod sensitivity parameters and lengths (d) of BVP, PSP, PPP.

Parameter	Apo	IR74371-54-1-1	KSK133	RSP1
BVP	25	31	39	33
PSP _s	22	19	23	13
PSP _L	93	91	78	68
PPP	30	29	32	36
f _{Op}	77	79	94	82
θ ₁	0.33	0.40	0.42	0.40
θ ₂	0.61	0.64	0.66	0.56
δ	0.154 (9)	0.159 (6)	0.139 (-6)	0.161 (18)
β	6.883 (13)	7.465 (9)	5.640 (-2)	7.730 (20)
γ	0.608 (-11)	0.698 (-14)	0.395 (-17)	0.815 (0)
k	-0.291 (-1)	-0.315 (-4)	-0.232 (-12)	-0.331 (10)

BVP=Basic vegetative period; PSP_s=Photoperiod sensitive phase under short day (10h d⁻¹) conditions; PSP_L=Photoperiod sensitive phase under long day (15h d⁻¹) conditions; PPP=Post-photoperiod-sensitive phase; f_{Op}= minimum number of days to flowering at the optimum photoperiod, θ₁ and θ₂ are development stages for the start and the end of the photoperiod-sensitive phase, respectively. Photoperiod parameters δ, β, γ and k for equations show in parentheses is the maximum error and in bold the parameter with which the best fit was obtained. Visualised in Fig. 4.3.

4.4. DISCUSSION

Ultimately, our aim was to improve our ability to predict phenology of modern aerobic rice genotypes under different environmental conditions, particularly in regards to day length and temperature. Methodologically the estimation of phenological parameters still poses many challenges, especially in PP-sensitive genotypes. We found that conceptually and technically, the two step approach worked well. The philosophy behind this two-step approach is straight forward: parameter estimation is much simpler if fewer parameters have to be estimated simultaneously. The two-step approach splits up the parameter estimation problem into two simpler sub-problems: the PP-sensitive parameters are first estimated at constant temperature and subsequently these parameters are used to estimate parameters that describe the temperature response. The implicit assumption is that PP-sensitive parameters (θ_1 , θ_2 , δ , β , γ and k) are not dependent on temperature. Actually, our model does consider the interaction between temperature and photoperiod during the PSP, as shown by the multiplicative form of equation 1. The way we parameterised the model, however, did not accommodate the interaction well. This was for practical reasons, since, as usual, we did not have a factorial combination of temperature and photoperiod in our experiment. Such experiment, allowing a full quantification of temperature and photoperiod interactions would be far too expensive. Therefore, we followed a two-step approach, which was formerly used by Yin et al. (1997a), but since then rarely followed up by other researchers. We suspect that this is due mostly for practical reasons, as facilities to impose a fixed day length are scarce and expensive. Often photothermal parameters are estimated from field observations only, making it very difficult to disentangle temperature and photoperiod effects (e.g. van Oort et al., 2011).

All tested genotypes in this study were strongly PP-sensitive. Plants started to respond to photoperiod after 25 to 39 d at 26°C, depending on genotype. The duration of BVP was well within the range of 20.0 to 45.4 d described by Yin et al. (1997c) for *indica* type genotypes. Rice breeders consider a short BVP to be a key for early flowering (Tsai, 1986). Apo, the genotype with the shortest BVP, was indeed among the genotypes with the shortest duration to flowering at P_0 of 10h d⁻¹. The PSP₁₀ of all four genotypes was well within the range reported by Vergara and Chang (1985), who indicated that the minimum number of photo-inductive cycles required to initiate panicle primordia formation varied from 4 to 24 d. These results are also in agreement with Yin et al. (1997c), who reported a value of 3.6 to 24.1 d. Under long day conditions, the extended duration to flowering was just over 70 d for Apo and IR74371-54-1-1, compared to an extension of just 55 d for the local genotypes KSK133 and RSP1. This shows that the local genotypes are less PP-sensitive. The

transition from BVP to PSP occurs abruptly in rice (Best, 1961). It seems that the response of f to transfer was uniform when moved from LD to SD and non-uniform when moved from SD to LD, which is in line with the findings of Yin et al. (1997c) but the cause of this non-uniform response is not well understood. For KSK133 the extension was relatively small when photoperiod was extended from 10 to 12.5h d⁻¹, whereas the further extension to 15h d⁻¹ caused a considerable delay in flowering. For the other three genotypes the delay was more equally distributed between the initial extension to 12.5h d⁻¹ and the further extension to 15h d⁻¹. Related to this, the $r(P)$ function of KSK133 was best described by the beta function, whereas for the other three genotypes inverse or exponential functions gave the best fit.

For field conditions, we showed that using default cardinal temperatures for rice leads to considerable overestimation of the time to flowering. We further showed that this error could not be attributed to overestimation of the amount of twilight, because even with 0h twilight the bias was large. Under flooded conditions temperature around rice stems and in canopy is cooler than the ambient temperature (Dingkuhn and Miezan, 1995; Lobell et al., 2008). Differences in temperature conditions between phytotron, field under flood water conditions, and meteorological observatory might lead to an error when predicting phenology. In our experiments the crop was grown under non-flooded aerobic conditions and plants in phytotrons were also maintained under well-watered aerobic conditions. In this regard, we had comparable soil water conditions and avoided the possible error that might be caused by the different conditions mentioned above. Instead, sensitivity analysis suggested that the bias was caused mostly by overestimation of the rate of development at temperatures below ~31°C, whereas the bilinear model also suggested an underestimation of the rate of development at temperatures above ~31°C. Our data shows that this conclusion is valid even though there was no clear convergence to a unique optimal set of cardinal temperatures. A similar finding for temperature responses above and below ~31°C was also reported for five lowland varieties grown in Senegal (van Oort et al., 2011). More recently, a comparison of five rice phenology models by Zhang and Tao (2013) also suggested that the optimum temperature for rice development is above 30°C and more likely to be found in the range 30–35°C.

Our data set combined with our two-step analytical approach resulted in a robust set of photoperiod parameters for the four genotypes we investigated. These parameter sets might prove useful in future investigations about the influence of temperature and twilight on phenological processes. Our approach greatly simplifies phenology calibration. Our sensitivity analysis showed that more experiments are needed to accurately estimate the temperature parameters. This can be done by running experiments on a single location with different planting dates. Alternatively, a better

approach might be to grow the same set of genotypes at different locations and planting dates, or grow them across a wide range of temperatures under controlled environmental conditions.

4.5. CONCLUSIONS

Better insight in phenology of aerobic rice genotypes is essential for matching phenology to available resources in the target (aerobic) environments as well as designing optimal cropping calendars. The phenology of aerobic rice is still poorly understood and this study is the first to report on the phenology of four modern aerobic rice genotypes. The two-step approach presented here provides a solid basis for studying pre-flowering phenology of aerobic rice genotypes. All four genotypes studied are used in aerobic rice breeding programmes throughout Asia and were found to be highly PP-sensitive. The significant variation in optimal flowering time and PP-sensitivity could be exploited by breeders to develop genotypes that can avoid adverse environmental conditions such as pre- and post-monsoon drought. The PP-response parameters were estimated with great accuracy (Figs. 4.2 and 4.3). Our work further showed that with use of default cardinal temperatures time to flowering was severely overestimated. The results strongly suggest that below 31°C development rate was overestimated. Unfortunately, accurate estimation of the temperature response parameters was hindered by a too narrow range of temperatures (Figs. 4.5 and 4.6). However, knowing the photoperiod parameters makes estimation of the temperature parameters much easier. To further improve the general validity of obtained parameter sets we suggest experiments that represent a wider range of environmental conditions. This would require field experiments with different planting dates across different sites or controlled environment studies on photoperiod $\times$ temperature interactions.

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CHAPTER 5

Transformation of transplanted flooded rice system to direct seeded aerobic rice system: the farmers' perspective *

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Abstract

The sustainability of conventional flooded rice systems is threatened by diminishing resources—land, water, and labour. Aerobic rice, an alternative to the conventional systems, could considerably increase resource-use efficiencies. Our aim was to understand and analyse farmer perceptions about aerobic rice in regards to future adoption. We conducted our study in the Pakistani Punjab with rice and non-rice farmers (n=215) in three cropping systems viz. rice-wheat, mixed-cropping, cotton-wheat, using a pretested semi-structured questionnaire. Data were analysed using descriptive statistics and chi-square tests to relate farmer and farms' characteristics to the awareness, interest, perceptions, and adoption potential of aerobic rice systems. More than half of respondents had never heard of aerobic rice, though, 76% were open to experimenting. Farmers perceived aerobic rice as a means of increasing resource-use efficiency particularly for labour, net profitability, and an option for crop diversification in the mixed-cropping system. Perceived threats were weeds, diseases, poor germination, spikelet sterility, low yields and frequent irrigation requirement. Overall, 73% farmers who trialled aerobic rice in a participatory research, were positive about planting it again, especially those with large landholdings and clayey-soils. Deciding factors for planting again were: ease of operation due to direct seeding, good income, and low input requirement. Deciding factors against planting again were: unavailability of suitable fine grain *basmati* varieties, falling water table, weeds, and inadequate soil type. The results suggest that aerobic rice is potentially an interesting transformational technology evident from the willingness to plant again by demonstration households but the unavailability of well-adapted *basmati* varieties hampers its expansion. Our research captures farmer perceptions and provides guidelines for further research and policy settings. Farmers' appreciation of risks and benefits can pave the way for large-scale adoption.

Keywords: resource use efficiency, farmer perceptions, transformation technologies, sustainable production system, water saving, Punjab.

* Accepted subject to revision in Land Use Policy

5.1. INTRODUCTION

The sustainability of conventional flooded rice systems is threatened by diminishing resources of water, labour, and energy. Resource conservation technologies (RCTs) are being developed and propagated to increase rice production worldwide (CGIAR, 2010; IRRI, 2010). Aerobic rice i.e. growing rice like an upland crop such as wheat or maize is one of the technologies showing great potential to improve resource use efficiencies, in systems constrained by scarcity of the precious resources. Aerobic rice systems have been developed in temperate environments and efforts are underway to extend these systems to tropical and subtropical regions to enhance local farm incomes and regional/national food security (Maclean et al., 2002; Prasad and Donald, 2011).

Paddy rice is traditionally grown by transplanting 25–35 day old seedlings in well prepared, puddled fields requiring huge quantities of freshwater. The challenge for Pakistan is to ensure food security while water resources are diminishing and population growth remains high at two per cent p.a. (Briscoe and Qamar, 2009). During the summer of fiscal year-2011/12, surface water availability from canal irrigation was 10% less than the long-term average system use of 128 billion m³ (GOP, 2012a). Water tables are falling at a rate of approximately 0.3 m per year (Hussain, 2002) and over the years have declined by more than 7 m due to exploitation of groundwater (Kahlowan et al., 2007). Increasing diesel and electricity prices lead to high costs for pumping groundwater, causing decreased net economic profits. Labour shortage during critical growth periods is another important issue. Manual uprooting and transplanting of nursery is an arduous task, especially at the high temperatures of around 35–40°C. The scarce labour force consists predominantly of unskilled and contractual women and teenagers, resulting in a lack of quality assurance such as uneven plantings and resultant plant densities much lower than agronomically optimal (Chaudhary et al., 2001; Baloch et al., 2005; Baloch et al., 2007; Farooq et al., 2011).

In response to the challenges of water scarcity, labour shortage, huge energy consumptions, and low farm income, RCTs including zero tillage, direct seeding, parachute transplanting, bed planting, laser land levelling and crop residue management were introduced in South Asia by a rice-wheat consortium (PARC-RWC, 2003; Jehangir et al., 2007; Kahlowan et al., 2007; PARC, 2010). Zero tillage and laser land levelling (both for wheat) were the most widely adopted in Pakistani Punjab (Ahmad et al., 2007). More recently, water-saving technologies for rice viz. alternate wetting-drying, direct seeding, mechanized/partial system of rice intensification, and aerobic rice, have been tested and up-scaled in Punjab and Sindh provinces by the Pakistan Agricultural Research Council (PARC) in collaboration with

national and international research organisations (IRRI, 2010; Sharif, 2011). For a discussion of the differences between these technologies we refer to Bouman et al. (2007a). Here we are interested in the performance of aerobic rice system, where instead of transplanting, the crop is direct seeded. Direct seeding reduces the labour requirement for establishment by transferring field activities to periods when labour costs are comparatively lower (Pandey et al., 2002; Pandey and Velasco, 2005). The availability of chemical weed control methods further reduces the labour requirement for weeding later in the season (Farooq et al., 2011). Irrigation is applied in unpuddled fields when soil water drops below critical levels. This generally lowers yields, but also lowers labour and water inputs. The overall result can be a more profitable and environmentally-sustainable rice production system. For these reasons, aerobic rice may be an attractive ‘technology package’ in water limited environments (Bouman et al., 2005; Bouman et al., 2007a).

Major activities by PARC regarding aerobic rice included germplasm testing, demonstration plots and farmers’ participatory research trials. Promising results for water and labour savings were reported in the trials (IRRI, 2010; PARC, 2010). The successful conduct of experimental trials or demonstration plots, however, is not a guarantee that the new technology will be adopted. There are different socio-technological factors that determine adoption or disadoption. With ‘disadoption’ we mean that farmers may try a new technology for one or two cropping seasons and abandon it if it did not deliver what they were hoping for, or caused unexpected negative side effects. Hence, it is important to revisit study areas and draw lessons. Such targeted reflection can (1) help to characterise the group of farmers for which a technology is potentially interesting, (2) support promotion of the technology by drawing on experience by early adopters, and (3) provide guidance for further technology development.

To date, there has been very little research on farmer perceptions, adoption and disadoption of the aerobic rice system in Pakistan. Our aim was to understand and analyse farmer perceptions about the aerobic rice system. In particular, we were interested in elucidating incentives and barriers that might lead to adoption, non-adoption or disadoption of this technology.

5.2. METHODS

5.2.1. Background information, scope, and research questions

In Pakistan, rice is grown under diverse conditions that are categorised into four ecological zones. Zone-I is the northern mountainous areas with sub-humid monsoon

climate and 750–1,000 mm average annual rainfall. Zone-II is the broad strip of land between two rivers (Ravi and Chenab) with sub-humid, sub-tropical climate and 400–700 mm rainfall. Zone-III is the west bank of river Indus with an arid, sub-tropical climate and 100 mm rainfall. Zone-IV is the Indus delta with an arid tropical marine climate (Salim et al., 2003; Bashir et al., 2007).

The Punjab province (Zone-II) was selected for this study because a large amount of the Pakistani rice is produced in this province (67% of rice area, 55% of rice production) and because aerobic rice is considered a potentially viable crop in this area. An international collaborative research programme on water saving technologies in rice was conducted in this province in previous years. This enabled us to interview two types of farmers: those who had grown aerobic rice before and those who did not. We asked questions about their experiences and perceptions and thus established some baseline data to study disadoption. Table 5.1 lists general characteristics of the study area.

Table 5.1. District profile, major crops and general soil types of the study area.

Districts	Main cropping system	Other important crops	General soil types
Hafizabad, Mandibahauddin, Sialkot, Narowal, Sheikhpura, Gujranwala,	Rice-wheat	Sugarcane, Cotton, Tobacco, Maize, Potato, Sunflower	Loam, Clay loam
Jhang, Khushab, Sargodha, TT Singh, Faisalabad, Pakpattan	Mixed-cropping (Rice/cotton/sugarcane /fodder/vegetables-wheat, Maize-potato)	Oilseeds, Pulses, Millets, Sorghum, Fruit crops	Loam, Clay or sandy loam
Layyah, RY Khan, Bahawalpur, Rajanpur, DG Khan, Lodhran	Cotton-wheat	Pulses, Oilseeds, Vegetables, Sugarcane, Tobacco	Sandy loam, Clay loam, Silt loam, Alluvial clay

Source: Agriculture Marketing Information Service, Pakistan.

We addressed these specific research questions.

- 1) Are there any farmer and farm characteristics that might explain differences in awareness, interest, perceptions, experiences, and adoption potential of aerobic rice system?
- 2) What is the current level of awareness and interest in aerobic rice system?

- 3) How do perceptions about aerobic rice vary among different cropping systems viz. rice-wheat, mixed-cropping, cotton-wheat as well as farmer groups consisting of rice and non-rice farmers?
- 4) What are the key drivers for farmers involved in abovementioned PARC projects to decide whether or not to plant aerobic rice again?
- 5) Based on our findings, what are the prospects for aerobic rice system in Pakistan?

5.2.2. Sampling

Respondents (n=215) were categorised according to two criteria (1) their cropping system and (2) their experience with rice and specifically aerobic rice. The second criterion led to a distinction between three groups of respondents: group I (n=70) were key-informant farmers from the rice-wheat system who had tried aerobic rice technology in a participatory research trial implemented by PARC in 2010; group II (n=97) were rice-growing farmers from each cropping system who did not participate in the PARC trials; these farmers had no experience with aerobic rice but they did grow lowland rice. Group III (n=48) were non-rice-growing farmers with experience in mixed-cropping or the cotton-wheat cropping system. Although rice is not a major crop in the cotton-wheat system, some farmers grow it for domestic use or to better their net income. Table 5.2 lists the number of respondents in each category.

Table 5.2. Distribution of respondents according to cropping systems and farmer group.

	Group I ^a	Group II ^b	Group III ^c	Total
Rice-wheat	70	35	0	105
Mixed-cropping	0	35	25	60
Cotton-wheat	0	27	23	50
Total	70	97	48	215

^arice growers who trialled aerobic rice; ^brice growers who did not trial aerobic rice; ^cnon-rice growing farmers.

5.2.3. Data collection and analyses

A semi-structured interview questionnaire with open and closed questions was constructed. The questionnaire was pre-tested and then slightly modified. All

respondents were interviewed in their native language (i.e. Punjabi) by the first author of this chapter (MA). Interviews were conducted individually and face-to-face to minimise bias. First the background of the study was explained. All interviews were conducted with the household heads who are responsible for the managerial decisions on the farm. Table 5.3 lists the survey questions. Survey questions 1 to 10 served to determine farmer or farm characteristics, questions 11 to 17 were about rice cultivation in general. Questions 18 to 25 covered farmers' opinions and experiences with aerobic rice.

We first analysed in general these opinions and experiences. Next we investigated if opinions and experiences were different depending on farm characteristics, cropping system and experiences with aerobic rice. For the farmers in group I who had one year of experience with aerobic rice, their motivations to continue or stop growing aerobic rice (disadoption) were of particular interest. Those who had not yet tried aerobic rice (groups II and III, Table 5.2) indicated their likely future preferences whether or not to grow aerobic rice. From the list of questions in Table 5.3, questions 19, 22, and 23 were only asked to those who already had experience with aerobic rice (Table 5.2 group I). In addition to the set of closed questions we invited farmers to make additional comments on issues they considered being important.

The data were analysed by descriptive statistical tools of frequency distribution and percentages. Chi-square test was used to determine the relation between individual and farm characteristics of respondents in response to a question at five percent level of significance using the statistical software Statistical Product and Service Solutions (SPSS Version 19.0).

5.3. RESULTS

5.3.1. Farmer and farms' characteristics of the study area

Farmer and farms' characteristics are important determinants of technology adoption (Li et al., 2010). The relation of these characteristics with perceptions and experiences about aerobic rice, including levels of adoption (i.e. the willingness to plant or not plant aerobic rice again) are discussed in the subsequent sections. The main reasons why our surveyed farmers grow rice are in Fig. 5.1. The reasons for growing or not growing rice differed among the three cropping systems (Table 5.4). Given that decreasing water availability is a major concern for rice cultivation in general, we asked specific question about sources of irrigation and water scarcity. Most respondents (83%) had access to both surface (canal) and groundwater (tubewell water) for irrigation; yet 96% answered 'yes' when asked about having experienced

Table 5.3. Survey questions.

No.	Question	Remarks
1	What is your age?	closed question, 3 categories
2	How many years of experience do you have in rice farming?	closed question, 6 categories
3	What is your educational level?	closed question, 4 categories
4	How large is your farm?	closed question, 3 categories
5	What type of land tenure do you have?	closed question, 3 categories
6	How did you become owner of the land?	closed question, 3 categories
7	Are you a subsistence farmer or commercial?	closed question, 2 categories
8	What is the main soil type of your farm?	closed question, 4 categories
9	How many crops do you grow per year?	closed question, 3 categories
10	What sources of water do you use?	closed question, 4 categories
11	What are the main constraints to rice cultivation?	open question
12	Why or why not you cultivate rice?	open question
13	What type of variety do you grow?	closed question, 3 categories
14	Is water scarcity a real issue?	yes or no
15	How does water scarcity affect rice cultivation?	open question
16	Would you like to replace rice crop in the face of water shortage?	yes or no
17	If "yes", with which crop?	open question
18	Are you aware of aerobic rice or direct seeding?	awareness means first hearing about anything
19	What attracted you to aerobic rice cultivation or direct seeding?	closed question, 3 categories
20	What are the positive attributes of aerobic rice?	open question
21	What are the negative attributes of aerobic rice?	open question
22	Would you like to plant again?	yes or no
23	Why or why not plant again?	open question
24	Would you like to try aerobic rice if there are suitable rice varieties?	interest stage
25	Regarding the aerobic rice cultivation, what factors can impede its adoption?	closed question, 10 categories

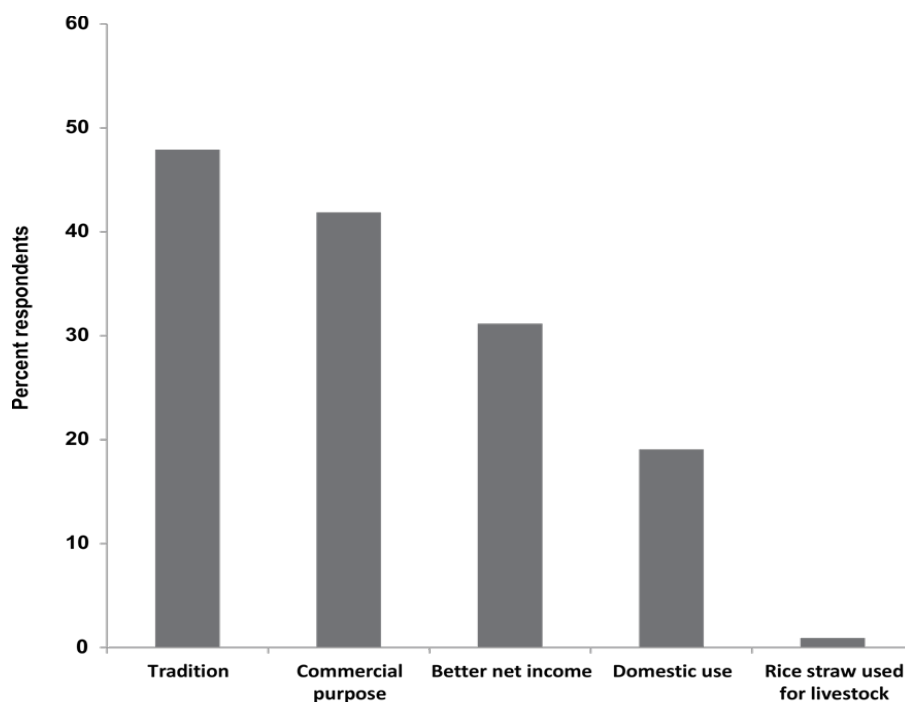


Fig. 5.1. Distribution of respondents (%) according to the reasons for growing rice.

Table 5.4. Distribution of respondents according to the reasons for growing or not growing rice in three cropping systems.

Rationale	No. of farmers		
	Rice-wheat	Mixed-cropping	Cotton-wheat
<i>I am growing rice because of...</i>			
Tradition	102	0	1
Better net income	38	18	11
Domestic use	5	20	16
Commercial purpose	48	27	15
Rice straw	0	0	2
<i>I am not growing rice because of...</i>			
Better net income from other crops	0	16	11
Water shortage	0	15	17
Flooding risk	0	1	0

water scarcity. About 80% experienced the problem during summer season, whereas, 14% experienced it both during summer as well as winter season. The problem is exasperated during pre- and post-monsoon period, i.e. June to September. This

constitutes an economic water scarcity, rather than a physical scarcity. Farmers responded differently to different types of water scarcity (Fig. 5.2).

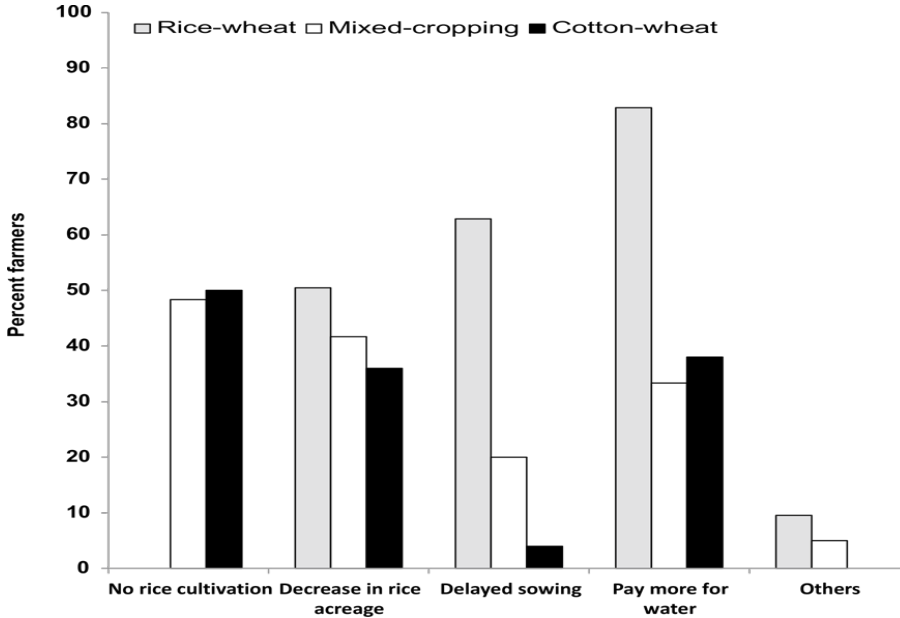


Fig. 5.2. Farmers' response to water scarcity in relation to rice cultivation in three cropping systems.

5.3.2. Awareness and interest of farmers in aerobic rice system

Before asking farmers about experiences and perceptions we asked farmers in groups II and III whether they were aware of aerobic rice and whether they considered the technology as potentially interesting. Of course the farmers in group I, who had been involved in a project on aerobic rice, were already aware of it. The awareness was highest in the mixed-cropping system (n=22, 37%), followed by the rice-wheat system (n=11, 31%, excl. the group I farmers), and the cotton-wheat system (n=12, 24%). Of the existing rice growers with no experience in aerobic rice (group II), 35% had heard of aerobic rice or direct seeding which they often refer to as 'broadcast method'. Awareness was lower (i.e. 29%) in the group of non-rice growers (group III). Awareness was correlated with the size of landholding ($p \leq 0.001$): large farmers (≥ 10 ha) were more aware of the technology (71%). We found no significant correlations between awareness and age, education level, or land tenure. To farmers, unaware of aerobic rice, we first described basic characteristics of how this crop is grown. Next

we asked all respondents if they would be interested in trialling aerobic rice with suitable varieties (drought tolerant, fine grain premium quality *basmati* type). Most responded positively (76%). Interest in aerobic rice technology differed ($p \leq 0.01$) between the three cropping systems. Interest in aerobic rice was higher for those who had already tried it (group I, 89%) than for those who had not (group II and III, 72% and 67%).

5.3.3. Farmer perceptions about aerobic rice

The ranking of perceptions about positive and negative attributes of aerobic rice (Tables 5.5 and 5.6) is fairly similar among farmers. The most often mentioned positive attribute is reduced labour requirement (see Table 5.5 for the rationales), followed by water saving because of the fact that aerobic rice is grown under unsaturated, unpuddled conditions and labour requirement was reduced due to direct seeding instead of transplanting and the availability of chemical herbicides that gave effective weed control. Farmers who have trialled aerobic rice (group I) were more positive about it than farmers who had not trialled aerobic rice (groups II and III). Since all of the farmers in group I were located in the rice-wheat cropping system, we also found that farmers were more positive about aerobic rice, in that cropping system. The group I ($n=70$) considered reduced labour requirement, water saving, and evenly high plant densities as the top positive attributes of aerobic rice. Evenly high plant densities are the result of direct seeding at higher and more regular sowing densities than in traditional systems that rely on transplanting. Further, direct-seeded plants do not suffer from transplanting shocks. About 47% of the farmers in group II ($n=97$) had no opinion about positive or negative attributes of aerobic rice. The remaining 51% considered reduced labour requirement, time saving, and water saving as the top positive attributes of aerobic rice. About 50% farmers in group III ($n=48$) had no opinion about positive or negative attributes of aerobic rice. The remaining 50% considered reduced labour requirement, time saving, profitability, and water saving as the top positive attributes of aerobic rice. Perceived negative attributes are listed in Table 5.6. The group I ($n=70$) considered weed infestation, disease attack, and poor germination as the top negative attributes of aerobic rice. The group II ($n=97$) and group III considered weed infestation and low yields as the top negative attributes of aerobic rice.

We asked farmers who had already experimented with aerobic rice for one season (group I) whether they were planning to grow aerobic rice again. On average, 73% farmers in group I answered positively but results were markedly different between

Table 5.5. Farmer perceptions about positive attributes of aerobic rice in the two categories of cropping system and farmer group.

	% in different cropping systems			% in groups with different experience w. rice and aerobic rice			% all farmers
	R-W ^a	M ^a	C-W ^a	I ^b	II ^b	III ^b	
Reduced labour requirement (Direct seeding saves labour required for sowing, uprooting, and transplanting of nursery and puddling operations) ^c	70	33	48	86	39	42	55
Water saving (No puddling and no flooding during the season are required)	58	20	10	76	20	13	36
Optimum plant population (More number of plants per unit area due to drill sowing or broadcast; labour tends to leave patches in the field while transplanting)	24	2	6	30	7	2	13
Time saving (No puddling is required so crop can be sown directly after harvesting of the previous crop and no need to wait for the monsoon rains to start)	23	17	26	26	22	17	22
Economical/profitability (More net income due to savings in labour, water, and energy)	20	18	6	27	8	17	16
Resistance to lodging (Plants are stronger)	16	2	0	24	0	2	8
Early harvesting (No standing water in the field and time saving from no puddling)	12	3	8	19	4	4	9
Reduced maintenance cost of machinery (Puddling requires heavy machinery operation)	12	3	0	13	4	4	7
Environment friendly (Farmers indicated that their faces turned black during rice season most probably due to methane gas emission)	8	0	0	11	0	0	4
Less fertiliser requirement (Needs less fertiliser)	7	0	0	10	0	0	3
Resolve edaphic conflicts (Beneficial for subsequent crop as the puddled soil is much harder and puddling destroys soil structure)	4	3	2	3	3	4	3
Less disease attack	1	0	0	1	0	0	0
Good Quality (Due to less disease attack)	1	0	0	1	0	0	0
Crop diversification (Aerobic rice might be another option in the mixed-crops system)	0	17	0	0	4	13	5
Don't know	17	48	46	0	47	50	33

^a R-W =rice-wheat system, M =mixed-cropping system, C-W =cotton-wheat system.

^b I=rice farmers who trialled aerobic rice, II=rice farmers who did not trial aerobic rice, III=non-rice farmers.

^c In parentheses are the rationales.

Table 5.6. Farmer perceptions about negative attributes of aerobic rice in the two categories of cropping system and farmer group.

	% in different cropping systems			% in groups with different experience w. rice and aerobic rice			% all farmers
	R-W ^a	M ^a	C-W ^a	I ^b	II ^b	III ^b	
Weed infestation (More weed infestation due to aerobic conditions) ^c	57	35	38	70	35	35	47
Disease attack (Non-flooding conditions result in more attack of diseases such as blast)	34	13	10	47	9	15	23
Poor germination (In transplanted rice healthy seedlings are transplanted)	20	2	12	29	3	10	13
Spikelet sterility (empty grains due to heat stress)	19	5	10	27	3	13	13
Need more water due to more irrigation frequency (Number of irrigations increases due to non-flooded conditions)	16	15	12	20	8	21	15
Low yield (Rice farmers have a general belief that more water input, more yield and vice versa)	15	28	22	11	26	23	20
Need more seed rate due to direct seeding	9	5	4	6	8	4	7
Low tillering (Less growth under less favourable conditions)	7	0	0	10	0	0	3
Don't know	17	48	48	0	48	50	33

^a R-W =rice-wheat system, M =mixed-crops system, C-W =cotton-wheat system.

^b I=rice farmers who trialled aerobic rice, II=rice farmers who did not trial aerobic rice, III=non-rice farmers.

^c In parentheses are the rationales.

farmers in the two districts: 86% would plant it again in the Hafizabad district and only 52% (which is still large) in the Mandibahauddin district. This might be explained by difference in soil type ($P=0.006$) and the size of landholdings ($P=0.009$). In Hafizabad, the main soil type is clay loam compared to loam in Mandibahauddin. Clayey soils have higher water retention and may therefore be better suited for growing rice under limited water supply and water supply that is at times expensive or beyond control of the farmers. Farms are generally larger in Hafizabad (72% large farmers with average area under rice cultivation ~25 ha) than in Mandibahauddin (52% large farmers with average area under rice cultivation ~18 ha). It is possible that

the farm size could indirectly influence the willingness to adopt aerobic rice technology given that there is often a correlation between farm size and access to resources such as credit, which in turn influences risk preferences (Feder et al., 1985). Above we discussed perceptions of all farmers. Next we looked closer into experiences of farmers who had tried aerobic rice. We asked about positive experiences (Table 5.7) and negative (Table 5.8) and how these experiences correlate with the decision to plant or not to plant aerobic rice again. Surprisingly the “adopters” in comparison with the “disadopters” were also more negative about various attributes of aerobic rice, in particular the weed problem. The disadopters considered weed infestation, diseases, increased spikelet sterility and the higher irrigation frequency associated with aerobic rice as the top negative attributes. As a double check to the question about experiences, we asked farmers why they would or would not plant aerobic rice again. The reasons for decision to plant again were ease of operation due to direct seeding instead of laborious puddling and transplanting activities (n=45, 88%), good income (n=31, 61%), low input requirement especially for labour (n=30, 59%), and improved physical condition of the soil (n=10, 20%). The reasons for the decision not to plant again were unavailability of suitable varieties (n=11, 58%), falling water table (n=9, 47%), weed problems (n=8, 42%), and inadequate soil type (n=8, 42). Although not explicitly asked for, the farmers clearly indicated that with ‘availability of suitable varieties’ they mean that there are currently no suitable aerobic rice cultivars that produce premium quality *basmati* type rice.

Table 5.7. Relation between decision to plant again and positive attributes of aerobic rice in farmer group I.

	Plant again?	
	Yes (n=51)	No (n=19)
	Frequency	
Reduced labour requirement	44 (86%)	16 (84%)
Water saving	41 (80%)	12 (63%)
Optimum plant population	17 (33%)	4 (21%)
Resistance to lodging*	16 (31%)	1 (5%)
Economical	14 (27%)	5 (26%)
Time saving	13 (25%)	5 (26%)
Early harvesting	8 (16%)	5 (26%)
Environment friendly	7 (14%)	1 (5%)
Reduced maintenance cost of machinery	7 (14%)	2 (11%)
Less fertilizer requirement	5 (10%)	2 (11%)
Resolve edaphic conflicts	1 (2%)	1 (5%)
Less disease attack	1 (2%)	0
Good Quality	1 (2%)	0

*Significant at $p \leq 0.05$.

Table 5.8. Relation between decision to plant again and negative attributes of aerobic rice in farmer group I.

	Plant again?	
	Yes (n=51)	No (n=19)
	Frequency	
Weed infestation	38 (75%)	11 (58%)
Disease attack	22 (43%)	11 (58%)
Poor germination	15 (29%)	5 (26%)
Spikelet sterility (empty grains)	11 (22%)	8 (42%)
Need more water due to more irrigation frequency*	6 (12%)	8 (42%)
Low tillering	3 (6%)	4 (21%)
Need more seed rate due to direct seeding	2 (4%)	2 (11%)
Low yield***	1 (2%)	7 (37%)

*Significant at $p \leq 0.05$; ***significant at $p \leq 0.001$.

This constitutes one of the major constraints for the expansion of aerobic rice systems in the region. Several of the reported positive and negative experiences may seem contradictory. Farmers who have experience with aerobic rice were positive about reduced labour requirement but were negative about increased weed infestation, as one would expect higher labour requirement for weeding. Farmers were positive about water saving but complain about the higher irrigation frequency. They were positive about achieved plant populations but complain about poor germination. These results were discussed with them. They reported that aerobic rice required less labour due to unpuddled conditions coupled with direct seeding and that the expected increase in labour demand for weed control did not occur because herbicides provided effective weed control.

Table 5.9. Farmer perceptions about factors that are likely to impede adoption of aerobic rice across all cropping systems and farmer groups.

Factors	Yes%
Lack of technical knowledge	83
Lack of awareness	64
Unprofitability/Uneconomical	51
Unavailability of appropriate varieties	43
Unavailability of sound production technology	40
Small landholding	32
Poor financial position	25
Lack of interest	20
Tenancy status	2

All respondents were asked to comment on the possible factors that might impede the adoption of aerobic rice (Table 5.9). Group I (n=70) considered unavailability of appropriate varieties (100%), lack of technical knowledge (90%), and unavailability of sound production technology (71%) as the main impeding factors. The group II (n=97) considered lack of awareness (96%), lack of technical knowledge (79%), and unprofitability (64%) as the main impeding factors. The group III (n=48) considered lack of awareness (94%), lack of technical knowledge (81%), and unprofitability (77%) as the main impeding factors.

5.4. DISCUSSION

The traditional system of transplanting rice seedlings in the puddled field and keeping the field flooded during most part of the season was developed during times of abundant land, water and labour. The system is showing its limitations, particularly for resource-poor farmers. The main problems are low conversion efficiencies for scarce inputs and low income-generating ability (Sharif, 2011). Farmers have to supplement insufficient canal water with groundwater. It is clear from our surveys that there is a growing group of rice farmers for which canal water supply is becoming scarce while groundwater pumping is costly i.e. about 30 times or more than the canal water that costs approximately US\$3.9 ha⁻¹ season⁻¹ (Latif, 2007; Erenstein, 2009). The increasing dependence on groundwater suggests that the energy pricing becomes an influential driver for water management (Shah et al., 2009). For those farmers, aerobic rice can be an interesting alternative to the conventional system of growing flooded rice in puddled fields. The aerobic rice is suitable for irrigated lowland areas facing either physical or economic water scarcity (Bouman et al., 2007a). Our surveyed farmers perceive aerobic rice as a means of increasing use efficiency of scarce resources, particularly labour and water. Reduced labour requirement is reported as the top positive attribute which is consistent with the Chinese farmers' experience (Templeton and Bayot, 2011). Labour shortage, during peak season, results in delayed transplantation leading to severe yield losses. Delayed transplantation often results in an increased incidence of pest attack. Transplanting of rice nursery needs to be completed within a short period of time before the fields dry out or the nursery is too old (Pandey and Velasco, 1999; Pandey et al., 2002; Pandey and Velasco, 2005). Farmers consider water saving as the second most important attribute of aerobic rice. According to our discussions with farmers, water savings are largely perceived as saving water in seedbed preparation (no puddling) prior to sowing and reduced quantities of water per irrigation event due to non-flooded conditions during the growth season. Puddling i.e. creating a shallow hardpan to minimise percolation, needs

about 100 to 200 mm water and a further 100 mm might be required to complete land preparation before transplanting (Ahmad et al., 2007).

The amount of water saved in this way can be used to irrigate other crops/area as suggested by Bouman et al. (2005), and even farmers might consider selling their tubewell water to the neighbouring farmers and generate additional farm income. Puddling requires heavy machinery operations and increased maintenance costs. Some farmers mentioned reduced maintenance costs of machinery, resolving edaphic conflicts between rice and its succeeding crop, and time saving as the other valuable positive attributes. Our surveys clearly show that farmers consider aerobic rice as a potentially interesting option. As with any new technology it needs to be 'fit for purpose', i.e. it needs to seamlessly integrate into the existing cropping systems but also the social, economic and cultural setting.

Farmers are also aware of the associated management problems in aerobic rice systems such as weed infestation, diseases, and spikelet sterility. Changing the establishment system from transplanting to direct seeding, and soil hydrological conditions from flooding to alternate wetting-drying or aerobic conditions will bring more severe weed problems (Zhao et al., 2006). Instead of having increased labour input for weeding, farmers use herbicides for weed control. Thus aerobic rice system may lead to a higher dependency on herbicides, which raises concerns about potentially decreasing efficacy of herbicides in relation to weed infestation dynamics and changes in weed flora over time. Spikelet sterility or empty grains is another challenge as the crop might experience more heat or drought stress due to non-flooding conditions. Flooded water layer can have a cooling effect on canopy temperature (Dingkuhn and Miezán, 1995; Lobell et al., 2008). To keep the fields moist but not flooded (i.e. as in aerobic rice) requires more frequent irrigations (with less water per irrigation event). Many consider this higher irrigation frequency as a disadvantage. Direct seeding does allow for higher sowing densities than achieved with arduous transplanting at high temperatures. But this advantage may be off-set by the fact that according to our surveyed farmers not all of the directly sown seeds emerge well. Farmers think manual broadcasting of seeds is more effective than drill sowing. This might be due the fact that often a wheat drill is used for sowing rice that might not be appropriately calibrated for rice seeds because of differences in shape, size, and weight.

While many farmers who experimented with aerobic rice are on the whole positive about aerobic rice, it is clear that there are both positive and negative attributes. Insight in both can help reducing the reported negative attributes and enhancing the positive. Farmers consider ease of operation, labour requirement, water availability, net profitability, availability of *basmati* varieties, and severity of weed problems as the

major factors for decision making criteria. Our interviews revealed that many farmers would be interested in growing aerobic rice but only if suitable *basmati* type aerobic rice varieties are available, which is currently not the case. Farmers with larger landholdings and farmers on clay soils are more likely to adopt aerobic rice; the latter is probably related with larger soil water retention on clay soils. Whether lower costs outweigh the lower returns due to lower yields will differ between farmers and will be an important factor in the decision to grow aerobic rice.

Results are encouraging in terms of farmers' positive response to trying aerobic rice and the decision to plant again by demonstration households. There is a potential for crop intensification in areas like the Pakpattan district where already two rice crops (coarse grain followed by fine grain *basmati*) are grown each year. Based on our findings, we expect that the Sindh province and the non-traditional rice belt of Punjab can be important target domains for aerobic rice because most of these farmers grow *non-basmati* coarse grain varieties and because water is relatively scarce to maintain puddling conditions (Mann et al., 2007). More than 0.9 Mha area is currently planted to rice (replacing non-rice crops) in the non-traditional rice belt of Punjab, mainly with *non-basmati* type varieties (IRRI, 2010; PARC, 2010). Sindh province is important target domain because rice area in the province is predominantly covered by coarse grain varieties. The two provinces (Punjab and Sindh) together account for more than 90% rice area and production. Farmers in the typical rice-belt of Punjab take pride in growing *basmati* rice that is world-famous for its peculiar aroma and taste. The coarse grain varieties are mostly consumed by low income people and bring lower returns than *basmati* varieties. Farmers who are already growing rice are more interested in aerobic rice than those who are not growing rice. The need to improve resource use efficiencies necessitates the interventions that make aerobic rice an acceptable technology.

5.5. CONCLUSIONS

We have used the results from our interviews to develop recommendations for further policy settings and research on aerobic rice. Based on the survey outcomes we recommend 1) more research into best crop management practices such as water and fertiliser requirements and timing, nutrient dynamics, and changes in weed flora, 2) ensuring the availability of good quality herbicides and appropriate mechanisation of weeding and sowing, 3) development of early maturing *basmati* type varieties that are adapted to aerobic conditions, 4) moving from qualitative methods of identifying the target domains for aerobic rice to quantitative methods for doing so, 5) studying

suitable crop rotations and potential crop intensification areas, 6) testing and developing labour saving technologies e.g. mechanical and chemical weed control.

Pakistan, being amongst the top five rice exporting countries, plays a crucial role in global rice market and food security. Various stakeholders involved in technology development and dissemination can benefit from our recommendations. The final adoption will depend on the agro-climatic conditions and socioeconomic features of the environment in which farmers operate (including access to a well-functioning extension service) as the technology continues to evolve and results are yet inconclusive. Nonetheless, we have identified the prospects for aerobic rice in three major cropping systems among different farmer groups.

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CHAPTER 6

General Discussion

Demand for agricultural production is estimated to increase by 60% to feed over nine billion people by 2050 (FAO, 2012). Diminishing natural resources necessitate eco-efficient approaches for future management of agricultural systems. According to Keating et al. (2010) general resource use efficiency must increase by 50 to 100% in the next four decades to safeguard sustainable food production against resource constraints of land, water, nutrients, and energy. The current production system of transplanted-flooded rice is characterised by low conversion efficiencies for scarce inputs and by a low income generating ability for resource poor farmers (Sharif, 2011; Balasubramanian et al., 2013). Different projections and trends suggest that decrease in water availability is likely (Barker et al., 1998; GOP, 2007; Molden et al., 2007). The research work detailed in this thesis started with the observation that current production practices must transition towards water-saving rice cultivation. The aerobic rice system is one of the options to improve resource use efficiency, in particular for the most precious natural resource: water.

The emerging aerobic rice system is gaining in popularity across South Asia. However, much is still unknown at all levels of integration. Hence, this study explicitly addresses previously identified knowledge gaps and aims at: a) field level: improved understanding of aerobic rice crop performance under semi-arid, subtropical conditions of Punjab, Pakistan, b) plant level: quantification of pre-flowering photothermal responses, and c) socio-economic level: understanding farmers' perspective about the non-conventional system. In this chapter, I synthesised key findings of the field and phytotron experiments and discuss their implications for food security, productivity, eco-efficient resource management, and breeding. Farmer surveys complemented the biophysical research by identifying entry points for the developing aerobic rice technology. This chapter concludes with future research directions and main conclusions based on this study.

6.1. Crop performance under aerobic conditions

6.1.1. Improvement of water productivity

Decreasing availability of irrigation water is a major concern for agriculture worldwide (Rijsberman, 2006). The situation in Pakistan, where the Indus River is a major source of water supply, is no exception (Table 6.1). With a relatively high

population growth rate of 2% p.a. the future per capita water availability will continue to decline. This means that water productivity (amount of product per unit of water input) must be increased. In this study, field experiments contributed important quantitative information on aerobic rice performance in response to varying levels of water and N inputs. Under aerobic system, I found water productivity (WP_g ; g grain kg^{-1} total water input through rainfall and irrigation) values of up to 0.38, which is more than double the national average of 0.16 for the conventional flooded system. The WP_g consistently increased with increasing the water input in all local (KSK133, RSP1, IR6) and exotic genotypes (Apo, IR74371-54-1-1). Local genotype KSK133 achieved the highest WP_g in the high irrigation treatment, whereas exotic genotypes performed better than the local genotypes under water stress conditions of the moderate and low irrigation treatments. Compared to the gross water requirements of 1600 mm, the total water use (~1300 mm in the high irrigation treatment) resulted in a 20% water savings (*chapter 2*). Relatively harsh growing conditions in field experiments with a deep groundwater table and highly permeable soil indicate that further improvement in WP_g and water savings is possible.

Table 6.1. Percent decrease in actual surface water availability (2001-02 to 2011-12).

Period	Decrease (%)
2001-02	29.4
2002-03	15.2
2003-04	5.9
2004-05	20.6
2005-06	2.5
2006-07	8.9
2007-08	4.6
2008-09	11.3
2009-10	10.8
2010-11	15.0
2011-12	13.4

*Percent decrease compares to the average system usage of 128 billion cubic metres (BCM).

Source: Indus River System Authority (IRSA), Government of Pakistan.

6.1.2. Crop growth and grain yield

Crop growth and grain yield (GY) consistently increased with the increasing level of water input (*chapter 2*), indicating that still higher GYs are possible. Among the tested genotypes, KSK133 consistently performed better than the other local genotypes

in both growing seasons (2009 and 2010). High yielding genotypes are characterised by a high total aboveground dry biomass (TDM) and ability to maintain harvest index (HI) (Ying et al., 1998). Based on the performance, if we take KSK133 as a benchmark genotype, KSK133 accumulated the highest TDM in the high irrigation accompanied by the highest values of total aboveground N uptake (TNU) and GY (Fig. 6.1). In the high irrigation treatment, compared to the two exotic genotypes grown in 2010 season, KSK133 had higher TDM and comparable GY but a lower HI and longer growth duration. Under the moderate and low irrigation treatment, the exotic genotypes exhibited a relative advantage; TDM was comparable with KSK133 but GY was comparatively higher in the exotic genotypes under these conditions (Fig. 6.2). Differences in GY among three irrigation treatments were mainly due to a lower panicle number and reduced HI under moderate and low irrigation treatment. Depending on the growing season, significant two- or three-way interactions were found between irrigation, N, and genotype for TDM, GY, HI, and TNU (*chapter 3; Table 3*).

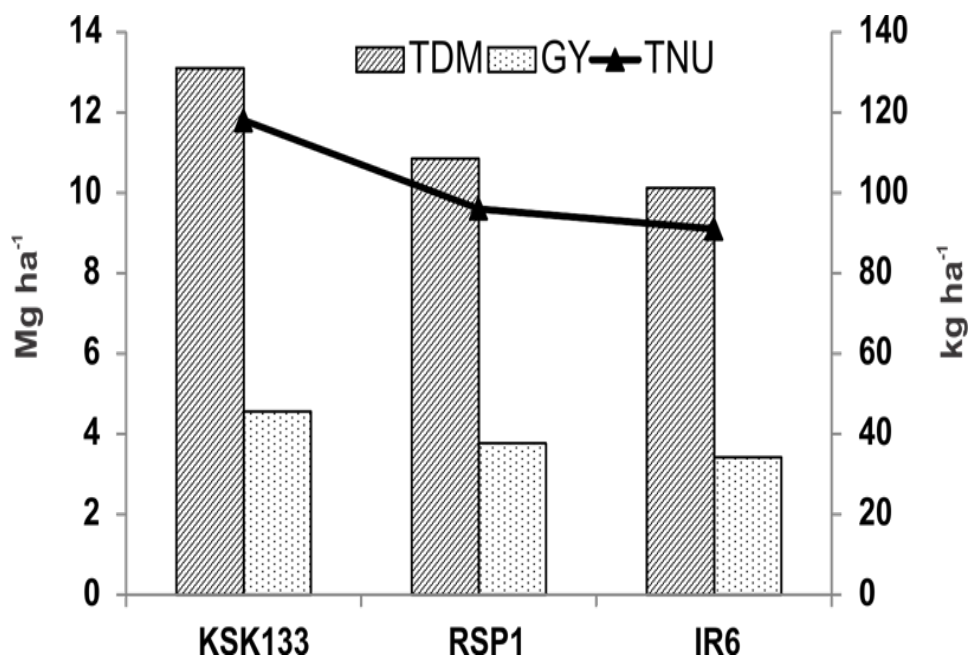


Fig. 6.1. Total aboveground dry biomass (TDM; Mg ha^{-1}), grain yield (GY; Mg ha^{-1}) and total aboveground N uptake (TNU; kg ha^{-1}) of three local genotypes at the highest level of irrigation across two growing seasons.

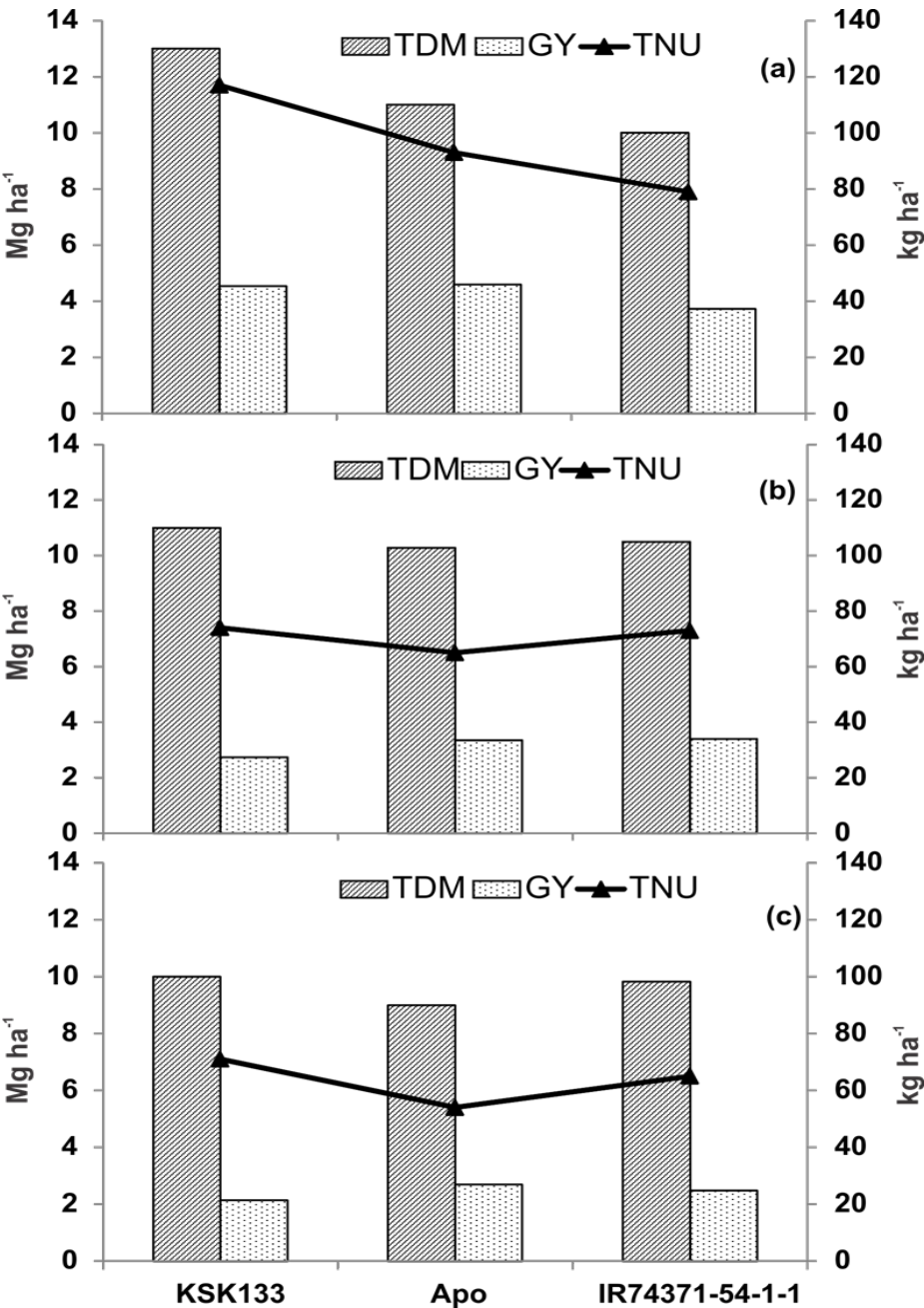


Fig. 6.2. Total aboveground dry biomass (TDM; Mg ha⁻¹), grain yield (GY; Mg ha⁻¹) and total aboveground N uptake (TNU; kg ha⁻¹) of KSK133 and two exotic genotypes in the high (a), moderate (b), and low (c) irrigation treatments in 2010.

The interactions between different interacting factors of genotype, management, and environment varied depending on the site specific conditions and farmer management skills. The GY is determined by the interaction of genotypic and environmental factors which can be modified by management e.g. choice of genotype, and soil/crop management (Jing, 2007). Absence of water $\times$ N interaction in previous studies was reported under shallow water table and fine-texture soil conditions (Belder et al., 2004; Cabangon, 2004). In this study, however, N interacted with genotype and the level of water input. Genotype KSK133 recorded the highest TDM at high irrigation combined with high N. Highest GY and HI occurred in KSK133 at high irrigation combined with high N. General trend was that the crop performance was mainly affected by the level of water input and differed between three genotypes. Surprisingly, responses to the applied N were unclear and inconsistent, indicated by the non-significant values of TNU in response to the main N factor. However, GY had a strong positive correlation with the TNU. The full N balance cannot be calculated due to insufficient experimental data. Small differences between the three N application rates, though, suggest that a significant amount of the applied N was not taken up by the crop. The N taken up by crop might be supplied by the indigenous soil N, decomposition of organic matter, or irrigation water. The unaccounted N is presumably lost to the atmosphere.

6.2. Zooming in on crop development

The success of a crop in capturing available resources depends on the timing of different events in plant growth and development. Phenology of the rice crop is important because it is one of the factors determining the crop water requirement: generally a shorter duration crop requires less water. Additionally, crops may differ in the degree to which development is delayed when exposed to water limitations. Quantitative understanding of the phenology of a rice crop is therefore essential when exploring the yielding ability of rice in environments with sub-optimal resource supply (Wopereis et al., 1996; Fukai, 1999; Fischer et al., 2003). Photoperiod (PP) and temperature are the two principal factors controlling pre-flowering development of plants. The PP-sensitivity varies among rice genotypes and may act as a safety mechanism under sub-optimal environmental conditions. For example, insufficient rainfall often delays sowing and transplanting in rainfed systems. A PP-sensitive genotype may still mature at its usual time even when planted late, thus shortening the growth period. Better understanding the interactions between phenology and growth allows for improved planning of harvest operations as synchronised maturation of the crop simplifies harvesting/drying operations and reduces damage by insects and rats. The growth duration of PP-sensitive genotypes is generally long enough to accumulate

sufficient carbohydrates and to recover from short spells of water limitations (Oka, 1958; Pushpavesa and Jackson, 1979).

Water stress during the vegetative stage delays flowering and hence maturity. Stress during the reproductive phase usually has a negative effect on yield components (Wopereis, 1993). This phenomenon was clearly observable in the field experiments, by the differential response to the irrigation treatments in a low (i.e. 2009) and a high (i.e. 2010) rainfall season. In 2009, flowering time was extended in the moderate and low irrigation treatment, showing that water stress delayed flowering. In the 2010 season, in contrast, there was no difference in flowering time between the three irrigation treatments for a given genotype. Using the high irrigation treatment as a benchmark, the results show that the duration from emergence to flowering (and hence total growth duration) was extended by 5 to 11 days (d) under water stress conditions of moderate and low irrigation. Genotype RSP1 was most sensitive to these water stress conditions. KSK133 and IR6 had longer duration compared to RSP1, Apo, and IR74371-54-1-1. Compared to the values reported by Akhter et al. (2007) and Bashir et al. (2007) for KSK133 and IR6 under the conventional flooded system, the duration to flowering extended under aerobic rice system even in the high irrigation. Extended duration of flowering under the aerobic rice system demands short duration adaptable aerobic genotypes for efficient utilisation of resources.

Observations on phenology from field experiments helped to understand and characterise the duration of pre-flowering rice phenology. Phenology calibration from field observations is especially difficult in case of PP-sensitive genotypes (van Oort et al., 2011), since under field conditions it is very difficult to disentangle photoperiod and temperature effects. A dedicated phytotron experiment gave a robust set of parameters for characterisation of the genotype specific PP-response (step 1). Next the phenological observations from field experiments were combined with data from phytotron experiment to study the temperature response using an improved rice phenology calibration program (step 2).

Experimental set-up was such that two local i.e. KSK133 and RSP1 and two exotic genotypes i.e. Apo and IR74371-54-1-1 were subjected to short (10h d^{-1}), intermediate (12.5h d^{-1}), and long (15h d^{-1}) daylengths in three separate climate chambers. Reciprocal transfers of plants between short and long day chambers started at 5 days after emergence (DAE) and terminated at 50 DAE as discussed in more detail in *chapter 4* (sections 4.2.2.2-3). Observations on non-transfer control plants showed that all four genotypes were sensitive to photoperiod. For each genotype the number of days from emergence to flowering (f) increased with an increase in day length from 10 to 12.5 or 15h d^{-1} . For KSK133 the extension was relatively small when photoperiod was extended from 10 to 12.5h d^{-1} , whereas the further extension to 15h d^{-1} caused a

considerable delay in flowering. For the other three genotypes the delay was more equally distributed between the initial extension to 12.5h d^{-1} and the further extension to 15h d^{-1} . Related to this, the PP-response $r(P)$ of KSK133 was best described by a beta function, whereas for the other three genotypes inverse or exponential functions gave the best fit.

Observations on reciprocal transfer plants showed that the plants started to respond to photoperiod after 25 to 39 d, depending on genotype. Flowering followed a pattern in which f was constant until a certain transfer date, after which a linear increase (transfer from 15 to 10h d^{-1} chamber) or a linear decrease (transfer from 10 to 15h d^{-1} chamber) occurred. Statistical analysis of these patterns resulted in estimates of the length (d) of three successive pre-flowering phases i.e. a basic vegetative phase; BVP, a PP-sensitive phase; PSP, and a post-PSP; PPP. The PP-response parameters (f_{op} , θ_1 and θ_2) were derived from the length of these three pre-flowering phases.

In the next step, I determined the temperature response. First, temperature sum was determined from the temperature in the climate chambers using standard cardinal temperatures i.e. base 8, optimum 30, maximum 42°C . With these parameters the duration of f in the field was considerably overestimated for all four tested genotypes for both a bilinear and a beta temperature response model. This was in the order of 20–35 d for the bilinear and 17–29 d for the beta model with 0h twilight and increased when 0.9h of twilight was added to field day lengths. Separate calibrations with 0 and 0.9h twilight showed that the error in estimation of f was not due to the overestimation of the amount of twilight. Subsequent optimisation of cardinal temperatures for genotypes KSK133 and RSP1 identified parameter sets that could reduce errors to 2 d or less in the climate chambers (3 daylengths, constant temperature) and the field experiments. Sensitivity analysis showed that there was no clear convergence to a unique optimal parameter set. A wide range of parameter sets resulted in similarly accurate predictions, indicating that a broader environmental temperature range must be sampled to improve parameter estimation and hence predictions. Despite this apparent lack of parameter convergence, all near-optimal parameter sets had one thing in common: they all simulated slower development below around 31°C for KSK133 and RSP1.

6.3. Implications

6.3.1. Food security and sustainable rice production

An emerging threat to food security in South Asia, the decrease in or lack of water available for agriculture, highlights the need for improved WP (Chauhan et al., 2012). Pakistan is one of the few rice exporting countries, thus contributing to global food

security. Crop WP is a critical benchmark for food production and resource use efficiency (Bessembinder et al., 2005; Passioura, 2006). Results of this study promise improvements in WP and water saving by replacing some of the conventional paddy systems with aerobic rice. Every effort should be made to improve WP for sustainable rice production. Water savings of about 20% might save farmers three to four irrigations. The saved water can be used to produce more rice by increasing the irrigated rice area. Rice has relatively assured produce prices and state-controlled marketing channels than other commodities e.g. maize in India and Pakistan (Erenstein, 2012). However, if many farmers would switch from flooded to aerobic rice, then more land would be needed to produce the same quantity of rice and even more if rice production is to increase. Quantitative land suitability mapping should therefore go hand-in-hand with socio-economic assessments of aerobic rice as a transformational technology.

6.3.2. Productivity and eco-efficient resource management

The increasing evidence of benefits associated with aerobic rice systems has encouraged additional research related to productivity and risk reduction. In this study, GY levels of tested genotypes were generally within the target GY of 4–6 Mg ha⁻¹, with the exception of IR6. The exotic genotypes (Apo and IR74371-54-1-1) better coped with water stress, clearly lowering the risk of obtaining low GY and WP. Producing more rice per unit area and with less water is rarely possible: reduced water input increased WP but decreased the GY compared to the flooded system. For traditional rice belt of Punjab, PARC (2010) recommends a partially aerobic water saving technology for transplanted-flooded rice system. With this technology, the long duration *basmati* varieties grow under flooded conditions for initial 35 d. Following this 35-d period, the water regime changes to alternate wetting and drying conditions (AWD). This is also in line with the recommendation of de Vries et al. (2010) for hot and dry climate of Sahel. For the non-traditional rice belt of Punjab and Sindh, where *non-basmati* varieties are also grown in relatively coarse-textured soils, the Pakistan Agricultural Research Council (PARC) recommends aerobic rice system. Results of this study support agronomic feasibility of the aerobic rice system in these target domains. The non-traditional rice belt of Punjab and the Sindh province are important target domains for aerobic rice because most of these farmers grow *non-basmati* coarse grain varieties and because water is often too scarce to maintain puddling conditions (Mann et al., 2007). Nearly one Mha area is currently planted to rice (replacing non-rice crops) in the non-traditional rice belt of Punjab, mainly with coarse varieties (IRRI, 2010; PARC, 2010).

Aerobic rice can minimise water losses such as seepage, percolation, and evaporation. In case of a sufficient rainfall event, farmers may skip irrigation and thus effectively utilise rainwater, which will be lost in flooded system where fields are already flooded (Shashidhar, 2008). Rational use of water, an eco-efficient approach, will enhance sustainability of rice-based systems by diverting the saved water to increase the irrigated area as water is getting scarcer than land. Water savings will indirectly increase the efficiency of energy used for pumping groundwater and puddling operation; energy pricing is becoming an influential driver for water management (Shah et al., 2009). Improvement in the eco-efficiencies of water and energy however might bring high N-losses (*chapter 3*), also reported in previous studies (Belder et al. 2005a, b; Kadiyala et al. 2012; Mahajan et al. 2012) and possibly the risk of organic matter rundown. This warrants the design of integrated nutrient management practices for the newly proposed system. Addition of compost and maintaining an optimum level of all other factors including soil water, macro- and micro nutrients is recommended to enhance N use efficiency. Further optimisation of WP, N response, TDM, and GY levels is possible by increasing water input relative to the levels applied in this study and with the introduction of suitable genotypes.

6.3.3. Breeding

Since the available rice cultivars were bred under conventional flooded system, it is recommended to screen germplasm under aerobic system both under stress and non-stress conditions according to protocols developed by Zhao et al. (2010). Breeding should incorporate the promising local lines i.e. KSK133 and RSP1 as well as improved genetic material, i.e. Apo and IR74371-54-1-1 to develop local genotypes well adapted to aerobic soil conditions. The on-going breeding efforts should focus on improved HI, brought about by high panicle number and high spikelet fertility, and screening for drought and salt tolerant germplasm. A well-developed root system is crucial for extracting water from the soil. Most rice genotypes, including the ones tested in this study, lack a prolific root system. With the emerging focus on aerobic rice systems, targeted breeding efforts should also consider root growth and development. Unavailability of suitable *basmati* varieties is a major factor hampering the expansion of aerobic rice system in the typical rice-belt (*chapter 5*). The extended duration under aerobic conditions is probably one of the reasons for failure of long duration *basmati* genotypes under limited irrigation regimes (*chapter 2*). Since the crop duration has direct implications for resource use and the sowing window, aerobic rice genotypes should be early-maturing. The tested aerobic rice genotypes are used in aerobic rice breeding programmes throughout Asia and were found to be highly PP-

sensitive. The significant variation in optimal flowering time and PP-sensitivity could be exploited by breeders to develop genotypes that can avoid adverse environmental conditions such as pre- and post-monsoon drought (*chapter 4*). A good understanding of developmental processes such as PP-sensitivity and their interactions with other environmental factors (temperature, water, and N, in particular) is essential to avoid resource limitations during critical growth stages.

6.4. Farmers' perspective

The PARC have developed agro-technology for aerobic rice and conducted farmer participatory research trials (IRRI, 2010; PARC, 2010). I conducted farmer surveys (n=215) in three cropping systems with three groups: i.e. group I (n=70) consisting of key-informant farmers from the rice-wheat system who had trialled aerobic rice technology in a participatory research trial in 2010; group II (n=97) consisting of rice-growing farmers from all three cropping systems who grow lowland rice; group III (n=48) were non-rice-growing farmers with experience in mixed-cropping or the cotton-wheat cropping system. Farmers' response helped: a) to identify the technological gaps based on farmer perceptions, and b) to characterise farmer groups and cropping systems, for which the technology is potentially interesting (*chapter 5*).

More than 50% of surveyed farmers never heard of aerobic rice; yet most of the respondents (76%) were positive about trialling aerobic rice. Rice farmers, who have already heard about aerobic or dry direct-seeded rice, often call it *broadcast* or *dry rice* which reflects their appreciation for either shrinking labour or water resources. The most often mentioned positive attribute of aerobic rice was reduced labour requirement followed by water saving. The group I key-informant farmers considered reduced labour requirement, water saving, and evenly high plant densities as the top positive attributes. Groups II and group III mentioned reduced labour requirement, time saving, water saving, and profitability as the top positive attributes. Group I considered weed infestation, disease attack, and poor germination as the top negative attributes. Groups II and group III considered weed infestation and low yields as the top negative attributes.

Group I trialled aerobic rice technology in two districts, namely Hafizabad and Mandibahauddin. On average, 73% farmers were willing to plant again but results were notably different between farmers in the two districts: 86% were willing in Hafizabad and 52% in Mandibahauddin. The decision to plant again might be explained by difference in soil type and the size of landholdings. The main soil type is clay loam in Hafizabad compared to loam in Mandibahauddin. Farms were generally larger in Hafizabad (72% farms ≥ 10 ha) than in Mandibahauddin (52% farms ≥ 10 ha).

Farmers both willing and unwilling to plant again, pointed out various negative attributes of aerobic rice, in particular weeds. They stated that weed infestation, diseases, increased spikelet sterility, poor germination, higher irrigation frequency, more seed rate, and GY penalty were the associated risks. Reasons of the decision for planting again were ease of operation due to direct seeding instead of laborious puddling and transplanting activities, good income, low input requirement especially for labour, and improved physical condition of the soil. Reasons of the decision against planting again were unavailability of suitable varieties, falling water table, weeds, and inadequate soil type.

6.4.1. Identification of entry points

Identifying the entry points can answer this basic question: how can aerobic rice technology pick up momentum to be able to spread in the target domains? Farmer surveys revealed that there is awareness, to some extent, about aerobic rice technology and farmers expressed keen interest in trialling it. Extension activities such as farmer meetings, training activities, demonstration plots, and media outreach programmes should accelerate their efforts to raise awareness. For no-tillage technology, Sheikh et al. (2003) reported the correlation of contact between farmers and agro-technical popularisation department in Pakistani Punjab. Besides government departments, active involvement of private sector will help diffusion of the technology because private sector provides almost 70–80% advisory services in Pakistan (Riaz, 2010). Interest of the private sector will depend on the potential target area e.g. in regards to the trade of biocides.

According to our surveyed farmers, aerobic systems can save water due to unpuddled and non-flooded conditions. Puddling consumes 200–300 mm water prior to transplanting. Aerobic conditions during the growth season further reduce crop water requirement by reducing quantities of water per irrigation event. Results of field experiments showing irrigation water savings in this study also support this notion (*chapter 2*). Farmers might consider selling saved water to raise their income. Early irrigation could eliminate the wait for monsoonal rains for puddling, thus allowing for timelier sowing of rice. Some of the surveyed farmers, however, think that the unpuddled, non-flooded conditions will increase the irrigation frequency. Laser land levelling is considered a precursor technology for the success of aerobic rice systems by farmers and researchers (Kahlowan et al. 2002; Balasubramanian et al. 2013; Mahajan et al. 2013).

The other major driving force behind aerobic rice, besides water economy, is labour shortage. Reduced labour requirement, as a positive attribute, is often ranked higher

than water saving by farmers (Templeton and Bayot, 2011; Weerakoon et al., 2011; Mahajan et al., 2013). Labour shortage, during peak season, results in delayed transplantation and an increased incidence of pest attack, leading to severe GY losses. Transplanting operation needs to be completed within a short period of time (Pandey and Velasco, 1999; Pandey and Velasco, 2005). Availability of good quality herbicides and the fact that aerobic rice can be mechanised offer opportunities to reduce overall labour requirements (Farooq et al., 2011). A main reason for willingness of group I farmers to plant again was ease of operation due to direct seeding. Direct seeding results in even plant densities and transfers field activities to periods of relatively abundant and cheap labour. The advantage of even plant densities, however, may be off-set by the fact that not all of the directly-sown seeds emerge well. Farmers also opined that a high seed rate is required to compensate for low seed emergence and manual broadcasting of seeds was better than using a seed drill. Good seed quality, cultivars able to germinate under anaerobic conditions, seed priming, and availability of seed drills with a precise metering system will ensure even plant densities and reduce seed rate (Farooq et al., 2006; Ismail et al., 2009). Indian Punjab farmers used high seed rates of 80–120 kg ha⁻¹ which reduced to 20–25 kg ha⁻¹ when seed drills with precise seed metering system were made available (Mahajan et al., 2013). The optimum seed rate is crucial to reduce competition for water, nutrients, canopy closure, and weed competitiveness. According to surveyed farmers, savings achieved in water, labour, and energy will increase the net profitability.

Weed infestation is a major issue for aerobic culture. Mahajan et al. (2013) reported that weed management was effective in Indian Punjab where farmers applied both pre- and post-emergence herbicides. To address challenges such as changes in weed flora over time and herbicide resistance, it is imperative to ensure good quality of herbicides, development of mechanical weeders, weed suppressive cultivars, mulching, a vigilant weed monitoring programme, and farmer trainings about weed management (Caton et al., 2003; Rao et al., 2007; Singh et al., 2008).

Under aerobic system, rice crop is susceptible to various diseases mainly blast, brown leaf spot, and sheath blight. Developing resistance against blast disease has been an important breeding trait in Brazil (Bresseghello et al., 2011). Limited water availability, coarse-textured soils, and unbalanced fertilisation favour spread of the diseases under aerobic conditions (Farooq et al., 2011; Mahajan et al., 2013). Dry soil conditions in the field also favour termite infestations (Personal observation in field experiments). Symptoms often resemble N-deficiency and in case of an attack it may lead to crop failure if not managed properly. Field submergence and using chemical control methods (e.g. Chlorpyrifos) is effective in this regard.

6.5. Further research directions

Aerobic rice is a knowledge-intensive technology requiring precise/timely management practices (Mahajan et al., 2013). Identification of the technological gaps and entry points (i.e. suitable *basmati* varieties, good quality biocides, mechanical weeders, optimisation of crop management practices such as seed rate, water, and fertiliser inputs, crop protection strategies, an effective weed monitoring system, raising awareness, active involvement of private sector to ensure availability of good quality herbicides and advisory services, land levelling, potential areas for crop intensification/diversification) based on farmer perceptions can value add to the on-going research on water-saving rice cultivation.

Field- and phytotron experiments generated rich data-sets containing information on soil, crop, and weather variables, which can be used as input parameters for crop models. A crop modelling approach will be useful to underpin and focus experimental findings of this study. Specifically, improved modelling approaches e.g. APSIM-Oryza can be used to:

- develop hypotheses for optimal water and N inputs including a range of input levels not tested in field experiments
- optimise critical threshold level of re-irrigation for different soil types with varying field hydrology
- further optimisation of WP, irrigation amounts and timing
- quantify resource use in relation to crop duration
- simulate genotype-specific delay in flowering and yield components as a function of drought stress
- Better characterisation of temperature response for tested genotypes
- explore long-term dynamics of soil N and C in relation to yield decline and long term fate of organic matter in the soil
- investigate the trade-offs between yield and resource use efficiency
- study the long-term impact of climate change on emerging production systems in relation to cropping calendars and water use
- propose locally-adapted systems combining high water and N use efficiencies

6.6. Conclusions

This thesis evaluates the aerobic rice system as an option to improve resource use efficiency in irrigated rice systems. The general aim was to contribute important information on the non-conventional system at field, plant, and socio-economic level. Rice farmers may need to adapt due to likely further reductions in water availability. It

is now possible to state that the emerging system appears to be a viable option in the target domains – non-traditional rice belt in Punjab and the Sindh province – to improve WP and make more effective use of rainfall. Water savings will be accompanied by energy and labour savings as a result of reduced groundwater pumping, fewer tillage operations, and direct drill seeding instead of manual transplanting. Although improved eco-efficiencies of water, labour, and energy promise sustainable rice production across the study region, there are questions in regards to the long-term effects on N use, N use efficiency, and soil organic matter content.

In order to balance production and sustainability, risk on crop failure can be reduced by optimisation of scarce resources and provision of suitable genotypes. Understanding phenological chronology is crucial to attune (water or N) management to critical growth stages. Quantification of the pre-flowering photothermal responses gave a robust set of PP-parameters that can be used by breeders, agronomists, and crop modellers for further investigations with the tested genotypes. Breeding should focus on the development of aerobic genotypes especially for fine grain *basmati* rice.

Final adoption of the alternate production system will depend on relative benefits of aerobic rice technology and socio-ecological niche of famers. Analysis of farmer perceptions showed that farmers who are already growing rice are more interested in aerobic rice technology than those who currently do not grow rice. The knowledge-intensive aerobic rice technology requires precise management interventions to realise appreciable yields. The developing technology will benefit from well-informed knowledge-based entry points to fill the identified technological and attitudinal gaps.

Finally, a number of future studies using a crop modelling approach are apparent. Results and data-sets of this study provide a solid basis for further investigations at a larger scale.

References

- Adesina, A.A., Baidu-Forson, J., 1995. Farmers' perceptions and adoption of new agricultural technology: evidence from analysis in Burkina Faso and Guinea, West Africa. *Agr. Econ.* 13, 1-9.
- Aggarwal, P.K., Joshi, P.K., Ingram, J.S.I., Gupta, R.K., 2004. Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formulation. *Environ. Sci. Policy* 7, 487-498.
- Ahmad, M.D., Turrall, H., Masih, I., Giordano, M., Masood, Z., 2007. Water saving technologies: myths and realities revealed in Pakistan's rice-wheat systems. International Water Management Institute, Colombo, Sri Lanka, pp. 44.
- Akhter, M., Ahmad, M., Ramzan, M., Awan, T.H., 2007. KSK 133-A high yielding, stiff stemmed and extra long grain coarse variety. *J. Anim. Pl. Sci.* 17, 63-66.
- Akhter, J., Monneveux, P., Sabir, S.A., Ashraf, M.Y., Lateef, Z., Serraj, R., 2010. Selection of drought tolerant and high water use efficient rice cultivars through ¹³C isotope discrimination technique. *Pak. J. Bot.* 42, 3887-3897.
- Ali, R.I., Awan, T.H., Manzoor, Z., Ashraf, M.M., Safdar, M.E., Ahmad, M., 2007. Screening of rice varieties suitable for direct seeding in Punjab. *J. Anim. Pl. Sci.* 17, 24-26.
- AOAC, 1984. Official Methods of Analysis. Association of Official Analytical Chemists, Inc., Arlington, Virginia.
- Aslam, M., Qureshi, A.S., Horinkova, V.M., 2002. Water saving strategies for irrigated rice. *J. Drain. Water Manage.* 6, 25-36.
- Atlin, G.N., Lafitte, H.R., Tao, D., Laza, M., Amante, M., Courtois, B., 2006. Developing rice cultivars for high-fertility upland systems in the Asian tropics. *Field Crops Res.* 97, 43-52.
- Balasubramanian, V., Adhya, T.P., Ladha, J.K., 2013. Enhancing Eco-Efficiency in the Intensive Cereal-Based Systems of the Indo-Gangetic Plains. In: Hershey, C.H., Neate, P. (Eds.), *Eco-efficiency: From vision to reality*. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia, pp. 99-115.
- Baloch, M.S., Hassan, G., Morimoto, T., 2005. Weeding techniques in transplanted and direct wet-seeded rice in Pakistan. *Weed Biol. Manag.* 5, 190-196.
- Baloch, M.S., Awan, I.U., Hassan, G., Zubair, M., 2007. Studies on plant population and stand establishment techniques for increasing productivity of rice in Dera Ismail Khan, Pakistan. *Rice Sci.* 14, 118-124.
- Barker, R., Dawe, D., Tuong, T.P., Bhuiyan, S.I., Guerra, L.C., 1998. The outlook for water resources in the year 2020: Challenges for research on water management in

References

- rice production. Assessment and Orientation Towards the 21st Century. Proceedings of 19th Session of the International Rice Commission, FAO, Cairo, Egypt, pp. 96–109.
- Bashir, K., Khan, N., Rasheed, S., Salim, M., 2007. Indica rice varietal development in Pakistan: an overview. *Paddy Water Environ.* 5, 73-81.
- Belder, P., Bouman, B.A.M., Cabangon, R., Guoan, L., Quilang, E.J.P., Yuanhua, L., Spiertz, J.H.J., Tuong, T.P., 2004. Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. *Agr. Water Manage.* 65, 193-210.
- Belder, P., 2005. Water saving in lowland rice production: an experimental and modelling study. PhD thesis, Wageningen University, Wageningen, The Netherlands.
- Belder, P., Bouman, B.A.M., Spiertz, J.H.J., Peng, S., Castañeda, A.R., Visperas, R.M., 2005a. Crop performance, nitrogen and water use in flooded and aerobic rice. *Plant Soil* 273, 167-182.
- Belder, P., Spiertz, J.H.J., Bouman, B.A.M., Lu, G., Tuong, T.P., 2005b. Nitrogen economy and water productivity of lowland rice under water-saving irrigation. *Field Crops Res.* 93, 169-185.
- Bessembinder, J.J.E., Leffelaar, P.A., Dhindwal, A.S., Ponsioen, T.C., 2005. Which crop and which drop, and the scope for improvement of water productivity. *Agr. Water Manage.* 73, 113-130.
- Best, R., 1961. Some Aspects of Photoperiodism in Rice (*Oryza sativa* L.). Elsevier publishing company, Amsterdam, The Netherlands. pp. 87.
- Borrell, A., Garside, A., Fukai, S., 1997. Improving efficiency of water use for irrigated rice in a semi-arid tropical environment. *Field Crops Res.* 52, 231-248.
- Bhatti, M.A., Kijne, J.W., 1992. Irrigation Management Potential of Paddy/Rice Production in Punjab of Pakistan., *Soil and Water Engineering for Paddy Field Management*. AIT, Bangkok, Thailand., pp. 355-366.
- Black, B.L., Swartz, H.J., Deitzer, G.F., Butler, B., Chandler, C.K., 2005. The effects of conditioning strawberry plug plants under altered Red/Far-red light environments. *Hort. Sci.* 40, 1263-1267.
- Borrell, A., Garside, A., Fukai, S., 1997. Improving efficiency of water use for irrigated rice in a semi-arid tropical environment. *Field Crops Res.* 52, 231-248.
- Bouman, B.A.M., Tuong, T.P., 2001. Field water management to save water and increase its productivity in irrigated lowland rice. *Agr. Water Manage.* 49, 11-30.
- Bouman, B.A.M., Kropff, M.J., Tuong, T.P., Wopereis, M.C.S., Ten Berge, H.F.M., Van Laar, H.H., 2001. ORYZA2000: modeling lowland rice. *International Rice*

- Research Institute, Los Baños, The Philippines, and Wageningen University and Research Centre, Wageningen, The Netherlands.
- Bouman, B.A.M., Peng, S., Castañeda, A.R., Visperas, R.M., 2005. Yield and water use of irrigated tropical aerobic rice systems. *Agr. Water Manage.* 74, 87-105.
- Bouman, B.A.M., Yang, X., Wang, H., Wang, Z., Zhao, J., Chen, B., 2006. Performance of aerobic rice varieties under irrigated conditions in North China. *Field Crops Res.* 97, 53-65.
- Bouman, B.A.M., Lampayan, R.M., Tuong, T.P., 2007a. Water management in irrigated rice: coping with water scarcity. International Rice Research Institute (IRRI), Manila, The Philippines, pp. 54.
- Bouman B.A.M., Feng, L., Tuong, T.P., Lu, G., Wang, H., Feng, Y., 2007b. Exploring options to grow rice using less water in northern China using a modelling approach. II. Quantifying yield, water balance components, and water productivity. *Agr. Water Manage.* 88:23-33.
- Bouman, B.A.M., 2009. How much water does rice use? *Rice Today*, pp. 28–29.
- Breseghello, F., de Moraes, O.P., Pinheiro, P.V., Silva, A.C.S., da Maia de Castro, E., Guimarães, E.P., de Castro, A.P., Pereira, J.A., De Matos Lopes, A., Utumi, M.M., de Oliveira, J.P., 2011. Results of 25 years of upland rice breeding in Brazil. *Crop Sci.* 51, 914-923.
- Briscoe, J., Qamar, U., 2009. *Pakistan's Water Economy Running Dry*. Oxford University Press, USA.
- Bueno, C.S., Bucourt, M., Kobayashi, N., Inubushi, K., Lafarge, T., 2010. Water productivity of contrasting rice genotypes grown under water-saving conditions in the tropics and investigation of morphological traits for adaptation. *Agr. Water Manage.* 98, 241-250.
- Cabangon, R.J., Tuong, T.P., Castillo, E.G., Bao, L.X., Lu, G., Wang, G.H., Cui, L., Bouman, B.A.M., Li, Y., Chen, C., Wang, J., 2004. Effect of irrigation method and N-fertilizer management on rice yield, water productivity and nutrient-use efficiencies in typical lowland rice conditions in China. *Paddy Environ.* 2, 195-206.
- Castillo, E.G., Tuong, T.P., Singh, U., Inubushi, K., Padilla, J., 2006. Drought response of dry-seeded rice to water stress timing and N-fertilizer rates and sources. *Soil Sci. Plant Nutr.* 52, 496-508.
- Caton, B.P., Cope, A.E., Mortimer, M., 2003. Growth traits of diverse rice cultivars under severe competition: implications for screening for competitiveness. *Field Crops Res.* 83, 157-172.

References

- CGIAR, 2010. Sustainable crop productivity increase for global food security: A CGIAR (Consultative Group on International Agricultural Research) Research Program on Rice-Based Production Systems. pp. 267.
- Chapagain, A.K., Hoekstra, A.Y., 2010. The green, blue and grey water footprint of rice from both a production and consumption perspective. UNESCO-IHE Institute for Water Education, Delft, The Netherlands in collaboration with University of Twente, Enschede, The Netherlands, and Delft University of Technology, Delft, The Netherlands.
- Chapagain, A.K., Hoekstra, A.Y., 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. *Ecol. Econ.* 70, 749-758.
- Chaudhary, R.C., Tran, D.V., Duffy, R., 2001. Speciality rices of the world : breeding, production and marketing. Food and Agriculture Organization (FAO), Rome, Italy.
- Chauhan, B.S., Mahajan, G., Sardana, V., Timsina, J., Jat, M.L., Donald, L.S., 2012. Productivity and sustainability of the rice–wheat cropping system in the Indo-Gangetic plains of the Indian subcontinent: problems, opportunities, and strategies. *Adv. Agron.* 117, 315-369.
- Choudhury, B.U., Bouman, B.A.M., Singh, A.K., 2007. Yield and water productivity of rice–wheat on raised beds at New Delhi, India. *Field Crops Res.* 100, 229-239.
- Collinson, S., 1992. Photothermal responses of pre-flowering development in rice (*Oryza sativa* L.) and soybean (*Glycine max* L.). PhD thesis, Department of Agriculture. University of Reading, U.K., Reading, p. 202.
- Cui, X., Xue, C., Yang, X., Yang, J., Zhang, Q., Wang, H., Bouman, B.A.M., 2008. Field evapotranspiration characteristics and water use efficiency of aerobic rice under different water treatments. *Nongye Gongcheng Xuebao/Trans. Chin. Soc. Agr. Engg.* 24, 49-54.
- Dahri, Z.H., Ahmad, S., Moshabbir, P.M., 2008. Adjusting crops and cropping pattern with water availability. *Water Shortage and Future Agriculture in Pakistan – Challenges and Opportunities*, NARC, Islamabad, pp. 56-67.
- De Datta, S.K., 1987. Principles and practices of rice production. Robert E. Krieger Publishing Company, INC. Malabar, Florida, USA, p. 618.
- de Vries, M.E., Rodenburg, J., Bado, B.V., Sow, A., Leffelaar, P.A., Giller, K.E., 2010. Rice production with less irrigation water is possible in a Sahelian environment. *Field Crops Res.* 116, 154-164.
- de Vries, M.E., Leffelaar, P.A., Sakane, N., Bado, B.V., Giller, K.E., 2011. Adaptability of irrigated rice to temperature change in Sahelian environments. *Exp. Agr.* 47, 69-87.

- Debaeke, P., Aboudrare, A., 2004. Adaptation of crop management to water-limited environments. *Eur. J. Agron.* 21, 433-446.
- Devkota, K.P., Manschadi, A., Lamers, J.P.A., Devkota, M., Vlek, P.L.G., 2013. Mineral nitrogen dynamics in irrigated rice–wheat system under different irrigation and establishment methods and residue levels in arid drylands of Central Asia. *Eur. J. Agron.* 47, 65-76.
- Dingkuhn, M., Miezán, K.M., 1995. Climatic determinants of irrigated rice performance in the Sahel — II. Validation of photothermal constants and characterization of genotypes. *Agr. Syst.* 48, 411-433.
- Dobermann A., Fairhurst T., 2000. *Rice: Nutrient Disorders & Nutrient Management* Singapore : Potash & Phosphate Institute, East & Southeast Asia Programs; Makati City Philippines: IRRI.
- Dunn, B.W., Gaydon, D.S., 2011. Rice growth, yield and water productivity responses to irrigation scheduling prior to the delayed application of continuous flooding in south-east Australia. *Agr. Water Manage.* 98, 1799-1807.
- Erenstein, O., 2009. Comparing water management in rice–wheat production systems in Haryana, India and Punjab, Pakistan. *Agr. Water Manage.* 96, 1799-1806.
- Erenstein, O., 2012. Conservation agriculture-based technologies and the political economy: lessons from South Asia. In: Sumberg, J., Thompson, J. (Eds.), *Contested agronomy: Agricultural Research in a Changing World*. Routledge, New York, NY, pp. 47-63.
- FAO, 2012. World agriculture towards 2030/2050: the 2012 revision. Global perspective studies team. Food and Agriculture Organisation (FAO). <http://www.fao.org/docrep/016/ap106e/ap106e.pdf>
- FAO, 2013. *FAO Rice Market Monitor*. Trade and Markets Division, Food and Agriculture Organization of the United Nations, p. 38.
- Farooq, M., Basra, S.M.A., Tabassum, R., Afzal, I., 2006. Enhancing the performance of direct seeded fine rice by seed priming. *Plant Prod. Sci.* 9, 446-456.
- Farooq, M., Basra, S.M.A., Asad, S.A., 2008. Comparison of conventional puddling and dry tillage in rice-wheat system. *Paddy Water Environ.* 6, 397-404.
- Farooq, M., Kobayashi, N., Wahid, A., Ito, O., Basra, S.M.A., 2009. Strategies for producing more rice with less water. *Adv. Agron.* 101, 351-388.
- Farooq, M., Siddique, K.H.M., Rehman, H., Aziz, T., Lee, D.-J., Wahid, A., 2011. Rice direct seeding: experiences, challenges and opportunities. *Soil Tillage Res.* 111, 87-98.
- Feder, G., Just, R.E., Zilberman, D., 1985. Adoption of agricultural innovations in developing countries: a survey. *Econ. Dev. Cult. Change* 33, 255-298.

References

- Feng, L., Bouman, B.A.M., Tuong, T.P., Cabangon, R.J., Li, Y., Lu, G., Feng, Y., 2007. Exploring options to grow rice using less water in northern China using a modelling approach. I. Field experiments and model evaluation. *Agr. Water Manage.* 88, 1-13.
- Fischer, K.S., Lafitte, R., Fukai, S., Atlin, G., Hardy, B., 2003. Breeding rice for drought-prone environments. International Rice Research Institute, Los Baños, The Philippines.
- Frolking, S., Li, C., Braswell, R., Fuglestedt, J., 2004. Short- and long-term greenhouse gas and radiative forcing impacts of changing water management in Asian rice paddies. *Global Change Biolo.* 10, 1180-1196.
- Fukai, S., 1999. Phenology in rainfed lowland rice. *Field Crops Res.* 64, 51-60.
- George, T., Magbanua, R., Garrity, D.P., Tubaña, B.S., Quiton, J., 2002. Rapid yield loss of rice cropped successively in aerobic soil. *Agron. J.* 94, 981-989.
- GOP, 2007. "Overall Water Availability". Pakistan Statistical Year Book 2007. Ministry of Economic Affairs and Statistics, Statistics Division, Government of Pakistan.
- GOP, 2012a. Pakistan Economic Survey 2010-11. Economic Advisory Wing Finance Division, Government of Pakistan, Islamabad, Pakistan.
- GOP, 2012b. PARB Newsletter. Punjab Agricultural Research Board, Government of Pakistan, pp. 1.
- GOP, 2013. Cropping Pattern. Agriculture Marketing Information Service (AMIS), Government of Pakistan, Directorate of Agriculture (Economics and Marketing), Punjab, Lahore.
- Goudriaan, J., Van Laar, H.H., 1994. Modelling Potential Crop Growth Processes. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Gupta, P.K., Sahai, S., Singh, N., Dixit, C.K., Singh, D.P., Sharma, C., Tiwari, M.K., Gupta, R.K., Garg, S.C., 2004. Residue burning in rice-wheat cropping system: Causes and implications. *Curr. Sci.* 87, 1713-1717.
- Haefele, S.M., Jabbar, S.M.A., Siopongco, J.D.L.C., Tirol-Padre, A., Amarante, S.T., Sta Cruz, P.C., Cosico, W.C., 2008. Nitrogen use efficiency in selected rice (*Oryza sativa* L.) genotypes under different water regimes and nitrogen levels. *Field Crops Res.* 107, 137-146.
- Hansen, V.E., Israelsen, O.W. Stringham, G.E., 1980. Irrigation Principles and Practices. Wiley, New York, pp. 50-51.
- Hussain, T., 2002. Groundwater management: a case study of Rechna Doab - Pakistan. *J. Drain. Water Manage.* 6, 69-76.
- Hussain, I., Sakthivadivel, R., Amarasinghe, U., 2003. Land and water productivity of wheat in the western Indo-Gangetic plains of India and Pakistan: a comparative

- analysis. In: Kijne JW, B.R., D, M. (Eds.), *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CABI Publishing in association with the International Management Institute, Colombo, Sri Lanka, pp. 255–274.
- Hussain, I., 2007. Water demand management and economic value of water in the Indus basin. PhD thesis, Department of Economics. University of Sargodha, Sargodha, p. 250.
- Hussain, I., Hussain, Z., Sial, M.H., Akram, W., Farhan, M.F., 2011. Water balance, supply and demand and irrigation efficiency of Indus basin. *Pak. Econ. Soci. Rev.* 49, 13-38.
- IRRI, 2010. Developing and disseminating water-saving rice technologies in South Asia. International Rice Research Institute, Manila, The Philippines.
- Ismail, A.M., Ella, E.S., Vergara, G.V., Mackill, D.J., 2009. Mechanisms associated with tolerance to flooding during germination and early seedling growth in rice (*Oryza sativa*). *Ann. Bot.* 103, 197-209.
- Jehangir, W.A., Masih, I., Ahmed, S., Gill, M.A., Ahmad, M., Mann, R.A., Chaudhary, M.R., Qureshi, A.S., Turrall, H., 2007. Sustaining crop water productivity in rice-wheat systems of South Asia: A case study from the Punjab, Pakistan. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 45.
- Jing, Q., 2007. Improving resource use efficiency in rice-based cropping systems: experimentation and modelling. PhD thesis, Wageningen University, Wageningen, The Netherlands.
- Kadiyala, M.D.M., Mylavarapu, R.S., Li, Y.C., Reddy, G.B., Reddy, M.D., 2012. Impact of aerobic rice cultivation on growth, yield, and water productivity of rice–maize rotation in semiarid tropics. *Agron. J.* 104, 1757-1765.
- Kahlowan, M.A., Gill, M.A., Ashraf, M., 2002. Evaluation of Resource Conservation Technologies in Rice–Wheat System of Pakistan. Pakistan Council of Research in Water Resources (PCRWR), Islamabad.
- Kahlowan, M.A., Raoof, A., Zubair, M., Kemper, W.D., 2007. Water use efficiency and economic feasibility of growing rice and wheat with sprinkler irrigation in the Indus Basin of Pakistan. *Agr. Water Manage.* 87, 292-298.
- Kato, Y., Kamoshita, A., Yamagishi, J., 2006. Growth of three rice cultivars (*Oryza sativa* L.) under upland conditions with different levels of water supply 2. Grain yield. *Plant Prod. Sci.* 9, 435-445.
- Kato, Y., Kamoshita, A., Yamagishi, J., 2007. Evaluating the resistance of six rice cultivars to drought: restriction of deep rooting and the use of raised beds. *Plant Soil* 300, 149-161.

References

- Keating, B.A., Carberry, P.S., Bindraban, P.S., Asseng, S., Meinke, H., Dixon, J., 2010. Eco-efficient Agriculture: concepts, challenges, and opportunities. *Crop Sci.* 50, 109-119.
- Keating, B., Carberry, P., Thomas, S., Clark, J., 2013. Eco-Efficient Agriculture and Climate Change: Conceptual Foundations and Frameworks. In: Hershey, C.H., Neate, P. (Eds.), *Eco-efficiency: From vision to reality*. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia, pp. 19-28.
- Khan, S., Tariq, R., Yuanlai, C., Blackwell, J., 2006. Can irrigation be sustainable? *Agr. Water Manage.* 80, 87-99.
- Kondo, M., Singh, C.V., Agbisit, R., Murty, M.V.R., 2005. Yield response to urea and controlled-release urea as affected by water supply in tropical upland rice. *J. Plant Nutr.* 28, 201-219.
- Kreye, C., Bouman, B.A.M., Castañeda, A.R., Lampayan, R.M., Faronilo, J.E., Lactaoen, A.T., Fernandez, L., 2009. Possible causes of yield failure in tropical aerobic rice. *Field Crops Res.* 111, 197-206.
- Kumar, A., Bernier, J., Verulkar, S., Lafitte, H.R., Atlin, G.N., 2008. Breeding for drought tolerance: direct selection for yield, response to selection and use of drought-tolerant donors in upland and lowland-adapted populations. *Field Crops Res.* 107, 221-231.
- Kumar, V., Ladha, J.K., Donald, L.S., 2011. Direct seeding of rice: recent developments and future research needs. *Adv. Agron.* 111, 297-413.
- Kumazawa, K., 1984. Beneficial effects of organic matter on rice growth and yield in Japan. *Organic Matter and Rice*. International Rice Research Institute, Manila, The Philippines, pp. 431- 444.
- Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., Hobbs, P.R., 2003. How extensive are yield declines in long-term rice-wheat experiments in Asia? *Field Crops Res.* 81, 159-180.
- Ladha, J.K., Pathak, H., J. Krupnik, T., Six, J., van Kessel, C., 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Adv. Agron.* 87, 85-156.
- Ladha, J.K., Kumar, V., Alam, M.M., Sharma, S., Gathala, M., Chandna, P., Saharawat, Y.S., Balasubramanian, V., 2009. Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice-wheat system in South Asia. In: Ladha, J.K., Singh, Y., Erenstein, O., Hardy, B. (Eds.), *Integrated Crop and Resource Management in the*

- Rice-Wheat System of South Asia. International Rice Research Institute, Los Baños, The Philippines, pp. 69-108.
- Lafitte, H.R., Courtois, B., 2002. Interpreting cultivar X environment interactions for yield in upland rice: assigning value to drought-adaptive traits. *Crop Sci.* 42, 1409-1420.
- Lafitte, H.R., Courtois, B., Arraudeau, M., 2002. Genetic improvement of rice in aerobic systems: Progress from yield to genes. *Field Crops Res.* 75, 171-190.
- Lampayan, R.M., Bouman, B.A.M., de Dios, J.L., Espiritu, A.J., Soriano, J.B., Lactaoen, A.T., Faronilo, J.E., Thant, K.M., 2010. Yield of aerobic rice in rainfed lowlands of the Philippines as affected by nitrogen management and row spacing. *Field Crops Res.* 116, 165-174.
- Larson, W.E., Clapp, C.E., 1984. Effects of Organic Matter on Soil Physical Properties. *Organic Matter and Rice*. International Rice Research Institute, Manila, The Philippines, pp. 363-386.
- Latif, M., 2007. Spatial productivity along a canal irrigation system in Pakistan. *Irrig. Drain.* 56, 509-521.
- Laza, M.R.C., Peng, S., Akita, S., Saka, H., 2003. Contribution of biomass partitioning and translocation to grain yield under sub-optimum growing conditions in irrigated rice. *Plant Prod. Sci.* 6, 28-35.
- Li, Z.K., Pinson, S.R.M., Stansel, J.W., Park, W.D., 1995. Identification of quantitative trait loci (QTLs) for heading date and plant height in cultivated rice (*Oryza sativa* L.). *Theor. Appl. Genet.* 91, 374-381.
- Li, D., Liu, M., Deng, G., 2010. Willingness and determinants of farmers' adoption of new rice varieties. *China Agr. Econ. Rev.* 2, 456-471.
- Li, S.-X., Wang, Z.-H., Stewart, B.A., Donald, L.S., 2013. Responses of crop plants to ammonium and nitrate N. *Adv. Agron.* 118, 205-397.
- Lin, S., Dittert, K., Tao, H.B., Kreye, K., Xu, Y.C., Shen, Q.R., Fan, X.L., Sattelmacher, 2002. The ground-cover rice production system (GCRPS): A successful new approach to save water and increase nitrogen fertilizer efficiency? In: Bouman, B.A.M., Hengsdijk, H., Hardy, B., Bindraban, P.S., Tuong, T.P., Ladha, J.K. (Eds.), *Water-wise rice production*. International Rice Research Institute, Los Baños, The Philippines, pp. 187-196.
- Lobell, D.B., Bonfils, C., Faurès, J.M., 2008. The role of irrigation expansion in past and future temperature trends. *Earth Interact.* 12, 1-11.
- Luo, Y.F., Khan, S., Cui, Y.L., Feng, Y.H., Li, Y.L., 2006. Modeling for water balance for aerobic rice: A dynamics approach. MODSIM 2005. Proceedings of the International Congress Modeling and Simulation, Melbourne, Australia, pp. 1860-1866.

References

- Maclean, J.L., Dawe, D., Hardy, B., and Hettel, G.P., 2002. Rice Almanac. International Rice Research Institute (IRRI), Manila, The Philippines.
- Mahajan, G., Chauhan, B.S., 2011. Effects of planting pattern and cultivar on weed and crop growth in aerobic rice system. *Weed Technol.* 25, 521-525.
- Mahajan, G., Chauhan, B.S., Timsina, J., Singh, P.P., Singh, K., 2012. Crop performance and water- and nitrogen-use efficiencies in dry-seeded rice in response to irrigation and fertilizer amounts in northwest India. *Field Crops Res.* 134, 59-70.
- Mahajan, G., Chauhan, B.S., Gill, M.S., 2013. Dry-seeded rice culture in Punjab State of India: Lessons learned from farmers. *Field Crops Res.* 144, 89-99.
- Mann, R.A., Ahmad, S., Hassan, G., Baloch, M.S., 2007. Weed management in direct seeded rice crop. *Pak. J. Weed Sci. Res.* 13, 219-226.
- Mann, R.A., Hussain, S., Saleem, M., 2011. Impact of dry seeding with alternate wetting and drying on rice productivity and profitability in Punjab-Pakistan. *World Congress on Conservation Agriculture*. Australian Centre for International Agricultural Research (ACIAR), Brisbane.
- Mateo, N., Ortiz, R., 2013. Resource Use Efficiency Revisited. In: Hershey, C.H., Neate, P. (Eds.), *Eco-efficiency: From vision to reality* Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia, pp. 1-17.
- Matthews, R.B., Kropff, M.J., Bachelet, D., van Laar, H.H., 1995. Modeling the Impact of Climate Change on Rice Production in Asia. IRRI/CAB International.
- Molden, D., Frenken, K., Barker, R., de Fraiture, C., Mati, B., Svendsen, M., Sadoff, C., Finlayson, C.M., 2007. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan/International Water Management Institute, London/Colombo, Sri Lanka.
- Muhammed, A., 1985. Collaborative Research: Pakistan's experience. *Impact of Science on Rice*. International Rice Research Institute, Manila, Philippines, pp. 199-209.
- Negatu, W., Parikh, A., 1999. The impact of perception and other factors on the adoption of agricultural technology in the Moret and Jiru Woreda (district) of Ethiopia. *Agr. Econ.* 21, 205-216.
- Nie, L., Peng, S., Bouman, B.A.M., Huang, J., Cui, K., Visperas, R.M., Park, H.K., 2007. Alleviating soil sickness caused by aerobic monocropping: Responses of aerobic rice to soil oven-heating. *Plant Soil* 300, 185-195.
- Nie, L., Peng, S., Bouman, B.A.M., Huang, J., Cui, K., Visperas, R.M., Xiang, J., 2008. Alleviating soil sickness caused by aerobic monocropping: responses of aerobic rice to nutrient supply. *Field Crops Res.* 107, 129-136.

- Oka, H., 1958. Photoperiodic adaptation to latitude in rice varieties. *Phyton* 11, 153-160.
- Okumoto, Y., Ichitani, K., Inoue, H., Tanisaka, T., 1996. Photoperiod insensitivity gene essential to the varieties grown in the northern limit region of paddy rice (*Oryza sativa* L.) cultivation. *Euphytica* 92, 63-66.
- Pandey, S., Velasco, L.E., 1999. Economics of alternative rice establishment methods in Asia: a strategic analysis. Social Sciences Division Discussion Paper. International Rice Research Institute (IRRI), Manila, The Philippines.
- Pandey, S., Mortimer, M., Wade, L., Tuong, T.P., Lopez, K., Hardy, B., 2002. Direct seeding: research issues and opportunities. International Workshop on Direct Seeding in Asian Rice Systems: Strategic Research Issues and Opportunities Los Baños (The Philippines): International Rice Research Institute, Bangkok, Thailand, p. 383.
- Pandey, S., Velasco, L., 2005. Trends in crop establishment methods in Asia and research issues. In: *Rice is Life: Scientific Perspectives for the 21st Century*, pp. 178-181.
- PARC-RWC, 2003. Pakistan Agricultural Research Council – Rice-Wheat Consortium for the Indo-Gangetic Plains. National workshop on Rice-Wheat Systems Pakistan Agricultural Research Council, Islamabad, Pakistan and Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India Islamabad, Pakistan, pp. 118.
- PARC, 2010. Aerobic rice technology, Pakistan Agricultural Research Council (PARC), Islamabad, Pakistan (in Urdu).
- Passioura, J., 2006. Increasing crop productivity when water is scarce—from breeding to field management. *Agr. Water Manage.* 80, 176-196.
- Peng, S., Bouman, B., Visperas, R.M., Castañeda, A., Nie, L., Park, H.K., 2006. Comparison between aerobic and flooded rice in the tropics: agronomic performance in an eight-season experiment. *Field Crops Res.* 96, 252-259.
- Pingali, P.L., Shah, M., 2001. Policy re-directions for sustainable resource use: The rice-wheat cropping system of the Indo-Gangetic plains. *J. Crop Prod.* 3, 103-118.
- Pinheiro, B.D.S., Castro, E.D.M.D., Guimarães, C.M., 2006. Sustainability and profitability of aerobic rice production in Brazil. *Field Crops Res.* 97, 34-42.
- Poonyarit, M., Mackill, D.J., Vergara, B.S., 1989. Genetics of photoperiod sensitivity and critical daylength in rice. *Crop Sci.* 29, 647-652.
- Prasad, G.S.V., Muralidharan, K., Rao, C.S., Prasad, A.S.R., 2001. Stability and yield performance of genotypes: A proposal for regrouping world rice area into mega-environments. *Current Sci.* 81, 1337-1346.
- Prasad, R., Donald, L.S., 2011. Aerobic rice systems. *Adv. Agron.* 111, 207-247.

References

- Pushpavesa, S., Jackson, B.R., 1979. Photoperiod sensitivity in rainfed rice. In: Rainfed Lowland Rice. Selected papers from the 1978 international rice research conference, International Rice Research Institute, Los Baños, The Philippines., pp. 139-147.
- Qian, X., Shen, Q., Xu, G., Wang, J., Zhou, M., 2004. Nitrogen form effects on yield and nitrogen uptake of rice crop grown in aerobic soil. *J. Plant Nutr.* 27, 1061-1076.
- Rao, A.N., Johnson, D.E., Sivaprasad, B., Ladha, J.K., Mortimer, A.M., Donald, L.S., 2007. Weed management in direct-deeded rice. *Adv. Agron.* 93, 153-255.
- Rashid, M.H., Alam, M.M., Khan, M.A.H., Ladha, J.K., 2009. Productivity and resource use of direct-(drum)-seeded and transplanted rice in puddled soils in rice-rice and rice-wheat ecosystems. *Field Crops Res.* 113, 274-281.
- Riaz, M., 2010. The role of the private sector in agricultural extension in Pakistan. *Rural Development News. AGRIDEA*, Lindau (Switzerland), pp. 15-22.
- Rijsberman, F.R., 2006. Water scarcity: fact or fiction? *Agr. Water Manage.* 80, 5-22.
- Sahrawat, K.L., 2009a. Nitrogen mineralization in lowland rice soils: the role of organic matter quantity and quality. *Arch. Agron. Soil Sci.* 56, 337-353.
- Sahrawat, K.L., 2009b. The role of tolerant genotypes and plant nutrients in reducing acid-soil infertility in upland rice ecosystem: an appraisal. *Arch. Agron. Soil Sci.* 55, 597-607.
- Sahrawat, K.L., 2012. Soil fertility in flooded and non-flooded irrigated rice systems. *Arch. Agron. Soil Sci.* 58, 423-436.
- Saini, H.S., Westgate, M.E., Donald, L.S., 1999. Reproductive development in grain crops during drought. *Adv. Agron.* 68, 59-96.
- Salim, M., Akram, M., Ehsan, M., Ashraf, A.M., 2003. Rice, a production handbook. In: PARC (Ed.). Pakistan Agricultural Research Council, Islamabad.
- Santhi, P.K., Ponnuswamy, K., Kempuchetty, N., 1998. A labour saving technique in direct-sown and transplanted rice. *IRRN* 23, 35-36.
- Sariam, O., Zainuddin, P.M.D., 2007. Potential of aerobic rice in Malaysia. *International Workshop on Aerobic Rice*, Beijing, P.R. China, October 22-24.
- Sarwar, G., Schmeisky, H., Hussain, N., Muhammad, M., Ibrahim, M., Safdar, E., 2008. Improvement of soil physical and chemical properties with compost application in rice-wheat cropping system. *Pak. J. Bot.* 40, 275-282.
- Sarwar, N., Ali, H., Ahmad, A., Ullah, E., Ahmad, S., Mubeen, K., Hill, J.E., 2013. Water wise rice cultivation on calcareous soil with the addition of essential micronutrients. *J. Anim. Plant Sci.* 23:244-250.

- Shah, T., Ul Hassan, M., Khattak, M.Z., Banerjee, P.S., Singh, O.P., Rehman, S.U., 2009. Is irrigation water free? A reality check in the Indo-Gangetic Basin World Dev. 37 422–434.
- Sharif, A., 2011. Technical adaptations for mechanized SRI production to achieve water saving and increased profitability in Punjab, Pakistan. Paddy Water Environ. 9, 111-119.
- Shashidhar, H., 2008. Aerobic rice—An efficient water management strategy for rice production. In: Aswathanarayana, U. (Ed.), Food and Water Security. Taylor and Francis, London, UK, pp. 131-139.
- Sheikh, A.D., Rehman, T., Yates, C.M., 2003. Logit models for identifying the factors that influence the uptake of new ‘no-tillage’ technologies by farmers in the rice–wheat and the cotton–wheat farming systems of Pakistan's Punjab. Agr. Sys. 75, 79-95.
- Sinclair, T.R., 1990. Nitrogen influence on the physiology of crop yield In: Rabbinge, R., Goudriaan, J., van Keulen, H.W.P.M., Library., W.U. (Eds.), Theoretical Production Ecology: Reflections and Prospects. Wageningen UR, The Netherlands, Wageningen, pp. 41-55.
- Singh, P., 2008. Federalism, Nationalism and Development: India and the Punjab Economy. Routledge, London; New York.
- Singh, S., Ladha, J.K., Gupta, R.K., Bhushan, L., Rao, A.N., 2008. Weed management in aerobic rice systems under varying establishment methods. Crop Prot. 27, 660-671.
- Stoop, W.A., Uphoff, N., Kassam, A., 2002. A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. Agr. Sys. 71, 249-274.
- Templeton, D., Bayot, R., 2011. An impact assessment of the ‘Developing a System of Temperate and Tropical Aerobic Rice (STAR) in Asia’ project. CGIAR Challenge Program on Water and Food.
- Timsina, J., Connor, D.J., 2001. Productivity and management of rice-wheat cropping systems: issues and challenges. Field Crops Res. 69, 93-132.
- Tsai, K.H. , 1986. Gene loci and alleles controlling the duration of basic vegetative growth of rice. In: Rice Genetics. International Rice Research Institute Manila, The Philippines, pp. 339-350.
- Tuong, T.P., Bouman, B.A.M., 2003. Water Productivity in Agriculture: Limits and Opportunities for Improvements. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Rice production in water-scarce environments. CABI Publishing, UK, pp. 53–67.

References

- van Oort, P.A.J., Zhang, T., de Vries, M.E., Heinemann, A.B., Meinke, H., 2011. Correlation between temperature and phenology prediction error in rice (*Oryza sativa* L.). *Agr. Forest Meteorol.* 151, 1545-1555.
- Vergara, B.S., Chang, T.T., 1985. The Flowering Response of the Rice Plant to Photoperiod, a Review of the Literature. International Rice Research Institute Manila, The Philippines.
- Verulkar, S.B., Mandal, N.P., Dwivedi, J.L., Singh, B.N., Sinha, P.K., Mahato, R.N., Dongre, P., Singh, O.N., Bose, L.K., Swain, P., Robin, S., Chandrababu, R., Senthil, S., Jain, A., Shashidhar, H.E., Hittalmani, S., Vera Cruz, C., Paris, T., Raman, A., Haefele, S., Serraj, R., Atlin, G., Kumar, A., 2010. Breeding resilient and productive genotypes adapted to drought-prone rainfed ecosystem of India. *Field Crops Res.* 117, 197-208.
- Vlek, P., Craswell, E., 1981. Ammonia volatilization from flooded soils. *Fert. Res.* 2, 227-245.
- Wailes, E.J., Chavez, E.C., 2012. World Rice Outlook International Rice Baseline with Deterministic and Stochastic Projections, 2012-2021. Department of Agricultural Economics and Agribusiness Division of Agriculture, Agriculture Building, University of Arkansas Fayetteville, AR 72701.
- Wang, H., Bouman, B.A.M., Zhao, D., Wang, C., Moya, P.F., 2002. Aerobic rice in northern China—Opportunities and challenges. In: Bouman, B.A.M., Hengsdijk, H., Hardy, B., Bindraban, P.S., Tuong, T.P., Ladha, J.K. (Eds.), *Water-Wise Rice Production*. International Rice Research Institute, Los Baños (Philippines), pp. 143–154.
- Weerakoon, W.M.W., Mutunayake, M.M.P., Bandara, C., Rao, A.N., Bhandari, D.C., Ladha, J.K., 2011. Direct-seeded rice culture in Sri Lanka: lessons from farmers. *Field Crops Res.* 121, 53-63.
- Wei, X., Jiang, L., Xu, J., Zhang, W., Lu, G., Zhang, Y., Wan, J., 2008. Genetic analyses of heading date of Japonica rice cultivars from Northeast China. *Field Crops Res.* 107, 147-154.
- Wopereis, M.C.S., 1993. Quantifying the impact of soil and climate variability on rainfed rice production. PhD thesis, Wageningen UR, Wageningen.
- Wopereis, M.C.S., Kropff, M.J., Maligaya, A.R., Tuong, T.P., 1996. Drought-stress responses of two lowland rice cultivars to soil water status. *Field Crops Res.* 46, 21-39.
- Xiaoguang, Y., Bouman, B.A.M., Huaqi, W., Zhimin, W., Junfang, Z., Bin, C., 2005. Performance of temperate aerobic rice under different water regimes in North China. *Agr. Water Manage.* 74, 107-122.

- Xue, C.Y., Yang, X.G., Bouman, B.A.M., Deng, W., Zhang, Q.P., Yang, J., Yan, W.X., Zhang, T.Y., Rouzi, A.J., Wang, H.Q., Wang, P., 2008a. Effects of irrigation and nitrogen on the performance of aerobic rice in Northern China. *J. Integr. Plant Biol.* 50, 1589-1600.
- Xue, C., Yang, X., Bouman, B., Deng, W., Zhang, Q., Yan, W., Zhang, T., Rouzi, A., Wang, H., 2008b. Optimizing yield, water requirements, and water productivity of aerobic rice for the North China Plain. *Irrig. Sci.* 26, 459-474.
- Yan, J., Yu, J., Tao, G.C., Vos, J., Bouman, B.A.M., Xie, G.H., Meinke, H., 2010. Yield formation and tillering dynamics of direct-seeded rice in flooded and nonflooded soils in the Huai River Basin of China. *Field Crops Res.* 116, 252-259.
- Yin, X., Kropff, M.J., McLaren, G., Visperas, R.M., 1995. A nonlinear model for crop development as a function of temperature. *Agr. Forest Meteorol.* 77, 1-16.
- Yin, X., Kropff, M.J., 1996. Use of the Beta function to quantify effects of photoperiod on flowering and leaf number in rice. *Agr. Forest Meteorol.* 81, 217-228.
- Yin, X., Kropff, M.J., Horie, T., Nakagawa, H., Centeno, H.G.S., Zhu, D., Goudriaan, J., 1997a. A model for photothermal responses of flowering in rice I. Model description and parameterization. *Field Crops Res.* 51, 189-200.
- Yin, X., Kropff, M.J., Nakagawa, H., Horie, T., Goudriaan, J., 1997b. A model for photothermal responses of flowering in rice. II. Model evaluation. *Field Crops Res.* 51, 201-211.
- Yin, X., Kropff, M.J., Ynalvez, M.A., 1997c. Photoperiodically sensitive and insensitive phases of preflowering development in rice. *Crop Sci.* 37, 182-190.
- Yin, X., Struik, P.C., Tang, J., Qi, C., Liu, T., 2005. Model analysis of flowering phenology in recombinant inbred lines of barley. *J. Exp. Bot.* 56, 959-965.
- Yin, X., 2008. Analysis of reciprocal-transfer experiments to estimate the length of phases having different responses to temperature. *Ann. Bot.* 101, 603-611.
- Ying, J., Peng, S., He, Q., Yang, H., Yang, C., Visperas, R.M., Cassman, K.G., 1998. Comparison of high-yield rice in tropical and subtropical environments: I. determinants of grain and dry matter yields. *Field Crops Res.* 57, 71-84.
- Yoshida, S., 1981. *Fundamentals of Rice Crop Science*. International Rice Research Institute, Manila, Philippines.
- Yue, J., Shi, Y., Liang, W., Wu, J., Wang, C., Huang, G., 2005. Methane and nitrous oxide emissions from rice field and related microorganism in black soil, Northeastern China. *Nutr. Cycl. Agroecosyst.* 73, 293-301.
- Zhang, X., Lee, J.H., Abawi, Y., Kim, Y.H., McClymont, D., Kim, H.D., 2007. Testing the simulation capability of APSIM-ORYZA under different levels of

References

- nitrogen fertiliser and transplanting time regimes in Korea. *Aus. J. Exp. Agr.* 47, 1446-1454.
- Zhang, T., Zhu, J., Yang, X., 2008. Non-stationary thermal time accumulation reduces the predictability of climate change effects on agriculture. *Agr. Forest Meteorol.* 148, 1412-1418.
- Zhang, L., Lin, S., Bouman, B.A.M., Xue, C., Wei, F., Tao, H., Yang, X., Wang, H., Zhao, D., Dittert, K., 2009. Response of aerobic rice growth and grain yield to N fertilizer at two contrasting sites near Beijing, China. *Field Crops Res.* 114, 45-53.
- Zhang, S., Tao, F., 2013. Modeling the response of rice phenology to climate change and variability in different climatic zones: comparisons of five models, *Eur. J. Agron.* 45, 165-176.
- Zhao, D.L., Atlin, G.N., Bastiaans, L., Spiertz, J.H.J., 2006. Comparing rice germplasm groups for growth, grain yield and weed-suppressive ability under aerobic soil conditions. *Weed Res.* 46, 444-452.
- Zhao, D.L., Bastiaans, L., Atlin, G.N., Spiertz, J.H.J., 2007. Interaction of genotype $\times$ management on vegetative growth and weed suppression of aerobic rice. *Field Crops Res.* 100, 327-340.
- Zhao, D.L., Atlin, G.N., Amante, M., Cruz, M.T.S., Kumar, A., 2010. Developing aerobic rice cultivars for water-short irrigated and drought-prone rainfed areas in the tropics. *Crop Sci.* 50, 2268-2276.
- Zia, M.S., 1990. Fertility evaluation and management of flooded lowland rice soils of Pakistan. PhD thesis, Kyoto University, Japan.
- Zia, M.S., Nizami, M.I., Salim, M.I., 1994. Problems of soil degradation in Pakistan. In the collection of land degradation data. Regional office for Asia and the Pacific. Food and Agriculture Organization of the United Nations, Bangkok, Thailand, pp. 179-202.
- Zia, M.S., Hussain, F., Aslam, M., Hashmi, N.I., Hameed, A., 2002. Integrated plant nutrition system for sustainable rice-wheat cropping sequence. *Int. J. Agric. Biol.* 4, 175-182.
- Zou, J., Huang, Y., Jiang, J., Zheng, X., Sass, R.L., 2005. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue, and fertilizer application. *Global Biogeochem. Cycles* 19, 1-9.

SUMMARY

Transplanted-flooded rice systems developed during times of abundant land, water and labour resources. This conventional system is now showing its limitations for resource poor South Asian rice farmers in the face of diminishing resources. Declining water availability threatens sustainable rice production and food security. Farmers supplement insufficient surface water by pumping groundwater using diesel or electric pumps, putting additional pressure on limited energy resources. Labour shortage, rising rural wages, and difficulties associated with manual transplanting of rice seedlings result in uneven plantings and low plant population densities. These are just some of the important factors limiting rice productivity in conventional rice-production systems. An alternative to the conventional system is ‘aerobic rice’ – a fundamentally different approach of growing rice in unpuddled, non-flooded fields under aerobic soil conditions just like wheat and maize. The aerobic rice system aims at improving resource use efficiency of rice-based cropping systems, in particular for water and labour. While the non-conventional system is gaining in popularity across South Asia, the system is still very much in the development phase under (sub-)tropical conditions. This research project evaluates the aerobic rice system, from a biophysical and socio-technological perspective, in Punjab, Pakistan. Rice is a highly valued cash crop in Pakistan, which covers 2.7 million hectares producing about 6 million tonnes annually. Through this project I addressed the overarching research questions: Is the transformation of transplanted-flooded rice system to direct-seeded aerobic rice system a viable option to improve resource use efficiencies? How do farmers perceive such a transformation? To answer these questions I employed a combined approach of experimentation and farmer surveys.

I conducted three field experiments during 2009 and 2010 at the research station of the University of Agriculture, Faisalabad–Pakistan. The experimental site lies in the non-traditional rice belt, which is an important target domain for aerobic rice. Field experiments, covering two rice seasons (2009/10), three irrigation levels (high, moderate, low), three nitrogen (N) rates (0, 170, 220 kg N ha⁻¹), three local (KSK133, IR6, RSP1) and two exotic (Apo, IR74371-54-1-1) genotypes, contributed important quantitative information on aerobic rice crop performance. I investigated the possible irrigation water savings and crop performance by analysing data of local and exotic genotypes in response to the three irrigation levels (*Chapter 2*). Water productivity (WP_g; g grain kg⁻¹ total water input) improved significantly with values up to 0.38 under aerobic system compared to the national average value of 0.16 under flooded system. About 20% water savings achieved in the high irrigation treatment might save

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farmers three to four irrigations. The highest values of WP_g (0.24–0.38), total aboveground dry biomass production (TDM; 9.6–13.3 Mg ha⁻¹), and grain yield (GY; 3.11–5.0 Mg ha⁻¹) occurred in the high irrigation treatment and consistently decreased in response to the decreasing water input in moderate and low irrigation treatment. The lower WP_g at moderate and low water input was accompanied by a lower panicle number and reduced harvest index (HI). Under limited water supply i.e. moderate and low treatments, the GY and WP_g of exotic genotypes were higher than that of local genotypes, owing to a high HI. In conclusion, there is great scope for improvement in WP and water saving by adopting aerobic rice systems where water scarcity is a greater threat to rice production than land scarcity. Results suggest that further optimisation of WP_g and GY is possible by applying more irrigation water.

Next I analysed field data of three local genotypes in relation to different water and N supply rates to study the interactions between irrigation, N and genotype factors, particularly for total aboveground N uptake (TNU) under aerobic conditions (*Chapter 3*). Irrigation levels strongly influenced the crop performance and TNU with differences between genotypes. Genotype KSK133 performed better than RSP1 and IR6, recording TDM of 13 Mg ha⁻¹ at the high irrigation and 220 kg N ha⁻¹ and a GY of 5 Mg ha⁻¹ at the high irrigation and 170 kg N ha⁻¹. Surprisingly, N application rate did not influence TNU, but the high irrigation regime increased TNU. Values of TNU ranged from 34 to 126 kg ha⁻¹ (2009) and from 52 to 123 kg ha⁻¹ (2010) in low to high irrigation regimes. The limited response to N application suggests that improved eco-efficiencies for water, labour and energy in aerobic rice systems might happen at the cost of N depletion and possible rundown of organic matter. Carefully designed N management strategies should be developed for aerobic systems so that N application matches periods of sufficient soil moisture availability and greatest crop demand.

Accurately characterising phenology is important to synchronise resource supply and demand. Understanding phenology × environment interactions is essential to devise management practices that improve resource use efficiency in environments with sub-optimal resource supply. To disentangle photoperiod (PP) and temperature effects, I used a two-step approach (*Chapter 4*). The PP-response was determined in growth chambers, through a reciprocal transfer experiment with variable daylength, conducted at a fixed temperature of 26°C. Consecutively, the temperature response was determined by combining the obtained PP-parameters with data from field experiments. Both conceptually and methodologically the two-step approach worked well, simplifying the phenology calibration. The growth chamber study resulted in a robust set of PP-parameters, and demonstrated that all four tested genotypes (KSK133, RSP1, Apo, IR74371-54-1-1) exhibited strong PP-sensitivity. Neither the bilinear nor the beta model converged to a unique set of optimal temperature response parameters.

Presumably the temperature range in the field experiments was too narrow. Sensitivity analysis clearly showed that using standard cardinal temperatures (8, 30, 42°C) overestimated time to flowering. In particular the rate of development below 31°C was overestimated, whereas the development rate above this temperature was underestimated.

Farmer surveys (n=215) with rice and non-rice farmers of Punjab province in three major cropping systems viz. rice-wheat, mixed-cropping, cotton-wheat supplemented the basic biophysical research (*Chapter 5*). The aim was to understand farmers' perspective about future adoption of aerobic rice system. Most of the farmers were unaware of its existence and the possibility it offers but expressed their keen interest in experimenting with aerobic rice. Farmers perceived aerobic rice as a means of increasing resource use efficiency for labour and water. Perceived threats were the necessity of improving the management expertise of farmers. Aerobic rice requires more attention to issues such as weeds, diseases, poor germination and spikelet sterility. Overall, 73% of the farmers who trialled aerobic rice in a participatory research project, were positive about planting it again, especially those with large landholdings and clayey-soils. The unavailability of suitable fine grain aerobic *basmati* varieties was identified as a major constraint for large scale adoption. Understanding farmers' perspective helped to identify the entry points for the emerging aerobic rice system: *basmati* varieties, optimisation of agronomic practices, mechanical weeders/seeder, a vigilant weed monitoring system, good quality biocides, extension outreach programmes, and prospective areas for crop intensification/diversification. Various stakeholders aiming for the successful adoption of aerobic rice can benefit from the guidelines developed in this study.

In *Chapter 6* I synthesised the core findings on aerobic rice performance under field conditions, phenology calibration, and farmers' perspective. These findings have implications for food security, sustainable rice production, eco-efficient resource management, and breeding. The aerobic rice system is a rational approach for improving WP_g and to safeguard sustainable rice production. Improvements in the efficiency of water use will be accompanied by the efficiencies achieved in labour and energy. My research has clearly shown that aerobic rice is a knowledge-intensive, transformational technology with significant potential, however, is not a silver bullet technology; there are risk factors associated with it that need to be considered on a case-by-case basis. Risks associated with aerobic rice are biophysical and socio-technological. Improved eco-efficiencies of water, labour, and energy might happen at the cost of declined efficiencies of N and land use and an increased reliance on biocides for managing biotic factors such as weeds, diseases, and insect pests. Addressing these issues requires carefully designed management strategies and

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optimal land use options. Risks of crop failure can be reduced by filling the still existing knowledge gaps through additional research and through farmer training in order to overcome the additional demand for sound agronomic management that this technology requires. Further, targeted breeding programmes especially for *basmati* rice are urgently needed to unlock the potential of aerobic rice in regions previously not considered for aerobic rice production. In the last part of this final chapter, I presented research directions for future research.

SAMENVATTING

Het geïrrigeerde rijststelsel, waarbij rijst wordt overgeplant van een zaaibed naar een productieveld met permanente bevoeiing, vindt zijn oorsprong in een tijdperk waarin schaarste aan land, water en arbeid nog geen rol van betekenis speelde. Door allerlei tekorten worden de beperkingen van dit conventionele teeltsysteem steeds duidelijker voelbaar voor de kleinschalige boeren in Zuid Azië. Waterschaarste bedreigt de duurzaamheid van het conventionele teeltsysteem en daarmee de voedselzekerheid. Boeren proberen het gebrek aan oppervlaktewater beschikbaar voor irrigatie te compenseren door grondwater op te pompen, daarbij beslag leggend op toch al beperkte energie voorraden. Een tekort aan arbeid, stijgende loonprijzen en moeilijkheden met het handmatig overplanten van opgekweekte rijstplanten resulteren in een ongelijkmatige veldbezetting en lage plantdichtheden. Dit zijn maar enkele van de factoren verantwoordelijk voor de begrenzing van de productiviteit in conventionele rijstproductie systemen. Een alternatief voor dit conventionele systeem is 'aerobic rice' – een fundamenteel andere manier voor het telen van rijst, waarbij het land niet nat geploegd wordt en de bodem onverzadigd met water blijft. De teelt van rijst wordt dan vergelijkbaar met die van gewassen als tarwe en mais. Doel van het aerobic rice systeem is de benuttingsefficiëntie van met name water en arbeid te verhogen. Terwijl de populariteit van dit nieuwe systeem in diverse delen van Zuid Azië aan het toenemen is, staat dezelfde technologie in meer (sub-) tropische gebieden nog in de kinderschoenen. Het in dit proefschrift beschreven onderzoek evalueert het aerobic rice systeem in de Pakistaanse provincie Punjab vanuit zowel biofysisch als sociaal-technologisch perspectief. Rijst is een belangrijk handelsgewas in Pakistan, waar op een oppervlak van 2.7 miljoen hectare jaarlijks ongeveer 6 miljoen ton rijst wordt geproduceerd. De hoofd-onderzoeksvragen waaraan ik in dit project heb gewerkt zijn: Is de overgang van het conventionele rijststelsel naar het direct gezaaide aerobic rice systeem een levensvatbare optie voor het verhogen van de benuttingsefficiëntie van productiemiddelen? Hoe ervaren boeren een dergelijke overgang? Voor het beantwoorden van deze vragen heb ik gebruik gemaakt van zowel experimenten als interviews met boeren.

Gedurende 2009 en 2010 heb ik drie veldexperimenten uitgevoerd op het onderzoeksstation van de Landbouwuniversiteit van Faisalabad in Pakistan. Dit experimentele station ligt in een niet specifiek rijstproductiegebied, maar is wel een belangrijk doelgebied voor de introductie van aerobic rice. Veldexperimenten uitgevoerd in twee seizoenen (2009 en 2010) met drie irrigatie niveaus (hoog, medium, laag), drie stikstof (N) niveaus (0, 170, 220 kg N ha⁻¹) en drie locale (KSK133, IR6,

RSP1) en twee exotische (Apo, IR74371-54-1-1) genotypes, leverden belangrijke informatie op over het gedijen van een aerobice rijstgewas. Ik heb de mogelijke besparingen op irrigatie water en de verrichtingen van het rijstgewas onderzocht, door de reactie van de lokale en de exotische genotypes op irrigatie niveau te analyseren (Hoofdstuk 2). De waterproductiviteit (WPg) berekend als graanopbrengst per eenheid waterverbruik (g kg^{-1}) verbeterde significant, met waarden tot 0.38 voor het aerobice rijst systeem, tegenover een nationaal gemiddelde van 0.16 voor het traditionele systeem. Een waterbesparing van 20%, zoals behaald met het hoogste irrigatieniveau, komt voor de boeren overeen met een besparing van drie tot vier bevloeiingen. De hoogste waarden voor zowel WPg (0.24-0.38) als de totale bovengrondse biomassa productie (TDM; $9.6\text{-}13.3 \text{ Mg ha}^{-1}$) en de graanopbrengst (GY; $3.1\text{-}5.0 \text{ Mg ha}^{-1}$) werden behaald met het hoogste irrigatie niveau en daalden stelselmatig als reactie op een verminderd wateraanbod in het medium en lage irrigatie niveau. De lagere WPg in deze twee irrigatiebehandelingen ging gepaard met een verminderde oogstindex (HI), vooral ten gevolge van een lager aantal pluimen. Onder beperkt wateraanbod, d.w.z. medium en lage irrigatieniveaus, lag, dankzij een hogere HI, zowel de GY als de WPg van de exotische genotypes hoger dan die van de lokale. Samengevat kan worden geconcludeerd dat de introductie van aerobice rijst systemen goede mogelijkheden biedt voor het verder verbeteren van WP en waterbesparing, vooral op plaatsen waar waterschaarste een grotere bedreiging voor de rijstteelt vormt dan een tekort aan land. De resultaten suggereren dat een verdere optimalisatie van WPg en GY mogelijk is.

Aansluitend heb ik veldgegevens geanalyseerd van drie lokale genotypes in relatie tot water en N aanbod. Op deze wijze is de interactie tussen irrigatie, N-bemesting en genotypes onder aerobe omstandigheden geanalyseerd met name t.a.v. de totale hoeveelheid opgenomen N in de bovengrondse delen (TNU) (Hoofdstuk 3). Irrigatie niveau had een duidelijke invloed op de verrichtingen van het gewas en met name de TNU, met duidelijke verschillen tussen de genotypes. Genotype KSK133 presteerde beter dan RSP1 en IR6, met een TDM van 13 Mg ha^{-1} onder de hoogste irrigatie en 220 kg N ha^{-1} en een GY van 5 Mg ha^{-1} onder de hoogste irrigatie en 170 kg ha^{-1} . Verrassend genoeg had N bemesting geen invloed op TNU, terwijl het hoge irrigatie niveau de TNU verhoogde. De TNU varieerde van laag naar hoog irrigatie niveau met waarden van 34 tot 126 kg ha^{-1} (2009) en van 52 tot 123 kg ha^{-1} (2010). De beperkte reactie op N suggereert dat verbeterde eco-efficiënties van water, arbeid en energie in aerobice rijst systemen gepaard gaan met N uitputting en mogelijk verlies aan organische stof. Er is behoefte aan zorgvuldig ontworpen strategieën voor aerobice rijst systemen waarbij de toediening van N samenvalt met periodes waarin de vraag vanuit het gewas het grootst is en er bovendien voldoende bodemvocht aanwezig is.

Om vraag en aanbod van de verschillende productiemiddelen goed op elkaar af te stemmen is een goede karakterisering van de fenologie van belang. Een goed begrip van de fenologie $\times$ omgeving interactie is essentieel voor de ontwikkeling van teeltmaatregelen om de benuttingsefficiëntie van diverse productiemiddelen te verbeteren in omstandigheden met een sub-optimaal aanbod aan productiemiddelen. Om het effect van fotoperiode (PP) en temperatuur op de ontwikkeling van het gewas los te koppelen, heb ik gebruik gemaakt van een twee-stappen benadering (Hoofdstuk 4). De PP-reactie werd bepaald met behulp van klimaatkamers, waarbij planten serieel werden omgewisseld tussen een lange-dag-behandeling en een korte-dag-behandeling bij een constante temperatuur van 26°C. Daaropvolgend werd de temperatuur respons bepaald door de verkregen PP-parameters te combineren met gegevens behaald uit veldexperimenten. Zowel conceptueel als methodologisch werkte de twee-stappen benadering goed, leidend tot een vereenvoudigde kalibratie van fenologie parameters. De klimaatkamer studie leverde een robuuste set van PP-parameters op en maakte duidelijk dat alle vier de geteste genotypes (KSK133, RSP1, Apo, IR74371-54-1-1) over een sterke fotoperiodegevoeligheid beschikken. Zowel met het bilineaire als met het beta model, resulteerde optimalisatie niet in een unieke set van temperatuur respons parameters. Naar alle waarschijnlijkheid was het temperatuur traject in de veldexperimenten te smal. Gevoeligheidsanalyse maakte echter duidelijk dat het gebruik van standaard kardinale temperaturen (8, 30, 42°C) het bloeitijdstip overschatte. Met name beneden een temperatuur van 31°C werd de ontwikkelingssnelheid van het gewas overschat, terwijl de ontwikkelingssnelheid boven deze temperatuur juist werd onderschat.

Als aanvulling op het biofysische onderzoek werd een enquête gehouden onder rijst en niet-rijst boeren (n = 215) afkomstig uit de provincie Punjab (Hoofdstuk 5). Deze boeren waren afkomstig uit drie belangrijke teeltsystemen, te weten het rijst-tarwe systeem, gemengde bedrijfssysteem en katoen-tarwe systeem. Het doel was om vanuit het gezichtspunt van de boer een beter begrip te krijgen over toekomstige acceptatie van het aerobic rice systeem. Uit de enquête kwam naar voren dat de meeste boeren niet op de hoogte waren van het bestaan en de mogelijkheden van het aerobic rice systeem. Wel toonde men volop belangstelling om het systeem uit te gaan proberen. Boeren onderkenden vooral de mogelijkheden om de waterbenuttingsefficiëntie en de arbeidsproductiviteit op te voeren. De noodzaak om het kennisniveau van de boer op te krikken werd ervaren als een mogelijke bedreiging voor de introductie van het systeem. Het aerobic rice systeem vraagt meer aandacht voor zaken als onkruiden, ziekten, kiemingsproblemen en steriliteit. Van de boeren die het systeem uitgeprobeerd hadden in een participatief onderzoeksproject was 73% van plan om het systeem nogmaals te proberen. Het betrof vooral de boeren op kleigrond

en in het bezit van relatief veel land. Het niet beschikbaar zijn van aromatische rijst variëteiten voor het aerobic rice systeem werd als belangrijkste obstakel voor grootschalige introductie gezien. Door te bestuderen hoe boeren aankijken tegen dit nieuwe systeem werd duidelijk welke punten de nodige aandacht verdienen: aromatische rassen, teeltoptimalisatie, mechanisatie t.a.v. zaai en onkruidbestrijding, onkruidherkenning, betrouwbare biociden, voorlichtingsprogramma's en mogelijkheden voor gewasintensivering en gewasdiversificatie. Voor diverse belanghebbenden kunnen de in dit project ontwikkelde richtlijnen voor een succesvolle adoptie van het aerobic rice systeem profijtelijk zijn.

In hoofdstuk 6 heb ik de belangrijkste bevindingen op het gebied van het onder veldomstandigheden functioneren van het aerobic rijst systeem, de kalibratie van de fenologie van rijstrassen en de mening van boeren t.a.v. het aerobic rice systeem geïntegreerd. De conclusies hebben duidelijke implicaties voor de voedselzekerheid, duurzame rijstproductie, de eco-efficiëntie van diverse productiemiddelen en de veredeling. Het aerobic rice systeem is een rationele benadering voor het verbeteren van de WPg en voor het veiligstellen van een duurzame rijstproductie. Verbeteringen op het gebied van de waterbenuttingsefficiëntie gaan gepaard met verhoogde efficiënties op het gebied van arbeid en energie. Mijn onderzoek laat zien dat aerobic rice een kennisintensieve, overdraagbare technologie is met grote potentie. Tegelijkertijd is het geen wondermiddel, maar zitten er risicofactoren aan, die maatwerk vereisen. Risico's verbonden aan het aerobic rice systeem zijn zowel biofysisch als socio-technologisch van aard. Verbeterde eco-efficiënties van water, arbeid en energie zouden gepaard kunnen gaan met een verminderde N benuttingsefficiëntie, terwijl meer land vereist is en een verhoogde afhankelijkheid ontstaat van biociden, voor het beheer van onkruiden, ziekten en plagen. Om op een goede manier met deze zaken om te gaan, zijn er zorgvuldig ontworpen beheersstrategieën en optimale landgebruiks-mogelijkheden vereist. Het risico op misoogsten kan verkleind worden door de bestaande leemtes in kennis op te vullen met aanvullend onderzoek en een goede training en begeleiding van boeren die aansluiten bij de vereisten van deze nieuwe technologie. Bovendien is er op korte termijn behoefte aan veredelingsprogramma's voor het ontwikkelen van aromatische rijstrassen die geschikt zijn voor het aerobic rice systeem. Op deze wijze kan aerobic rice een aantrekkelijke optie worden voor regio's waar tot op heden geen rijst werd geproduceerd. In het laatste deel van de discussie geef ik aan waarop toekomstig onderzoek zich zou moeten richten.

لاب کی منتقلی اور مسلسل کھڑے پانی میں چاول کی کاشت کے پیداواری نظام اس دور میں وضع کئے گئے جب زمین، پانی اور افرادی قوت کے وسائل وافر تھے۔ جنوبی ایشیاء میں محدود وسائل والے کاشتکاروں کے لئے، وسائل کی کمی کے پیش نظر، یہ روایتی نظام اپنی افادیت کھو رہا ہے۔ پانی کی شدید کمی نے چاول کی مجموعی پیداوار برقرار رکھنے اور غذائی تحفظ کے لئے خطرے کی گھنٹی بجادی ہے۔ نہری پانی کی کمی پوری کرنے کے لئے کاشتکار ڈیزل یا برقی پمپ کی مدد سے زیر زمین پانی نکال کر استعمال کرتے ہیں جو کہ توانائی کے محدود وسائل پر اضافی بوجھ ہے۔ افرادی قوت کی کمی، بڑھتی ہوئی اجرت اور ہاتھ سے لاب کی منتقلی میں مضر مشکلات کا نتیجہ غیر یکساں اور ناکافی پودوں کی تعداد کی صورت میں نکلتا ہے۔ چاول کے روایتی طریقہ کاشت میں یہ چند اہم مسائل ہیں۔ جوئی ایکڑ پیداوار میں کمی کے ذمہ دار ہیں۔

روایتی طریقہ کاشت کے متبادل ایک "چاول کا خشک طریقہ کاشت" ہے۔ بنیادی طور پر یہ ایک مختلف طریقہ کار ہے جس میں بغیر کدو و مسلسل پانی کھڑا کئے، گندم و مکئی کی طرح، خشک زمین میں چاول اگایا جاتا ہے۔ خشک طریقہ کاشت اختیار کرنے کا بنیادی مقصد چاول شریک فصلاتی نظام میں وسائل کے کٹتی استعمال میں بہتری لانا ہے، بالخصوص پانی اور افرادی قوت کے لئے۔ یہ غیر روایتی نظام جنوبی ایشیاء میں مقبولیت حاصل کر رہا ہے۔ تاہم اس گرم خطے کی آب و ہوا سے مطابقت پیدا کرنے کے لئے فی الحال ترقی کے مراحل میں ہے۔ اس تحقیقاتی کاوش کا مقصد صوبہ پنجاب پاکستان میں "چاول کے خشک طریقہ کاشت" کا طبعی و حیاتیاتی اور تکنیکی و سماجی تناظر میں جائزہ لینا ہے۔ چاول ۷۷ ملین ہیکٹر رقبہ پر کاشت کی جانے والی پاکستان کی ایک اہم نقد آور فصل ہے۔ جبکہ پیداواری تخمینہ ۶ ملین ٹن سالانہ ہے۔ میں نے اس پی ایچ ڈی مقالے میں ان مجموعی تحقیقاتی سوالات کو اٹھایا ہے۔

(الف) کیا وسائل کے کٹتی استعمال میں بہتری لانے کے لئے "لاب کی منتقلی و مسلسل کھڑے پانی والے پیداواری نظام" کو "سیدھی و بجائی و خشک طریقہ کاشت والے پیداواری نظام" سے بدلنا ایک مناسب حکمت عملی ہے؟
(ب) کاشتکار حضرات اس تبدیلی کو کس نظر سے دیکھتے ہیں؟

مندرجہ بالا سوالوں کے جوابات ڈھونڈنے کے لئے میں نے اپنے تجربات کے ساتھ ساتھ کاشتکار حضرات کی رائے کا جائزہ لیا۔ تحقیقاتی مرکز، جامعہ زرعیہ فیصل آباد میں سال ۲۰۰۹/۱۰ کے دوران میں نے تین فصلاتی تجربات کیے۔ تجرباتی زمین کا شمار چاول کی غیر روایتی کاشت والے علاقہ جات میں ہوتا ہے جو کہ خشک طریقہ کاشت کے فروغ کے لئے اہم اہداف تصور کئے جاتے ہیں۔ دو اوقات کاشت (۲۰۰۹/۱۰) تین سطح آبپاشی (کم، درمیانہ، زیادہ)، تین شرح نائٹروجن (۲۲۰، ۴۰، ۰) کلوگرام نائٹروجن فی ہیکٹر) تین مقامی (کے ایس کے ۱۳۳، آئی آر ۶، آر ایس پی ۱) اور دو غیر مقامی (ایپو، آئی آر ۳-۱-۵۴-۱۷۳۷) اقسام پر مشتمل فصلاتی تجربات نے خشک طریقہ کاشت کی جانکاری پر اہم اعداد و شمار کا اضافہ کیا۔

ممکنہ پانی کی بچت اور فصل کی کارکردگی کا جانچنے کے لئے میں نے مختلف سطح آبپاشی کے تحت مقامی و غیر مقامی اقسام کے اعداد و شمار کا تجزیہ کیا (باب دوم)۔ خشک طریقہ کاشت کے تحت ۳۸۰۰ کلوگرام آبی پیداوار (گرم پیداوار فی کلوگرام مجموعی مداخل پانی حاصل کی گئی جو کہ کدو طریقہ کاشت کی ملک گیر اوسط ۱۶۰ کی نسبت ایک واضح بہتری ہے۔ لہذا کاشتکار، ان نتائج کی روشنی میں، تقریباً ۲۰ فیصد پانی کی بچت کر سکتے ہیں۔ جو کہ تین سے چار بار آبپاشی کے برابر ہے۔ زیادہ سے زیادہ آبی پیداوار (۳۸۰۰-۲۲۰۰) مجموعی حیوی کیمت (۱۳-۶۹-۱۱ ٹن فی ہیکٹر) اور پیداوار (۵۵-۱۱ ٹن فی ہیکٹر) زیادہ درجے کی سطح آبپاشی میں حاصل کئے گئے جو درمیانی و کم سطح آبپاشی کے متناسب ہندرتج کم ہوتے گئے۔ اس کی کاسب اشاریہ برادشت (پیداوار لمحاظ مجموعی حیوی کیمت) اور مونوجروں کی فی ایکٹر تعداد میں کمی تھا۔ پانی کے کم استعمال (درمیانی و کم سطح آبپاشی میں) سے مقامی اقسام کے مقابل غیر مقامی اقسام کی (آبی) پیداوار زیادہ رہی۔

خلاصہ بحث: ایسے علاقہ جات جہاں دستیاب قابل کاشت زمین میں چاول اگانے کے رستے میں پانی کی شدید کمی حائل ہے وہاں خشک طریقہ کاشت اپنانے سے پانی کو بہتر طریقے سے استعمال کیا جاسکتا ہے۔ مزید برآں ان تجربات کے نتیجے میں حاصل ہونے والی (آبی) پیداوار میں مزید بہتری کی گنجائش موجود ہے۔

اس کے بعد میں نے مختلف سطح آبپاشی اور شرح نائٹروجن پر مقامی اقسام کے اعداد و شمار کا تجزیہ کیا۔ بالخصوص نائٹروجن کے حصول کے لئے تعامل آبپاشی، نائٹروجن، قسم پودوں پر کیسے اثر انداز ہوا (باب سوم)۔ فصل کی کارکردگی کیلئے بالعموم اور نائٹروجن کے حصول کے لئے بالخصوص سطح آبپاشی کا واضح اثر دیکھا گیا۔ جبکہ اقسام بھی ایک دوسرے سے مختلف پانی گئیں، کے ایس کے ۱۳۳ کی زیادہ سے زیادہ مجموعی جوی بہت ۱۳ ٹن فی ہیکٹر رہی جو زیادہ سطح آبپاشی پر ۲۲۰ کلوگرام نائٹروجن فی ہیکٹر ڈالنے سے حاصل ہوئی۔ زیادہ سے زیادہ پیداوار ۵۱ ٹن فی ہیکٹر رہی جو زیادہ درجہ آبپاشی پر ۱۲۰ کلوگرام نائٹروجن فی ہیکٹر ڈالنے سے حاصل ہوئی۔ حیران کن طور پر نائٹروجن کھاڈا لے کے باوجود نائٹروجن کے حصول پر کوئی فرق نہ پڑا۔ البتہ آبپاشی سے نائٹروجن کا حصول بڑھانے میں پودوں کو مدد ملی۔ نائٹروجن کے حصول کی مقدار (کلوگرام فی ہیکٹر) ۲۰۰۹ میں ۳۳ (کم درجہ آبپاشی) سے ۱۲۶ (زیادہ درجہ آبپاشی) کے درمیان رہی جبکہ ۲۰۱۰ میں ۵۲ سے ۱۲۳ کے درمیان رہی۔ نائٹروجن کھاڈ کے ضیاع سے یہ نتیجہ اخذ کیا جاسکتا ہے کہ پانی، افرادی قوت اور توانائی کے ماحولیاتی و کھیتی استعمال کا خلیزہ زمینی نائٹروجن اور نامیاتی مادے میں تحفیف کی صورت بھگتنا پڑے گا۔ لہذا نائٹروجن کے موثر استعمال کے لئے ایسی حکمت عملی درکار ہے جس کے تحت ضروری عوامل (جیسے زمین میں پانی کی دستیابی اور فصل کی ضروریات) کو مد نظر رکھتے ہوئے صحیح وقت پر کھاڈ ڈالی جائے۔

ارتقائی نشوونما کی درست تصویر کشی وسائل کی رسد و طلب میں مطابقت پیدا کرنے کے لئے اہم ہے۔ ارتقائی نشوونما اور ماحول کے تعامل کی سمجھ بوجھ نا موافق حالات میں وسائل کے کھٹی استعمال کے لئے اشد ضروری ہے۔ ضیائی دورانیہ اور درجہ حرارت کے آزادانہ اثرات کو سمجھنے کے لئے میں نے ایک دوگام حکمت عملی اختیار کی (باب چہارم)۔ ضیائی دورانیہ کے اثرات کا جائزہ لینے کے لئے میں نے پودوں کے باہمی تبادلے پر مشتمل تجربہ کیا۔ مصنوعی ماحول کے اس تجربے میں خانہ نشوونما کے اندر ایک مقررہ درجہ حرارت (۲۶ درجہ سیلسس) پر متغیر ضیائی دورانیہ فراہم کئے گئے (پہلے مرحلہ) تصوراتی و عملی، ہر دو حوالہ سے، ارتقائی نشوونما کو بعینہ ماپنے میں دوگام حکمت عملی کامیاب رہی۔ مصنوعی ماحول میں کئے گئے تجربات کے نتیجے میں ضیائی اثرات کی متعین مقداروں کا حصول ممکن ہوا جو کہ ہر طرح کے ماحول میں کارآمد ہے۔ علاوہ ازیں یہ بھی معلوم ہوا کہ زیر مطالعہ اقسام ضیائی دورانیہ کے لئے بہت زیادہ حساسیت رکھتی ہیں۔ اثرات درجہ حرارت کی مقدار میں متعین کرنے میں دو ماڈل، جرس و دو خطی، مرکوز نہ ہو سکے۔ غالباً اس کی وجہ فصلاتی تجربات میں کم انحراف درجہ حرارت ہے۔ تجزیہ حساسیت سے واضح ہو گیا کہ اگاؤ سے لیکر پھول بننے کے عمل تک کی مدت کا تخمینہ لگانے کے لئے ماڈل میں مستعمل معیاری اساسی درجہ حرارت (۸، ۳۰، ۴۲ درجہ سیلسس) ناموزوں ہیں۔ غلط تخمینے کا رجحان بالخصوص ۳۱ درجہ سیلسس کے ارد گرد دیکھا گیا۔

بنیادی طبعی و حیاتیاتی تحقیق کے ساتھ صوبہ پنجاب میں تین اہم فصلاتی نظام (چاول-گندم، کیرا، فصلاتی، کپاس-گندم) کے کاشتکاروں کی عمومی رائے کا جائزہ لیا گیا (باب پنجم)۔ اس ضمنی تحقیق کا مقصد آنے والے وقتوں میں خشک طریقہ کاشت اختیار کرنے کی بابت کاشتکاروں کے نقطہ نظر سے واقفیت حاصل کرنا تھا۔ زیادہ تر کاشت کار حضرات خشک طریقہ کاشت کے وجود اور ممکنہ فوائد سے بے خبر تھے البتہ انھوں نے اس طریقہ کار کی آزمائش میں گہری دلچسپی کا اظہار کیا۔ کاشت کاروں کی نظر میں یہ غیر روایتی نظام وسائل کے کھٹی استعمال کی صلاحیت رکھتا ہے، خاص کر پانی اور افرادی قوت کے لئے۔ دوسری طرف ممکنہ خطرات کا تعلق اس نظام سے کاشتکاروں کی ناواقفیت اور مہارت کی کمی تھا۔ خشک طریقہ کاشت جڑی بوٹیوں، بیماریوں، کم اگاؤ، اور دانہ بننے کے عمل میں رکاوٹ جیسے مسائل سے بچنے کے لئے زیادہ توجہ طلب نظام ہے۔ کچھ کاشتکاروں نے آزمائشی طور پر خشک طریقہ کاشت کے شرائط کی تجربات میں حصہ لیا۔ ان میں سے مجموعی طور پر ۳۷ فیصد کاشتکاروں کی رائے مثبت رہی اور وہ دوبارہ آزمائش کرنے کے لئے راضی تھے۔ خاص کر ایسے زمیندار حضرات جو بڑے رقبے

کے مالک تھے یا جن کی زمینیں زیادہ دیر تک پانی جذب رکھنے کی صلاحیت رکھتی ہیں۔ اس غیر روایتی پیداواری نظام کی راہ میں حائل ایک بڑی رکاوٹ موزوں باسستی اقسام کی عدم دستیابی ہے۔ کاشت کاروں کے زاویہ نگاہ سے واقفیت نے خشک طریقہ کاشت سے جڑے مواقع اور اندیشوں کی نشاندہی کرنے میں مدد دی جو کہ درج ذیل ہیں۔

موزوں باسستی اقسام، انتظام امور فلاح، مشینی کاشت و علائی، جڑی بوٹیوں کے تدارک کے لیے ایک مستعد نظام، معیاری حیات کش ادویات کی دستیابی، تو سمیعی منصوبے اور موزوں علاقہ جات کی نشاندہی۔ اس غیر روایتی پیداواری نظام کی توسیع و کامیاب فروغ کے لئے کام کرنے والے متعلقہ ادارے مندرجہ بالا تحقیق کی روشنی میں تجویز کئے گئے رہنما اصولوں سے فائدہ اٹھا سکتے ہیں۔

میں نے آخری باب میں فصلاتی کارکردگی، ارتقائی نشوونما کی تصویر کشی اور کاشتکاروں کی رائے پر مشتمل اس مقالے کے چیدہ چیدہ نتائج کا نچوڑ پیش کیا ہے۔ عمومی بحث کے تناظر میں یہ نتائج بطور خاص غذائی تحفظ، مجموعی پیداوار برقرار رکھنے کے لئے اقدامات، وسائل کے ماحولیاتی و کفٹی استعمال اور نئی اقسام کی دریافت کے لئے مضمرات رکھتے ہیں۔ سیدھی، بجائی و خشک طریقہ کاشت پر مشتمل پیداواری نظام (آبی) پیداوار میں بہتری لانے کے لئے ایک معقول حکمت عملی ہے۔ توقع کی جاتی ہے کہ پانی کی پخت کے ساتھ ساتھ افرادی قوت و توانائی کے کفٹی استعمال میں بھی بہتری آئے گی۔ روایتی نظام کے متبادل خشک طریقہ کاشت اپنے اندر بے پناہ امکانات سمیٹے ہوئے ہے۔ تاہم مطلوبہ مہارت کی ضروریات کو مد نظر رکھتے ہوئے یہ کوئی "گیدڑ سنگھی" نہیں ہے۔ یقیناً بھرپور مواقع کے ساتھ ساتھ کچھ اندیشے بھی لاحق ہیں۔ جن کا تعلق طبعی و حیاتیاتی اور سماجی و تکنیکی، پہلوؤں سے ہے۔ پانی، افرادی قوت اور توانائی کا کفٹی استعمال زمینی نائٹروجن اور فی ایکڑ پیداوار میں کمی کا باعث بن سکتا ہے۔ علاوہ ازیں حیاتیاتی عوامل مثلاً جڑی بوٹیاں، بیماریاں اور نقصان دہ کیڑوں کے تدارک کے لئے حیات کش کیمیائی ادویات پر انحصار بڑھ جائے گا۔ ان مسائل کے موثر حل کے لئے مستعد و مربوط حکمت عملی تیار کرنا اشد ضروری ہے۔ اس موضوع پر مزید تحقیق اور کاشت کاروں کی تربیت، علمی خلا کو پر کرنے کے علاوہ بہتر پیداوار کے لئے فلاح کے بنیادی اصولوں کے مطابق ایک جامع حکمت عملی ترتیب دینے میں مدد و معاون ثابت ہوگی۔ مزید برآں خشک طریقہ کاشت کے فوائد حاصل کرنے کے لئے موزوں اقسام کی دریافت پر فی الفور کام کرنے کی ضرورت ہے۔ اس سے ان علاقہ جات میں چاول کاشت کرنا ممکن ہو گا جو اس سے پہلے اس مقصد کے لئے ناموافق سمجھے جاتے ہیں۔ میں نے آخری باب کے اختتامیہ میں اس موضوع کے حوالے سے مستقبل میں مختلف تحقیقاتی ستوں کی نشاندہی کی ہے۔

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List of Publications

- Awan, M.I., Bastiaans, L., van Oort, P.A.J., Ahmad, R., Ashraf, M.Y., Meinke, H., 2013. Nitrogen use and crop performance of rice (*Oryza sativa* L.) under aerobic conditions in a semi-arid subtropical environment. Accepted in Agronomy Journal.
- Awan, M.I., van Oort, P.A.J., Bastiaans, L., van der Putten, P.E.L., Yin, X., Meinke, H., 2013. A two-step approach to quantify photothermal effects on pre-flowering rice phenology. Accepted subject to revision in Field Crops Research.
- Awan, M.I., van Oort, P.A.J., Ahmad, R., Bastiaans, L., Meinke, H., 2013. Transformation of transplanted flooded rice system to direct seeded aerobic rice system: the farmers' perspective. Accepted subject to revision in Land Use Policy.
- Awan, M.I., Bastiaans, L., van Oort, P.A.J., Ahmad, R., Ashraf, M.Y., Meinke, H., 2013. Water use and crop performance of rice (*Oryza sativa* L.) under aerobic conditions in a semi-arid subtropical environment. Under review in European Journal of Agronomy.
- Meinke, H., Bastiaans, L., Bouman, B.A.M., Dingkuhn, M., Gaydon, D.S., Hasegawa, T., Heinemann, A.B., Kiepe, P., Lafarge, T., Luquet, D., Masood, A., Möller, C., van Oort, P., Rodenburg, J., Yan, J., Yin, X., 2009. Adaptation of rice production under climatic constraints, EU-ASEAN Science and Technology Dialogue, Bogor, Indonesia, 11-12 November 2009.
- Meinke, H., Bastiaans, L., Bouman, B.A.M., Dingkuhn, M., Gaydon, D.S., Hasegawa, T., Heinemann, A.B., Kiepe, P., Lafarge, T., Luquet, D., Masood, A., Möller, C., van Oort, P., Rodenburg, J., Yan, J., Yin, X., 2009. An international collaborative research network helps to design climate robust rice systems, Keynote Paper from International Workshop on Crop Production under Heat Stress – Monitoring, Impact Assessment, and Adaptation, Tsukuba International Congress Centre, Tsukuba, Ibaraki, Japan, 5-9 October 2009. Published in Hasegawa T. and Sakai H., eds. 2009. Crop Production under Heat Stress: Monitoring, Impact Assessment and Adaptation. Proceedings of the MARCO Symposium 2009 held in Tsukuba, Japan, 5-9 October 2009. Tsukuba (Japan): National Institute for Agro-Environmental Sciences (NIAES).

Publications

- Hussain, A., Nadeem, A., Ashraf, I., Awan, M., 2009. Effect of weed competition periods on the growth and yield of Blackseed (*Nigella sativa* L.). Pakistan Journal of Weed Science Research, 15(1): 71-81.
- Ahmad, R., Awan, M., Waraich, E., Ashraf, M.Y., 2009. Sunflower response to foliar application of urea and integrated foliar fertilizers under water stress conditions. Abstract; In: International conference of sustainable food grain production: opportunities and challenges, 20-22 October, 2009, p. 3.
- Awan, M., Meinke, H., 2008. Aerobic rice for better resource use efficiency. Poster Presentation; In: Resource Capture by Crops: Integrated Approaches, University of Nottingham, 10-12 September, 2008.

PE&RC PhD Training Certificate

With the educational activities listed below the PhD candidate has complied with the educational 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 (5.7 ECTS)

- Aerobic rice for better resource-use efficiency

Writing of project proposal (4.5 ECTS)

- Improving resource-use efficiency in rice-based systems of Pakistan

Post-graduate courses (3 ECTS)

- Basic statistics; PE&RC (2011)
- Imaging science; PE&RC (2012)

Invited review of (unpublished) journal manuscript (2 ECTS)

- European Journal of Agronomy: Crop management for optimal low-linolenic rapeseed oil production – Field Experiments and modelling (2010)
- International Journal of Agriculture and Biology: evaluation of CSM-CERES-Maize for irrigation scheduling of maize under semi-arid conditions of Punjab (2012)

Deficiency, refresh, brush-up courses (3 ECTS)

- Crop ecology (2008)
- Technology and ecology of crop production (2008)

Competence strengthening / skills courses (4.5 ECTS)

- Information literacy including Endnote; WGS (2008)
- Interpersonal communication for PhD students; WGS (2008)
- Career assessment; WGS (2011)
- Project and time management; WGS (2011)
- Mobilising your scientific network: WGS (2011)
- Techniques for writing and presenting a scientific paper; WGS (2011)
- Interdisciplinary research: crucial knowledge and skills; WGS (2011)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)

- PE&RC Weekend (2008)
- Modelling symposium: 20 years theory and model at Wageningen UR (2008)
- PE&RC Day (2009)

Discussion groups / local seminars / other scientific meetings (5 ECTS)

- Discussion group PPS (2008-2013)
- Plant and soil interactions (2010-2012)
- Biochar: the soil is the limit (2012)

International symposia, workshops and conferences (3.8 ECTS)

- Resource Capture by Crops: integrated approaches (2008)
- Inception meeting on improving the robustness, sustainability, productivity and ecoefficiencies of rice based systems throughout Asia (2013)

Curriculum Vitae

Masood Iqbal Awan was born in Khushab, Pakistan on 7 September 1984. There, he attended Government High School Har Do Sodhi and Degree College Jauharabad for his primary and higher secondary education, respectively. Then, he commenced a Bachelor of Sciences (Agriculture) degree at the University of Agriculture, Faisalabad (UAF), graduating in 2005. During his internship at the Adaptive Research Farm, Sargodha, as part of bachelor studies, he gained practical farm experience related to greenhouse and field crops. In 2007, he finished his Master of Sciences (Agronomy) degree at UAF. For his master thesis, he investigated sunflower (*Helianthus annuus* L.) response to foliar fertilisation under water stress conditions. He got an offer for MS leading to PhD scholarship funded by the Overseas scholarship programme of Higher Education Commission, Pakistan. In November 2007, he relocated to the Netherlands to start his PhD at the Centre for Crop Systems Analysis, Wageningen University. During his PhD, he conducted detailed field experiments, phytotron studies, and farmer surveys to investigate the aerobic rice system as an option for improving resource-use efficiency. He also actively engages with rice researchers through an international collaborative network on rice.

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