Entry points for eco-efficient aerobic rice production system in Punjab, Pakistan

M.I. Awan[1], H. Meinke[2], P. van Oort[3], L. Bastiaans[3]

[1] Department of Agronomy, University of Agriculture, Faisalabad (UAF) 38040, Pakistan, masood.awan@uaf.edu.pk
[2] Tasmanian Institute of Agriculture (TIA), University of Tasmania, Hobart TAS 7005, TAS
[3] Centre for Crop Systems Analysis (CSA), Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands

Abstract
Major issues challenging the sustainability of conventional flooded rice systems in Pakistan are: low input conversion efficiencies, productivity stagnation, rising costs of production, and shortage of water, labour, and energy. An emerging opportunity is an alternative, eco-efficient production system called 'aerobic rice', which entails the growing of direct-seeded crops in non-puddled fields under non-flooded conditions. Eco-efficiency is about achieving more agricultural output per unit of input, through substitution of production factors including knowledge. We evaluated the aerobic rice system in Punjab, Pakistan from biophysical and socio-technological perspectives employing a combined approach of experimentation (i.e. field trials on resource-use efficiencies and growth chamber studies on phenology) and farmer surveys. Our findings suggest that the aerobic rice system is a rational approach for improving the eco-efficiencies of water, labour, and energy. However, for subtropical conditions, the knowledge-intensive system is still very much in the development phase, thus requiring a thorough understanding of the entry points (i.e. opportunities and threats). Based on our findings, the entry points for aerobic rice systems are: availability of fine grain *basmati* varieties; savings on water, labour, and energy; net profitability; extension outreach programmes to raise awareness among farmers; good quality biocides; prospective areas for crop diversification; optimisation of agronomic practices such as seed rate, water, and fertiliser inputs; land levelling; and mechanical interventions for appropriate seeding and weeding. In order to balance production and sustainability, risks of crop failure can be reduced by optimisation of scarce resources and provision of suitable genotypes.

Key words
Resource-use efficiency; rice systems; transformational technology; Punjab; Pakistan.

Introduction
Water is becoming scarcer than land in Pakistan. Water productivity of different crops is among the lowest in the world. Current practices in some parts must transition to water-saving systems for sustainable crop production, in particular for *'water-guzzling'* crops like rice. Rice crop, essentially grown on irrigated fields in Pakistan, covers 2.6 million hectares (Mha) with an annual production of about 6 million tonnes. Rice-based cropping systems are rice-wheat, rice-berseem, rice-pulses, rice-vegetables and rice-fallow (GOP, 2014; Chapagain and Hoekstra, 2011). The rice-wheat system covers 2.2 Mha and is the second largest cropping system after cotton-wheat. 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. (Ahmad *et al.*, 2007). The stagnation of productivity threatens the sustainability of intensive systems via the degradation of soil and water resources. Water shortage, low plant population per unit area due to labour shortage at critical time of transplanting, falling water tables and concomitant rise in energy requirement for pumping groundwater are the major limitations for rice production. With low income generating ability and low conversion efficiencies for the scarce inputs, the conventional transplanted-flooded rice system is now showing its limitations for resource poor farmers. (Farooq *et al.*, 2011; Ladha *et al.*, 2003).

Emerging global resource constraints have led to a renewed focus on improving the overall eco-efficiencies of agricultural systems (Keating *et al.*, 2010). 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. An emerging opportunity is an alternative and eco-efficient productions system called 'aerobic rice'. Aerobic rice entails the growing of direct-seeded rice crop in non-puddled fields under non-flooded conditions throughout the growing season. We used the term ‘aerobic rice system’ for the whole package of agronomic practices and biophysical and socio-economic boundary conditions. Aerobic rice could considerably improve eco-efficiencies in rice-based systems where water, labour, and energy are becoming increasingly scarce. The aerobic rice system is gaining momentum in South Asia as an alternate to the conventional transplanted-flooded rice system (Mahajan *et al.*, 2013). Under Pakistani conditions, water economy is the main driver behind aerobic rice systems. Changing the current production system to non-flooded aerobic rice could considerably increase resource use efficiencies. However, for subtropical conditions, such as those in Pakistan, the non-conventional system is still very much in the development phase.

Aerobic rice systems are knowledge-intensive thus requiring careful management interventions, heavily relying on biocides for managing weeds and nematodes. Essential plant nutrients (e.g. N, P, K, Fe, Zn, and Mn) may become deficient under aerobic conditions (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. In this paper we outline the main entry points (i.e. opportunities and threats), which are critical for further technology development and dissemination.

Approach

This paper is based on an interdisciplinary project (Awan, 2013). In the interdisciplinary project, we employed a combined approach of experimentation and farmer surveys to contribute important information on aerobic rice crop performance, preflowering 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 three local (KSK133, IR6, RSP1) and two exotic (Apo, IR74371-54-1-1) genotypes against different combinations of irrigation levels (Total water input through irrigation and rainfall in 2009-10: 1278-1318 mm (high), 934-979 mm (moderate), 701-938 mm (low)) and nitrogen (N) rates (0, 170, 220 kg N/ha) under aerobic conditions. The experimental site lies in the non-traditional rice belt, which is an important target domain for aerobic rice. 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, we used a two-step approach. The PP-response was determined in growth chambers, through a reciprocal transfer experiment with variable daylength (10, 12.5 and 15 h/d) 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. To supplement the basic biophysical research, we conducted farmer surveys in three major cropping systems of Pakistan Punjab viz. rice-wheat, mixed-cropping and cotton-wheat to understand farmers’ views about the future prospects of aerobic rice system. Respondents (n = 215) were grouped using two criteria: (1) their current cropping system and (2) their experience with rice and specifically aerobic rice system. The second criterion led to a distinction between three groups: group I (n = 70) were informant farmers from the rice–wheat system who had tried aerobic rice in a participatory research trial in 2010; group II (n = 97) were rice-growing farmers from each cropping system who did not participate in the trials; group III (n = 48) were non-rice-growing farmers with experience in mixed-cropping or the cotton–wheat cropping system (Awan et al., 2015). Based on the results of the interdisciplinary project and relevant information on aerobic rice experiences in other parts of the world, we have identified the key entry points in this paper.

Key findings and their implications

Eco-efficiencies of water, N, labour, and energy

Grain yield (GY) is a basic measure of eco-efficiency. The GY levels of tested genotypes were generally within the target GY of 4–6 t/ha for aerobic rice systems i.e. 80% GY attainable under transplanted-puddled rice system. Under aerobic system, the GY penalty in Pakistan and India ranged between 7.5–28.5% (Kumar et al., 2011). The exotic genotypes (Apo and IR74371-54-1-1) better coped with water stress, clearly lowering the risk of obtaining low GY. Under different irrigation regimes, the exotic genotypes recorded GY (t/ha) levels of 4.34 (high), 3.57 (moderate), and 2.64 (low) respectively as against the GY levels (i.e. 4.56, 2.55, 1.78) of the benchmark local genotype KSK133. The exotic genotypes clearly lower the risk of obtaining low GY under water stress conditions but under more optimal water supply conditions the local genotype

KSK133 was better. Under aerobic system, we found water productivity (WP_g; g grain/kg 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 in Pakistan. 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, which might save farmers three to four irrigations and also reduce energy requirements for pumping groundwater through diesel or electric pumps. Farmers ranked labour savings in direct-seeded aerobic system higher than water saving. Under subtropical, semiarid conditions as in Pakistan, producing more rice per unit area and with less water is rarely possible: reduced water input in our study increased WP_g but decreased the GY compared to the flooded system. Pakistan is one of the most water-stressed countries in the world, hence aerobic systems are more advantageous in terms of saving both water and labour compared to the direct seeded rice systems, which mainly focus on labour saving. The GY was positively correlated with total N uptake but we found small differences between the three N application rates, which suggest that a significant amount of the applied N was not taken up by the crop. The process of alternate wetting-drying is known to stimulate the 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 were a major factor in the overall N balance (Awan et al., 2014). In aerobic systems, the improved eco-efficiencies of water, labour, and energy might happen at the cost of declined efficiencies for N and land.

Resource-use in relation to phonological development
All four tested genotypes (KSK133, RSP1, Apo and IR74371-54-1-1) were PP-sensitive. The crop duration (i.e. sowing to maturity) extended under aerobic conditions. The extended crop duration under aerobic conditions is probably one of the reasons for failure of long duration fine grain *basmati* genotypes under limited irrigation regimes like aerobic rice. Since the crop duration has direct implications for resource use and the sowing window, aerobic rice genotypes should be early-maturing. The significant variation in optimal flowering time and PP-sensitivity among tested genotypes could be exploited by breeders to develop genotypes that can avoid adverse environmental conditions such as pre- and post-monsoon drought. 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.

Farmers' perspective
More than half of respondents never heard of aerobic rice; yet most of them (76%) were positive about trialling the non-conventional aerobic rice system. 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. Other positive attributes were: ease of operation due to direct seeding instead of laborious puddling and transplanting activities; good income; improved physical condition of the soil. The negative attributes or the associated risks were: weed infestation; diseases; increased spikelet sterility; poor germination; higher irrigation frequency; more seed rate; unavailability of suitable varieties; GY penalty (Awan et al., 2015). The greater water use efficiencies (yield per unit of water) are often associated with lower land use efficiencies (yield per unit of land). 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.

Entry points for aerobic rice systems
To feed over nine billion people by 2050, agricultural systems will rely on transformational technologies. For rational use of scarce resources, 'knowledge' as a production factor will play a decisive role. Aerobic rice is a knowledge-intensive technology that requires precise/timely management practices. Identifying the knowledge-based entry points can answer this basic question: how can aerobic rice technology pick up momentum to be able to spread in the target domains? Our interdisciplinary study underpins the potential for increasing use-efficiency of scarce resources of water, labour, and energy. However, the aerobic rice technology is still evolving and much needs to be done to increase its adoption rate. Identification of the technological and knowledge gaps can value add to the on-going research on water-saving rice cultivation. Farmers need to be educated through extension activities to raise awareness about the non-conventional

system and to tackle the associated risks like weed infestation. Field level studies on resource-conservation technologies documented the potential for water saving. To upscale the results at basin level, there is a need to adopt the required precursor technologies (e.g. laser land levelling) and to identify alternate uses of saved water. For example, the saved water can be used rationally for bringing more area under rice cultivation, thus compensating for yield penalty under aerobic rice systems. With the extension of irrigation system e.g. development of a 'Greater Thal Canal' in a region supporting pulses-based cropping systems, there is a need to identify alternate crop rotations, which might give a niche for aerobic rice systems.

Improved eco-efficiencies of water, labour, and energy might happen at the cost of declined efficiencies for N and land. Eco-efficient N management strategies (e.g. using composts and farmyard manure) and bringing the culturable wasteland under cultivation by provision of the saved irrigation water are some of the proposed measures for improving the productivity and sustainability of agricultural systems. Currently, the non-traditional rice belt of Punjab and Sindh province are the main target domains as coarse grain non-basmati varieties, which are comparatively better adapted to aerobic conditions, are grown there. In the typical rice belt of Punjab, the abode of world's famous aromatic *basmati* varieties, non-availability of well-adapted aerobic varieties of *basmati* rice is a major constraint for expansion of the aerobic rice systems. The on-going breeding efforts should screen rice germplasm for developing *basmati* varieties adaptable to heat and water stress conditions. Based on the results of farmer surveys, farmers already growing rice, in particular those having large size of landholding and farms with clayey soil types are most likely to be early adopters of the technology. Introduction and dissemination of aerobic rice technology will depend on filling the technological gaps: mechanical interventions for seeding and weeding; good quality biocides; optimisation of agronomic practices such as seed rate and balanced nutrition; quantitative estimation of potential areas for intensification or crop diversification.

Conclusion

Aerobic rice is a viable eco-efficient option to improve water productivity in regions like Pakistan where water is getting scarcer than land. The developing technology will benefit from well-informed knowledge-based entry points to fill the identified technological and attitudinal gaps.

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