Rice crop innovations and natural-resource management — A glimpse into the future

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Abstract

Rice is and will be the major global food crop. Cultivars, rice-based cropping systems and the rice itself will have to undergo adaptations and improvements in order to meet future demands for both food security of the growing population and environmental conservation. Growing more food will increase the pressure on natural resources such as land, water and nutrients, which must be used efficiently and sustainably. The challenge posed by imminent climate change forces the speeding-up of the innovation process, which will require collaboration by a large number of scientific disciplines and stakeholders. Rice's path into the future will have to follow several parallel lanes. On one hand, we cannot slacken our efforts to improve existing cropping-systems management to decrease the gap between potential and current productivity. On the other hand, we need to increase our knowledge base of the genomic, proteomic and metabolic make-up of rice to pave the way for future innovations through genetic-engineering based on in-depth knowledge of physiological processes. A third highly important approach is to maximize productivity in clearly defined high-input environments, such as irrigated rice and intensive rainfed production, using a strong systems approach. Another parallel approach must focus on the low-intensity production systems and those environments most vulnerable to changes in climate. Here, in contrast to the intensive systems, genotypic elasticity and region-specific management options need to be exploited to ensure a secure level of production in highly variable environments and those undergoing transition. Finally, existing networks addressing some or all of these options should be more tightly knit to increase information flow among, and the innovative power of, the scientists involved. This includes a strong focus on scientific capacity-building through North–South collaboration in research and education, with a strong role of the Consultative Group on International Agricultural Research in streamlining the combined efforts.

Factors influencing rice production systems

Rice production systems are highly diverse, ranging from fully irrigated systems via semi-water-controlled rainfed lowland systems to fully rainfed upland systems, with a multitude of different management practices and options. All rice systems are influenced by a multitude of controllable and uncontrollable factors (Fig. 1). Among the more prominent uncontrollable factors influencing productivity via demands and constraints are global changes in market access and commodity trade, population growth and, more recently, effects of climate change. Increase and application of knowledge through networks, research activities, and capacity-building via training and education, directly influence cropping-systems management with a slow but increasingly positive effect on rice production systems. Increasing information available on the genetic makeup of rice genotypes and varieties, along with improved knowledge of the phenotypic responses to environmental and management factors, enables better-informed management practices in cropping systems. Rice production systems are influenced either directly through improved local knowledge or indirectly through better-targeted research and capacity-building. Breeding and the development of targeted genetically modified rice genotypes increase the options and the potential for addressing constraints specific to production systems based on their resource-use level (high-input systems vs. low-input systems). Whereas high-input systems produce the nutrition base for millions of people on relatively small production areas, low-input systems cover larger areas (by several magnitudes), but provide the livelihood base for millions of the rural poor. It is evident that these contrasting systems need to follow different approaches in addressing rice productivity in the context of global and uncontrollable constraints.

Although we cannot slacken our efforts to improve the management components of the different rice production systems — for example, in seed distribution systems, post-harvest technologies, nutrient application and use, as well as conservation of soil organic matter — new technologies need to be developed that are based on sustainable and resource-conserving combinations of genotypes, their efficiency and their responses to environment including, where needed and useful, genetically modified organisms (GMOs).

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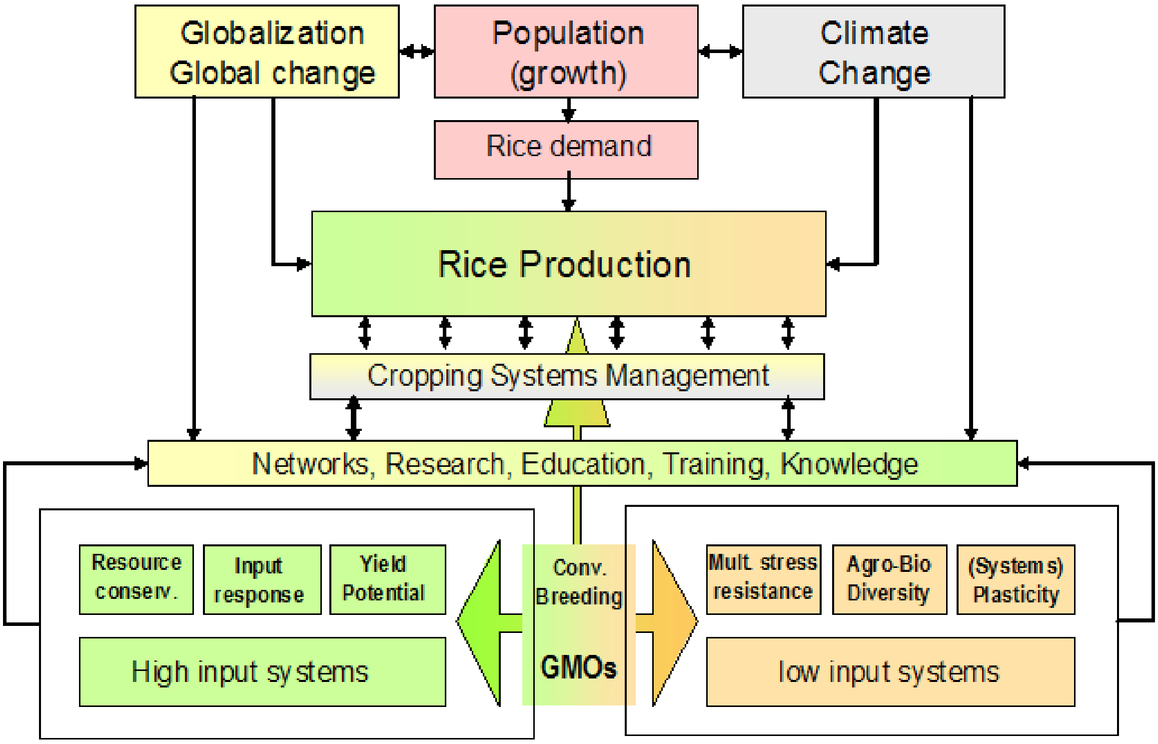

Figure 1. Schematic overview of factors influencing rice demand, rice production and management of rice-based systems (see text for details)

New drivers for development

Population growth directly influences global demand for rice. On this basis, demand will continue to increase until at least the middle of the 21st century (Fig. 2 left). Global figures (Fig. 2) indicate that production is very close to consumption and that there have been and will be years in which consumption exceeds production (e.g. the early 1990s and early 2000s), leading to a severe depletion of grain stocks. Thus, production in the years following poor production years must compensate for the reduction in stock as well meeting current needs, which was not achieved during the late 2000s, leaving the global rice market vulnerable to price hikes (as observed in 2008) that threaten the food security of millions. Global production and consumption figures lead to a distorted picture regarding regional constraints to food security. Figure 2 (right) shows rough rice production of eight major rice-producing countries with different production systems over the five decades from 1960. Whereas some countries, such as the USA and Egypt, achieve yields of 4 to 5 times the global average in medium- to high-input systems, others such as India and Côte d'Ivoire producing mainly in low-input systems, realize yields of 0.8 and 0.5 times the global average, respectively.

This clearly shows a split between productivity of low- and high-input systems and indicates that the drivers for developing those systems are of different strength. Subsistence-oriented systems are mainly labor and capital limited, but generally have sufficient access to resources such as land and know-how on the level needed for those systems. Systems in transition from subsistence to (local) market-orientation become increasingly land limited due to demographic growth, but have better access to labor. Increasing production with increasing inputs to meet the demands of a growing population renders the systems more and more land and labor limited and increases the need for capital and know-how, reducing the number of producers and increasing the level of non-farm income. Recently systems at all levels of evolution are facing additional constraints to which each system has to find specific responses. These new constraints emerge from globalization (reduction of distances between markets), climate change (vulnerability of production levels due to climatic constraints), energy availability and costs, as well as water use and availability (partly influenced by climate change). Since in each system of production (high input, low input) such drivers are effective at different scales, turning changes felt as constraints into opportunities for improving the agricultural and social productivity and sustainability of such systems requires region- and system-specific approaches. Some examples of how such approaches could be shaped are discussed below.

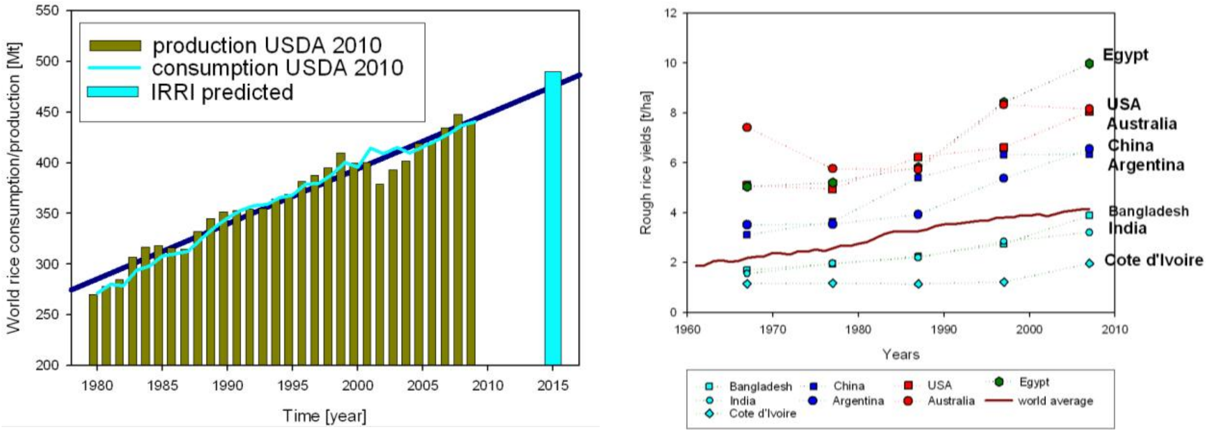

Figure 2. **Development of rice consumption and production** (USDA, 2010; IRRI, 2010)
Left graph: blue line = mean increase in rice production. Right graph: rough rice yields of selected rice producing countries as compared to the world average.

Maximize resilience in high-input systems

High-input systems (HIS) are the most productive in terms of yield per area. For example, irrigated agriculture accounts for 40% of global food production, even though it represents just 17% of global cropland (WMO, 1997, p 9). Thus, HIS ensure food security, particularly for staple food, on a global scale and cannot be allowed to suffer reductions in productivity due to climate change, energy or water shortages, nutrient deficiencies or any other lack of resources. All available resources should be invested in such systems to maximize productivity in a sustainable manner in order to ensure the resilience of the production systems. Creating a safety net against the effects of climate change requires multidisciplinary approaches to deal with changes in cropping cycles, water and nutrient efficiency, and cropping calendars.

Although a steady increase in rice yields and global production has been achieved since 1980 (Fig. 2 left), biological limits to yield potential will be encountered after traits such as fertilizer response, nutrient use efficiency, and water use efficiency have been fully optimized. Thus, developing stable genetically modified new rice types, for example rice with a C4 metabolism, may turn out to be the only possible approach if rice continues to be the staple food of the majority of the world's population. However, for the years to come, before such an ambitious goal may be achievable, rice cropping systems and in particular HIS leave sufficient room for improvement on many levels. Research in the 2010s must continue to concentrate on water and nutrient management, field and plot management, post-harvest technology improvement, as well as varietal improvement for cropping-calendar development. Multidisciplinary teams are needed to develop the models that will be required to fine-tune crop responses to changing environments with the aim of maximizing productivity and resilience in the HIS, while at the same time increasing knowledge of the links between genetic and phenotypic traits for future development of systems-targeted genotypes.

Maximize adaptation in low-input systems

Low-input systems (LIS) are (by definition) strongly constrained by a multitude of factors that cannot, in contrast to HIS, be overcome by additional inputs and these systems are in general most vulnerable to changes in climate. LIS need to respond to changes with adaptation, using new and innovative approaches in order to mitigate and avoid any negative effects (induced by changes) on the livelihood of the people depending on the systems outputs. Since rice-based LIS are very diverse and are located in a variety of agro-ecological zones from high-altitude areas in Nepal and Madagascar to the humid tropics in Indonesia and Brazil, options for adaptation need to target the specific local conditions. Thus, genotypic elasticity and region-specific management options need to be exploited to ensure a secure and sustainable level of production in such highly variable and transitional environments. In the following, we illustrate this approach with three examples on system-specific adaptations of germplasm.

Weed competition, genotypes, nutrient management

Upland rice systems are prone to weed infestation and thus weeds constitute a major threat to rice systems' productivity (Johnson *et al.*, 1998). Rice in its early growth phase predominately uses ammonium as major nitrogen source, whereas nitrate, even when available, is only taken up in minor amounts (Lin *et al.*, 2005; Li *et al.*, 2006). Rice genotypes having a highly active nitrate reductase may be more competitive against weeds, which thrive mainly on nitrate, due to better competition for the available nitrate. A study conducted at the Institute for Plant Nutrition at the University of Bonn showed that rice genotypes performed better against standard weeds when a low nitrate concentration was given during early growth (Fig. 3). The competitive index was highest for rice genotypes with a relatively high nitrate reductase activity in combination with a low nitrate dose during early growth (data not shown). These results indicate that, for LIS, genotypes with a strong early nitrate reductase activity should be selected, as they will be able to efficiently out-compete the weeds for nutrients, and that no nitrate fertilizer should be added to the system before the rice enters the active tillering stage to maximize N-use efficiency and the weed competiveness of the genotype (Ouko *et al.*, 2003).

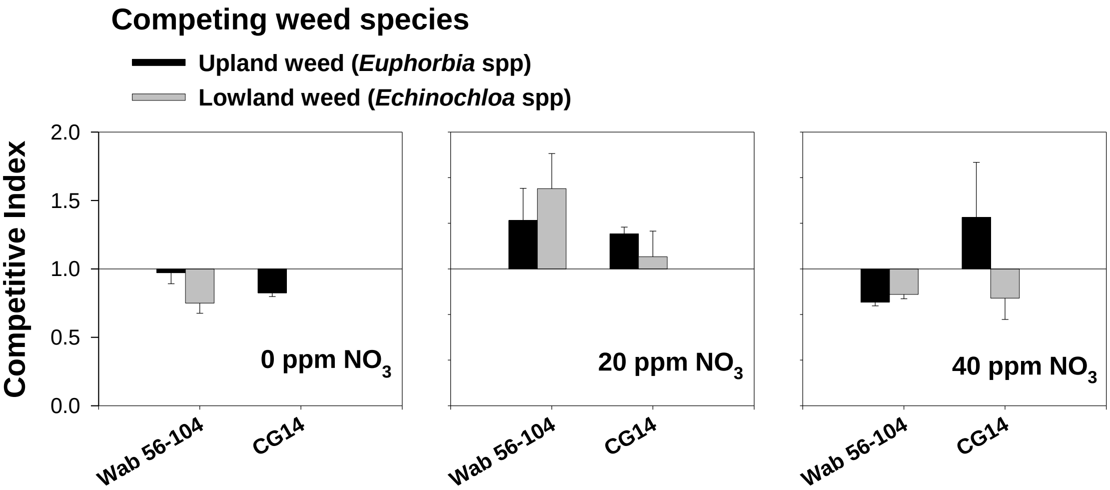

Figure 3. Rice genotypes (WAB 56-104; CG14) subjected to three levels of nitrate in the growing medium under competition with themselves or with either *Echinochloa* spp. or *Euphorbia* spp. in a replacement design.
The competitive index denotes the growth success relative to intraspecific competition (competitive index of rice alone = 1).
Source: Ouko *et al.* (2003).

The results of this study suggest a change in nutrient and genotype management for the adaptation of low-input, rainfed upland rice systems as well as a selection target (nitrate reductase activity) for the system-specific adaptation of upland rice genotypes.

High-altitude cropping, genotypes, chilling tolerance

Global warming is leading to changes in vegetation periods in high-altitude cropping systems (IPCC, 2007). Longer vegetation periods with higher mean temperatures create new opportunities for rice production at high altitudes and affects long-established cropping calendars (Shrestha *et al.*, 2011). Changes in potential planting dates require genotypes adapted to low temperatures during booting, as in this stage cold-induced floret sterility is the main yield-reducing factor in rice (Dingkuhn *et al.*, 1995).

A study conducted in the high-altitude (> 1700 masl) rice–wheat system of Nepal showed that out of 10 genotypes tested only two showed reduced spikelet sterility when mean temperatures during booting were below 17°C (Fig. 4; Shresta *et al.*, 2007). Thus, development of rice cropping options in environments hitherto unsuitable for rice needs newly developed rice genotypes with a high degree of chilling tolerance (Sthapit and Shrestha, 1991). There are no established selection tools available to screen the vast number of rice genotypes currently available for adaptive traits to such environments.

Lowland rice, genotypes, water-saving options

With increasing water scarcity and climate variability, the demand for water-saving crop production is growing. Irrigated rice is one of the largest consumers of fresh-water resources. Rising temperatures and shifts of seasons are already observed and are expected to increase. With a changing climate, adaptation of cropping calendars might be needed to lower water consumption and achieve stable, high yields. Saturated soil culture (SSC) is one option to reduce the irrigation-water input as compared to the conventional paddy system (CPS) and can reduce production costs (Stürz *et al.*, 2009).

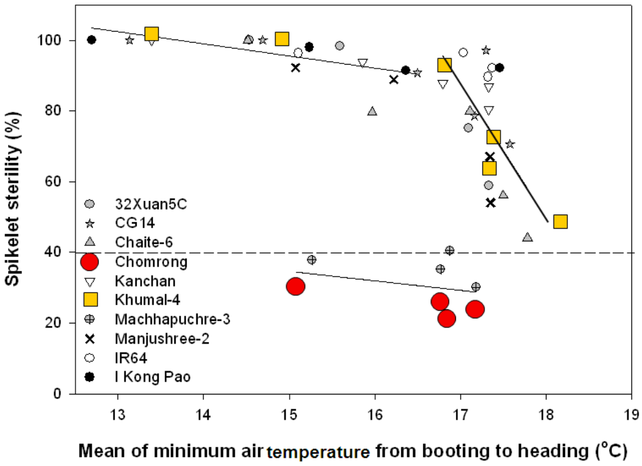

Figure 4. Relationship between spikelet sterility and the mean minimum air temperature between booting and heading stages, individually determined for each cultivar and date in Lumle, 2004. Except for Chomrong and Machhapuchre-3, other cultivars were broken down into two parts and the relations were linearly regressed taking Khumal-4 as a reference cultivar due to its spikelet sterility variation of about 45–100% within the range of less than 14° to 18°C mean minimum temperature from booting to heading.
Source: Shrestha *et al*. (2007).

A study at the Sahel station of the Africa Rice Center using 10 genotypes (Stürz *et al.*, 2008) showed that SSC can save up to 40% water on average over the season without affecting average yields (Fig. 5). However, the response of the individual genotypes involved in the study to SSC was highly variable. Largest amounts of water saved without affecting yield were observed in WAS 161 B-9-2 and Sahel 202 (approximately 300 mm per season), whereas the lowest amount of water saved was observed in Sahel 108 (approximately 50 mm per season; data not shown). Low water availability and changes in temperature at the growth meristem influence the phenology of the genotypes, inducing different genotypic responses. Thus, introducing water-saving technology into a rice production system must be accompanied by a genotype adapted to water-saving conditions.

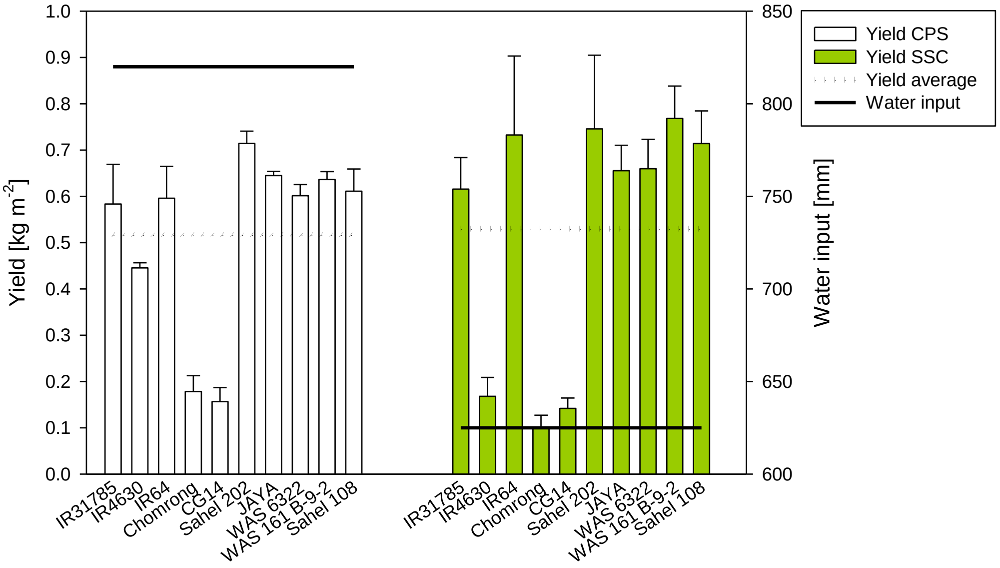

Figure 5. Comparison of yield of 10 rice genotypes cultivated in either the conventional paddy system (CPS) with a ponded water layer or in saturated soil conditions system (SSC) with the average seasonal yield across all genotypes and the average water input over the season (irrigation + precipitation) for the wet season 2008 in Ndiaye, Senegal.
Source: Schlegel (2009).

Capacity-building through international networks

The complexity of systems and their components, as well as the constantly increasing amount of knowledge and its management, no longer allow for singular-actor activities but urgently require concerted actions of qualified networks. Existing networks addressing some or all of the above options should be more tightly knit to increase information flow among, and innovative power of, the scientists involved. This includes a strong focus on scientific capacity-building through North–South collaboration in research and education, with a strong role for the Consultative Group on International Agricultural Research in streamlining the combined efforts. We need to include young scientists in multidisciplinary large-scale approaches, sharpening their visionary capacities, and instigate collaborations at all levels involving international agricultural research centers, national agricultural research systems (NARS), universities, private industries, NGOs, governmental organizations, and individual scientists and groups. Time is the major constraint here. Even if the projections for climate change effects by IPCC are only half reliable, changes will hit the poorest and most dependent members of societies within 10–30 years and the international scientific community needs to have some answers and approaches available by then.

Conclusions

Improvement in rice-based systems needs to be advancing rapidly. In order to address the multitude of avenues, clear system-specific activities must focus on a two-pronged approach: (1) Maximize the resilience of high-input systems so as not to lose a single one of their potential grains. This includes efforts to develop new high-yielding and nutrient-responsive genotypes, while at the same time mitigating any climate-change-induced stresses in those systems through appropriate management. (2) Maximize the adaptation capacity of low-input systems. This includes the choice of crops and cropping calendars suited to the changed climatic conditions, the diversification of the production base in order to mitigate the effects of extreme events such as drought and flooding, and concentration on sustainable management options to provide food and energy to rural areas in a long-term perspective (Asch and Huelsebusch, 2009). Increasing awareness and making sure the knowledge gets where it is most needed needs to include networks linking current research results to the people developing applicable technologies and those who are the targeted end-users of such innovations. This applies to both types of systems.

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