

An international collaborative research network helps to design climate robust rice systems

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Abstract: Rice is the world's most important staple food. Although mainly produced in Asia (91%), it is consumed on all continents and its global importance and consumption is increasing. The limited scope to expand production areas coupled with increasing resource constraints (mainly the lack of or competing demands for land and water) make it difficult to meet necessary production increases. Climate change in terms of increasing temperatures, more frequent droughts, anticipated loss of productive estuaries due to rising sea levels, more frequent and severe storms and rising CO₂ levels further compounds these problems. This constitutes a huge challenge for science, policy and farmers. The provision of effective solutions is complex due to the spatial-temporal dimensions that must be integrated when setting research, policy and management priorities. These challenges have motivated us to form a Community of Practice (CoP) of concerned scientists. We formed this CoP around the central theme of simulation modelling as a technology that allows integration of discipline-based component science across space and time. We also use modelling as an engagement tool with stakeholders and to connect seemingly disparate scientific disciplines. Here we put our Research for Development (R4D) activities into context and report on some of the research efforts that our CoP is currently involved in. In our quest to design locally-adapted, profitable and sustainable, climate-robust rice-based cropping systems, we welcome input from the wider, global R4D community.

Keywords: rice systems, modelling, resource use, food security, physiology, climate change

Rice is the staple food crop for about 3 billion people and feeds roughly half the planet's population. Approximately 750 million of the world's poorest people depend on rice to survive, according to IRRI (<http://beta.irri.org/news/images/stories/ricetoday/5-4/>). In 2007 global rice production reached 650 Mt; 91% of this production came from Asia (Table 1).

Table 1. World and regional rice production in 2007 (source: FAO).

Production	World	Asia	C & Sth America	USA	Africa	Europe	Australia
Mt	650	590	23.9	9.0	23.5	3.5	0.2
%	100	90.8	3.7	1.4	3.6	0.5	0.0

Global demand for rice is strong and will rise further as populations increase while the global food crisis continues [1]. Meeting this demand will require considerable production increases. Since the 1960s there has been a strong, near-linear trend in production, leading to a more than 3-fold increase in annual global production volume, made possible by the green revolution (mainly in Asia) and expansion of production area in nearly all regions (Fig. 1). Production trends for Africa show particularly strong increases with production volumes now equal to that of Central and South America (2007 figures, Table 1). At the same time production in the USA and Europe stagnated, while the Australian rice industry went into shutdown as a result of ongoing drought (Fig. 1).

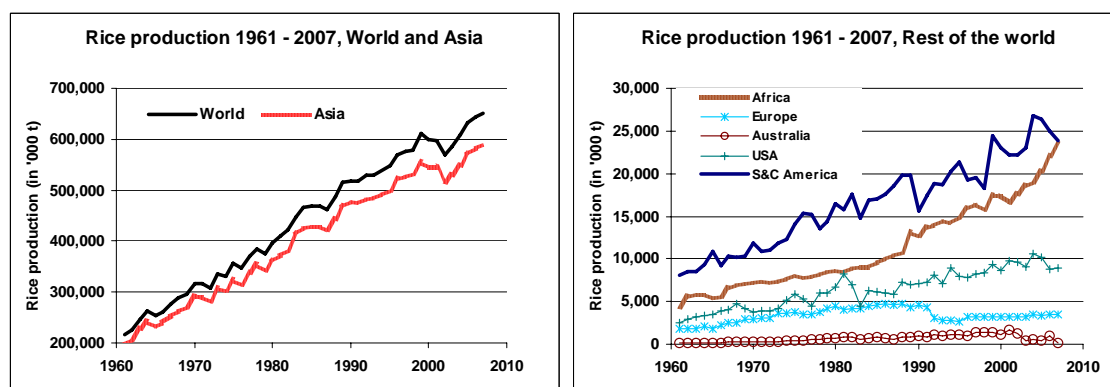


Fig. 1. Global and regional rice production since 1961 (source: FAO).

During the last decade some worrying trends emerged. Not only did the El Niño event of 2002 lead to the largest annual production decline ever (29 Mt or 5% less than in 2001; Fig. 1), but there is also mounting concern that the potential for further production increases is limited, especially in Asia. Although a cynic might argue that there is no real evidence of resource constraints impacting on the strong linear trend of increasing production, a report just released by IWMI [2] during World Water Week 2009 in Stockholm (<http://www.worldwaterweek.org/>) provides some sobering facts for Asia: while demand for food and animal feed will double during the next 50 years, there is little scope for expanding arable land, so developing new irrigation schemes is not a solution; in most places there are now clear limits on the amount of additional water that can be used for agriculture. The report concludes that *'Investments to raise yields and productivity from irrigated land must be key elements of a strategy to produce the extra food needed, while safeguarding the environment from additional stresses. Alternative options, such as upgrading rainfed farming and increasing international trade in food grains must also contribute, but they will need to be supplemented by a significant increase in production from irrigated agriculture'*. With a looming food crisis, demand for rice will continue to be strong, putting increasing pressure on the already stretched production resources, particularly water and land. How to meet this demand is a global challenge and science needs to play an important role in this process.

It is against this background that our Community of Practice (CoP) – an international and collaborative research network - formed in order to connect science with action. Using the central concept of simulation modelling as a means to capture and integrate a vast array of disparate research efforts, we aim to facilitate the intensification and expansion of sustainable, viable rice production for the benefit of rice farmers and consumers. A well-tested simulation modelling framework will allow evaluation of a range of adaptation options for the rice-growing world, as it adapts to some of these resource restrictions. We will further use this modelling framework as a vehicle to communicate with various stakeholders in order to connect science with adaptation action [3]. Here we outline some of the work that this CoP is involved in and invite others to join us in our quest.

1) The supply challenges

Meeting the ever-increasing demand for rice is already putting substantial pressure on resources, particularly land and water. In regards to land, further substantial expansion of paddy rice seems unlikely, given the strongly competing demands for the same areas from other food and energy crops, or non-agricultural land use such as urban expansion [4]. In regards to water, the situation is equally precarious, given the limited and dwindling water resources globally [5, 6]. A recent IFPRI report estimates that by 2025, water scarcity could cause annual global losses of 350 million metric tons of food production - slightly more than the entire current U.S. grain crop - if urgent measures are not taken now (www.ifpri.org/media/water_summaries.htm). This implies that future production increases must be achieved via productivity gains in terms of production per unit area and production per drop of water; *producing more with less* must therefore become the mantra of the rice industry.

2) The environmental challenges: risks and opportunities

Such productivity increases have to be achieved sustainably. For rice this means that the resource base, i.e. the land, must be maintained and the use of other resources such as water, fertilisers and pesticides must not impact negatively on the environment and the people living within. However, the environment is also changing, providing further challenges, but also some opportunities. Global changes are leading to increasingly limited and variable water supplies for most regions, while the frequencies of temperature extremes have already increased and continue to negatively impact production, particularly in warmer regions. In their recent report, Wassmann et al. [7] highlighted heat, drought, flooding and salinity as the key risk factors that need to be managed in order to increase production. However, climate changes can also have positive effects and related opportunities need to be identified and converted into productivity or efficiency gains. For instance, elevated CO₂ enhances plant growth under most environmental conditions due to increased photosynthetic rates and increased water use efficiency through decreased stomatal conductance. The degree of response depends on crop species and other variables such as temperature, soil moisture and soil nutrient availability, especially nitrogen [8]. Specifically for rice, Shimono et al. [9] found in their free-air CO₂ enrichment (FACE) experiments that elevated CO₂ can considerably reduce the incident of lodging under high N supply due to shortened and thickened lower internodes. Such CO₂-induced physiological changes could substantially reduce lodging-related yield losses in regions susceptible to damaging winds. At the lower end of the temperature spectrum some regions so far regarded as marginal for rice production could become increasingly important; suitable cultivars need to be identified and best management practices need to be designed. Likewise, water supply for certain regions might actually increase under climate change. Identifying these opportunities, matching opportunities to regions and providing guidance to ensure appropriate management is practised remains our research priority.

3) The scale challenges

Sustainable productivity increases can be achieved via a wide range of intervention actions ranging from breeding (either selective breeding or genetic modifications), improved matching of physiological traits to the environment, better management practices, improvements in irrigation technology, to the development of local, national and global policies that encourage productivity gains. In contrast to the green revolution, this time there are no obvious technological ‘winners’ – productivity increases have to come from a combination of efforts and technologies that have to be tailored to specific regional, bio-physical, economic and societal circumstances. This makes an effective connection between global and national policy and local agency even more imperative and draws attention to the fundamental importance of scale and the different perspectives that exist between the ‘macro’ and the ‘micro’ level [10]. Modelling offers the only way we know that can bridge this gap by providing tractable, quantifiable solutions that can be evaluated in terms of their desirability by multiple stakeholders and across scales. Therefore, our CoP has opted to use ‘modelling’ - in its broadest sense - as a means to facilitate prioritisation of R4D. We use these models to draw out synergies that arise from combining the most appropriate traits, technologies, policies and management actions.

4) Responding to the impacts of climate variability and change

Climate variability and change impact directly on rice production, mainly via changes in rainfall, temperature and CO₂ concentrations and indirectly through inundation (associated with salinity in coastal regions) and added pressure on land resources (Wassmann et al., 2009) [7]. Although we briefly discuss each of these parameters sequentially, we stress the importance of managing the **combined impact** of climate. The modelling approaches that we advocate provide the technological basis for such combined impact and feasibility assessments.

4.1) Rainfall and water supply

Water is the most critical resource for rice production - 1 kg of paddy rice requires approximately 2,500 l of water, whereby about 55% account for evapotranspiration and the rest for runoff, drainage or leakage. Hence, projected changes in rainfall patterns are hotly debated. At the time of writing (July/August 2009) another El Niño event has commenced [11] with impacts already felt in terms of a weaker than ‘normal’ Indian monsoon (Fig. 2).

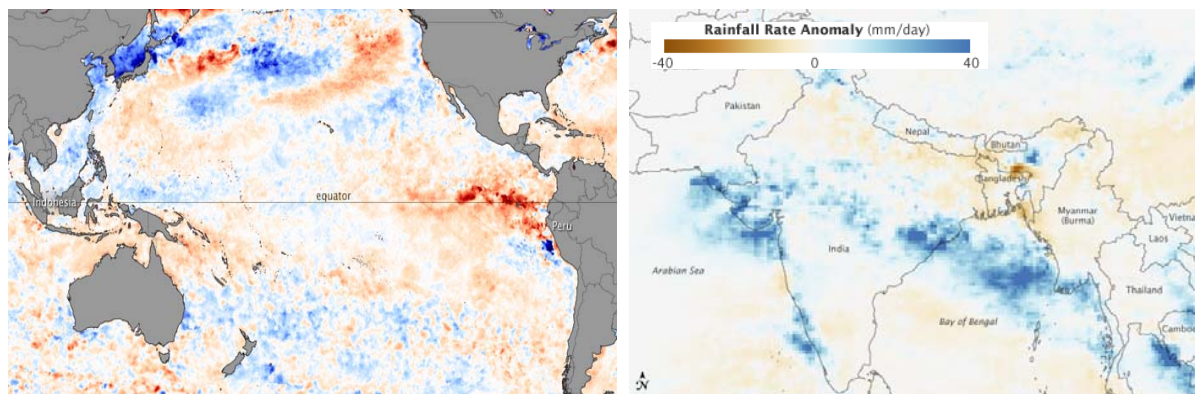


Fig. 2. (Left) Pacific sea-surface temperature (SST) anomalies on 26 July 2009 compared to long-term average temperatures (1985-1997); red = warmer, blue = cooler than normal. An area of dark red occupies the eastern Pacific off the coast of Peru and Ecuador, a ‘signature pattern’ for El Niño. (Right) Rainfall anomalies (mm d⁻¹) over India for the week 14 – 20 July 2009 (monsoon onset was around 25 May). Most of India and Bangladesh received considerably below average during this week, already sparking fears of further food shortages (<http://earthobservatory.nasa.gov/IOTD/view.php?id=39481>).

This is the third El Niño event this decade (after 2002 and 2004), which again triggers the discussion about possible consequences of climate change on ENSO behaviour (i.e. intensity and frequency of El Niño and La Nina events [12, 13]. The 2002 El Niño event – although regarded as ‘weak’ in terms of its climatological definition based on SST anomalies – resulted in one of the worst droughts ever in India [14] and in Australia (http://www.bom.gov.au/climate/enso/australia_detail.shtml). All-Indian rice yields were reduced by 23% compared to 2001 production levels (5% reduction across all of Asia, Fig. 1), while in Australia this drought marked the end of an era for the rice industry, providing some insights into possible shifts in rice-growing regions due to climate change [15, 7].

This highlights that coping strategies to better manage rice under water scarcity are urgently needed. Water savings can be achieved by reducing the non-productive water use (evaporation, runoff, drainage and leakage) and/or by increasing the efficiency of transpiration.

4.2) Reducing non-productive water losses

Many engineering or management options for reducing the non-productive sources of water loss are available. These range from better irrigations systems (improved irrigation channels, separate drainage systems) to fundamental changes in the way rice is grown (see Rice Today, Vol 9, 2009 and comments by Colin Chartres, DG of IWMI http://www.iwmi.cgiar.org/news_room/pdf/Taipei_Times.pdf). Among the promising new management practices are AWD (alternative wetting and drying, whereby the paddy is allowed to dry, but irrigation water is reapplied before water limitations start to impact on yields) and the aerobic rice systems, where especially developed rice varieties are grown in well-drained soil like dryland crops. This can save up to half of the normal water requirement while with good management yields between 4-6 t ha⁻¹ can be routinely achieved. However, what constitutes 'good' management when dealing with new production systems is not entirely clear, raising fears about the potential for maladaptation (i.e. questions such as 'Does AWD increase NO_x and/or NH₄ emission?' need to be addressed). This is where well-tested models become important: models offer a means to readily explore likely consequences of alternative options and allow the quantification of trade-off between attainable yield, resource-use efficiency and environmental outcomes. In line with our increasing scientific knowledge, these models require continuing improvement. To make the right choices, we urgently need models to assess the likely consequences of the many combinations of management practices, soils and climate (e.g. to assess the dynamics of the transitions from anaerobic to aerobic rice production or optimize the use of scarce resources such as water).

Departing from the established paradigm of growing rice under continuously flooded conditions - a peculiar system of conserving soil fertility and facilitating management of weeds, pests and diseases - involves much more than just fine tuning hydrology management. It requires adapting the plant to an ecosystem in which the commonly grown high yielding varieties (HYV) and hybrids are ecologically less competitive. Existing germplasm must be replaced by material deriving resilience from improved general adaptation, probably involving a host of traits that need to be identified and obtained from within or beyond the species. As it was the case for the green revolution, radically new water saving rice systems require profound innovation at both genetic and agronomic levels.

4.3) Sustaining high transpiration and conversion efficiencies

Transpiration use efficiency can principally be improved by two different means: either 1) by altering the crop's physiology or its genetic basis through breeding or 2) through breeding and crop management measures that ensure maximum yield for a given amount of transpiration (e.g. by avoiding yield reducing stress factors such as high temperatures during anthesis or pest or disease pressure). Both pathways will require knowledge of local micro-meteorological conditions and therefore model-aided geographical zoning from a thermal and a water perspective.

Reducing transpiration *per se* is not useful because it reduces growth almost proportionally and increases canopy temperature (although it may in some cases contribute to drought avoidance). A combination of high transpiration with high transpiration efficiency (TE) is needed and some genetic scope seems to exist to achieve that. On the other hand, securing high and stable conversion efficiency of biomass into grain under constraints of climate change requires a combined approach of heat/drought tolerance of reproductive and grain filling processes, sustained transpirational cooling of sensitive organs and climate informed management to avoid sensitive phenological phases and stresses to coincide.

5) Modelling rice-based systems – a pivotal technology for innovation in R4D

In order to design profitable and sustainable, climate-robust rice-based systems, research and monitoring activities must be supplemented by systems modelling [16]. We have identified several key areas of improvement required to existing models and are taking measures to address these short-comings through collaborative research actions.

5.1) Modelling systems processes and their transition

Although IRRI and WUR have a long tradition in rice modelling, their current model, ORYZA2000 [17], would have required substantial developmental work to handle the simulation of rice crops in complex farming systems, in rotation with other dryland and irrigated crops and pastures. On the other hand, Keating et al. [18] developed APSIM, a cropping systems modelling platform specifically designed to model cropping systems, but which did not contain rice. A merge of the two systems was logical and led to a prototype of APSIM-Oryza [19], a model configuration capable of modelling several crops sequentially, but still unequipped to describe the soil water, carbon and nitrogen dynamics under anaerobic conditions and the transitions from one system to the other. Gaydon et al. [20] included this functionality and added a new module, APSIM-Pond, to describe biological and chemical processes responsible for system loss/gain of C and N in rice ponds. No previous modelling framework has addressed the issue of switching between aerobic and anaerobic environments during a simulation, which is particularly important when

evaluating new farming system practices that include ponded rice in rotation with non-flooded crops. While this is an important feature to assist regions in transition (such as the collapsed Australian rice industry in the Riverina), such a capability is also needed for the simulation of greenhouse gas emissions associated with changed practices, where sensible accounting for C & N in pond and soil is essential.

5.2) Modelling temperature impacts and stresses

Traditionally, low temperatures were regarded as the key yield-limiting factor for rice production [21, 22]. However, the combination of climate change, expansion into new production areas, the increasing importance of dry season irrigated rice, the application of AWD technology and the emerging aerobic rice systems have increased the significance of high temperature constraints on production. Although the species rice is highly adaptable to diverse environments, even a short spell of excessive heat during sensitive growth stages can lead to substantial yield losses. Impact depends on severity and timing, but prediction of crop damage under field conditions is difficult, partly because of our limited understanding of the physiology involved coupled with a lack of data and uncertainties in predicting occurrences of extreme events. Furthermore, plant organs in which the heat sensitive, mostly reproductive processes take place can have substantially different temperature from ambient due to microclimate and transpirational cooling. This feeds back on phenology, adding uncertainty to the timing of sensitive phases and thus the predictability of heat impacts. None of the available rice crop models is currently able to simulate this.

Multi-site monitoring and coordinated experiments in contrasting thermal environments can help to detect changes and increase our causal understanding of impacts, enabling improvements of models. By linking our research efforts, we are creating a monitoring network that will allow us to determine the “hot spots” that are most vulnerable to further temperature increases. Coordinated, multi-site experiments are contributing to the establishment of valuable data resources needed to calibrate and validate models.

A major weakness of most crop models is their inability to simulate short but extreme temperature stresses. This has many reasons, not least that results obtained under controlled environments are not representative for field-level yield losses. For instance, we need to know the real temperatures experienced by certain plant parts where temperature-sensitive physiological processes take place (e.g. meristems, exerted panicles, leaves). Submerged meristems experience several degrees lower temperatures compared to air temperature and much smaller diurnal amplitudes. This, in turn, depends on source and depth of water, influencing growth and development. Under non-flooded conditions, spikelet sterility could be the response of either direct effects of changes in plant water relations or indirect effects through the reduction in evaporative cooling and thus an increase in panicle temperature. In fact, water deficit, increasing atmospheric CO₂ and high air temperatures all conspire to increase plant temperature and thus, the probability of spikelet sterility. Further complexity is added by the fact that temperature sensitive processes such as booting/microspore stage (occurring at plant base) and anthesis/pollination (plant tops) are exposed to different microclimates and by the fact that anthesis happens at a specific, genotype dependent time of day. Such knowledge needs to be systematically assembled on a quantitative basis and translated into integrative models predictive of microclimate effects on phenology and effective sink capacity. Exerted panicles can be up to 6° cooler than the surrounding air due to non stomatal transpirational cooling [23]. The exact amount depends on plant architecture (panicle below or above flag), water status of the plants and genotype (e.g. sterility is strongly affected by poor panicle exertion, which in turn is a function of genotypic morphology, temperature and plant water relations). Changing CO₂ levels also affect transpiration rates and therefore canopy temperatures, which further complicates feedbacks.

Complementary and coordinated research on this is being conducted in Japan (Tsukuba University), Philippines (IRRI/Tsukoba/Cirad), Senegal (Cirad/WARDA), Madagascar (CIRAD/FOFIFA) and France (CIRAD), with strong links to Hohenheim University in Germany provided by the GTZ RISOCAS project. Several models operating at different levels of detail and scale are being developed or improved, including the morphogenetic model EcoMeristem of CIRAD [24], a microclimate/heat balance model [26], the RIDEV model (WARDA/CIRAD) [27] linking phenology to microclimate, the crop model SARRAH [28] emphasizing water balance and phenology, and the summary crop model ORYZA providing a cropping systems dimension through the APSIM platform [16] [17] [18]. These efforts will be pooled to exchange modules and algorithms, and to assemble the best formalisms in combining models at appropriate scales.

One of our immediate research priorities is the improvement of phenology and microclimate modelling to better account for the complex ‘environment by development’ interactions. Currently the ORYZA2000 and SARRAH crop models describe phenological development as functions of photoperiod sensitivity and (atmospheric) thermal time, including delay in development due to transplanting shock and drought. Using datasets from many of the major rice growing regions (e.g. Brazil, China, Pakistan, Philippines), we pay particular attention to the simulation of thermal time accumulation, photoperiod sensitivity and effects of stress on development [29]. Our work will also address questions such as the supposed constancy of cardinal temperatures, a long-assumed yet contestable standard in phenology modelling. Complementary experiments using reference genotypes also expose rice to climates of different aridity x temperature combinations (France, Senegal & Philippines) and altitudes (Madagascar).

5.3) Genetic analysis of tolerance traits for drought and thermal stresses

Drought avoidance and drought tolerance mechanisms include early heading [30], the development of short duration varieties [31] and root characteristics such as thickness, rooting depth, root density, root pulling force and root penetration ability [32]. Osmotic adjustment [33] and membrane stability [34] are also important physiological criteria for selection under water limitations. Leaf characteristics such as glaucousness [35, 36], leaf size [37] and leaf pubescence [38]) are potentially important traits for avoiding excessive heat and regulating leaf temperature. Recently a new class of medium statured, moderately drought tolerant ‘aerobic rice varieties’ has been developed with high HI, improved lodging resistance and input responsiveness [39]. The selection for such traits will help plant survival under drought stress conditions depending on the magnitude of expression and utility of the traits.

5.4) Genetics and phenotyping of metabolic and photosynthetic pathways

Effects of water scarcity on crop growth and yield can be highly variable depending on the severity, timing and the duration of the dry spell. Consequently, breeding for drought tolerance / avoidance needs model-based strategic planning that can account for local environmental conditions. For instance, the impacts of certain types of drought could be mitigated via improved morphological traits such as rooting depth and root distributions [40]. Further, pollination is an important episodic process that is susceptible to various stresses including drought and extreme temperatures. Particularly pollen shedding under stress is impacted by anther morphology, an important characteristic for germplasm selection [41]. In both cases, detailed modelling studies can pin-point the environments where such traits are likely to have the highest pay-offs and so assist breeders in strategically designing cultivars best adapted to local conditions.

‘Supercharging’ photosynthesis is another option for potential, substantial increases in yield [42]. At least in principle it is possible to insert the C4 biochemical pathway into rice while simultaneously modifying leaf anatomy. Yin and Struik [43] incorporated equations for C3 and C4 photosynthesis into a diffusional conductance model running within the crop model GECROS in order to evaluate the impact of the successful introduction of the full C4 system into rice. Using GECROS conducted simulations for the dry seasons of the years 1979 to 2005 at IRRI’s experimental farm, assuming identical agronomy and physiology of the C3 and C4 rice crops except for the photosynthetic pathway and leaf anatomy. The grain yield advantage of simulated C4 rice averaged 23%, but varied considerably depending on climatic conditions. It was considerably less than the 50% yield increase hoped for by Mitchell and Sheehy (2006) [34]. Although leaf photosynthesis was greatly improved, the benefit of the C4 pathway for canopy photosynthesis fluctuated depending on daily radiation, and was mainly present during the pre-flowering period. At the end of grain filling, simulated canopy photosynthesis of C4 rice was lower than that of C3 rice. This emergent property of the model was associated with a higher carbon:nitrogen ratio in C4, leading to higher senescence rates in simulated C4 rice. These outcomes that are contestable need verification by future experimentation once the genetically modified rice varieties become available.

We also need to map genetic differences of environment-sensitive metabolic and growth processes, particularly with respect to thermal variation. For example, T-response of maintenance respiration (R_m) is generally believed to be responsible for the lower radiation use efficiency (RUE) of cereals in hot climates. However, we currently have simplistic views on R_m responses (almost a dogma: $Q_{10}=2$, function of tissue N). R_m is not truly understood, particularly in terms of GxE, and may be substrate driven too, resulting in destruction of excess assimilates under CO_2 enrichment or if thermal constraints to inhibit organ organogenetic processes and sink development. We know little on how metabolic efficiency and growth vigour will be affected in the field by combined environmental changes, and most of our tentative answers are based on erroneous models. Ongoing rice research on carbohydrate metabolism in relation to morphogenetic processes under drought [24] need to be extended to combinations of environmental factors including CO_2 and heat, and new studies on the components of the plant’s carbon balance need to be initiated. These studies must also capture any existing genetic diversity.

5.5) CO_2 and photosynthesis modelling – implications for breeding

Under elevated CO_2 , photosynthesis increases at single leaf and canopy level (mainly before anthesis) while respiration does not seem to be affected. As a result, more sinks can be committed, new organs are formed and biomass partitioning is modified. Despite the potential increase in yield and better competitiveness against certain weeds under elevated CO_2 , rice productivity is predicted to decline under future climates due to the down-regulation of photosynthesis, the stagnation of nitrogen uptake under elevated CO_2 , and the detrimental effect of increased temperature. Future crops will be exposed to further environmental changes, resulting in strong interactions influencing factors such as nitrogen uptake. Hence the typology of environments faced by crops in a given region is evolving, and so are the crop requirements to be targeted by breeders. Targeted experimentation combined with physiologically sound modelling can help breeders to identify the most CO_2 -responsive genotypes, provide guidance for future breeding programs and help with genetic screening to elucidate the mechanisms that underlie genotypic

differences in productivity. Such mechanisms include photosynthesis, stomatal control, organ initiation, sink regulation, elongation rates, panicle dimensioning, respiration, anther dehiscence, organ senescence, remobilization and grain filling. In particular, the maintenance of high root dry matter (e.g. by delaying root senescence, under elevated CO₂ after heading) might be crucial for providing greater nitrogen supply to meet higher sink strength. Most urgent is the investigation of genetic variability of growth response to temperature, within-day timing of anthesis and early flowering. Integrative and dynamic models play a key role in quantifying the morpho-physiological responses of crops to new combinations of environmental factors. Such models need to be able to predict sink regulation and spikelet fertility under variable and changing environmental conditions.

5.6) Management of rice-based systems

A better understanding of management options is also needed. Rice can shift to higher latitudes and can profit from river systems (via irrigation) so far not considered. To a lesser extent this is also true for altitude (e.g. Madagascar, Ethiopia, Andes). New opportunities might arise to produce more than one crop per year in areas where the off-season used to be too cold (e.g. parts of Sahel and sub-Himalayan river basins). Mapping this production potential and matching it with regional constraints will be an important first step in the targeted improvement of transpiration use efficiency. Managers of previously rice-dominated farming systems which are now experiencing water shortages may find that food production per unit of water can be increased by the incorporation of less water-intensive crops and pastures into rotation with rice (eg maize). The evaluation of water productivity at the cropping system level will be greatly enhanced by the farming systems modelling framework under development by this CoP, which includes rice as an integral component. The following are examples of rice-based farming system management research that are already in progress.

5.6.1) Modelling aerobic rice systems

Canopy management that maximises yields for a given amount of resources is a major challenge in the emerging aerobic rice systems. To address this, we are currently conducting field experiments in China, Pakistan and Brasil:

In China, water shortage in the Huai River Basin has sparked farmer interest in direct-seeded, aerobic rice. Yet, little is known about optimal planting densities and how different cultivation practices might impact on tiller growth and development. For two seasons (2005 and 2006) we tested four aerobic rice varieties under flooded and nonflooded conditions in Anhui Province, China. Yields in nonflooded soil ranged from 3.6 to 4.7 t ha⁻¹, and did not differ significantly from yields in flooded soil [44]. However, variety had a significant effect on biomass, yield, panicle number, spikelet number, grain weight, and grain filling percentage. Panicle number was the main factor limiting yield, resulting from a low tiller emergence frequency and a low fraction of reproductive tillers in both the flooded and the nonflooded soils. The contribution of productive tillers to yield varied between 7% and 47%. Frequencies of tiller emergence at most phytomer orders were higher in the flooded soil than in the nonflooded soil. Our findings suggest that in order to increase yield in aerobic rice production systems, both the tiller emergence frequency and the fraction of reproductive tillers should increase through breeding, improved crop management, or a combination of both. Results from this study will be used to parameterise APSIM-Oryza [19, 20].

Pakistan is one of the world's major rice exporters. In 2007, Pakistan produced 8.3 Mt of rice of which about 3 Mt were exported (FAO), while domestic demand is strong and rising. Pakistan is already a water-stressed country and there is urgency to identify and adopt measures that will reduce water use in rice production. Changing some of the current production system to aerobic rice cultivation has been proposed to cope with the problem of water scarcity. How viable this proposition is remains to be seen. Therefore resource implications of aerobic rice cultivation need to be quantitatively understood and managed at the cropping systems level. Explorative studies to quantify genotypic variability of N and water use efficiencies are currently underway. For this we are using modelling approaches in combination with field experimentation and socio-economic surveys. The improved and tested model will be used to define alternative management options for obtaining improved resource-use efficiencies in rice-based systems.

Central Brazil's savannah region contains the world's most productive aerobic rice systems. Responding to environmental concerns about land clearing, recent legislation has halted real expansion. To maintain productivity, aerobic rice must now become part of sustainable crop rotations, including zero or minimum tillage. Recent price increases for rice and low costs of production compared to soybean and maize make rice an attractive option for farmers. This raises many issues. For instance, row spacing for the main crops, soybean and maize, range from 45 to 60 cm, yet increasing row spacing for rice will increase weed infestations due to low initial vigour of upland rice. Further, zero-till, which is essential to maintain soil health, leads to compaction and reduces porosity of surface layers, further reducing the initial vigour of seedlings. For the aerobic rice systems of Brazil we focus on the following research priorities a) environmental characterization of the different production area; b) evaluating phenotype traits for early vigour (e.g. N absorption by roots during establishment); c) developing herbicide-tolerant cultivars and d) feeding research results into an aerobic rice breeding program. This research and the experimental data underpinning it will be used for further model development and testing.

5.6.2) Climate robust systems for Africa

'Climate robustness' is particularly important for Africa¹ where 93% of crop production is rainfed and rice production and consumption is rapidly increasing (Fig. 1). The continent is characterised by very high climate variability and climate change impacts that are already felt in many regions. Production is principally constrained by low soil fertility and a lack of water. Biotic factors, such as weeds, pests and diseases interfere with crop production and are a further determinant of the actual production level. Climate related research at the Africa Rice Center (WARDA) therefore addresses the following three domains: (i) genetic improvement through participatory research and shuttle breeding, (ii) integrated crop management and (iii) creating favourable policy environments.

Genetic improvement focuses on traits such as high temperature, drought and salt tolerance. Studies continue on the photo-thermal adaptation of irrigated rice in the Sahel zone of West Africa. A collection of lowland rice varieties comprising mainly of *Oryza sativa indica* sub-species were screened and selected for their temperature adaptation in terms of grain yield, grain filling and sterility. This resulted in germplasm adapted to the hot dry season or the cool wet season or both [45].

WARDA scientists also compare *O. sativa* with *O. glaberrima* accessions for adaptation to heat stress; it appears that *O. glaberrima* accessions are better adapted to heat stress due to earlier peak flowering. The critical temperature inducing sterility in rice was found to vary from 32° C for sensitive varieties to 37° C for tolerant varieties [46, 47]. *O. glaberrima* flowers early in the morning between 7 and 8 a.m, long before peak daily temperatures are reached. Further, *O. glaberrima* accessions appear to have higher leaf transpiration rates than *O. sativa*. Under water non-limiting conditions this attribute helps to dissipate heat faster from leaves.

Significant genetic variations also exist for drought tolerant traits like rapid leaf rolling, stomatal closure, high water use efficiency, osmotic adjustment and possession of deep and thick roots. The NERICA varieties show promise as an adaptation strategy to a changing climate due to their earliness, a drought escape characteristic. All these traits need to be captured by our models for full impact and suitability analyses.

Parasitic weeds, an important group of weeds in rain-fed rice-ecosystems throughout Africa, are progressively spreading due to their invasive nature and adaptive abilities [48]. In addition to competing with the rice for water and nutrients, these weeds also parasitize on rice roots, withdrawing carbohydrates and water, while exerting pathological effects. Understanding the host-parasite relationship, the dynamics of parasitic weed spread and predicting future impacts on rice production is essential for the design, development and implementation of effective policy measures and management practices.

5.6.3) Climate robust systems for Australia

Projected climate trends for Australian rice-growing districts indicate that significant farming system changes will be necessary to keep farmers viable in future. These are likely to include greater reliance of less water-intensive grain crops (cereals, pulses, and oilseeds), increased farm size, and in seasons when sufficient water is available, more water-efficient rice-growing practices. An additional focus on regions with greater projected future water supplies is underway. All these major industry shifts (currently the subject of Australian-funded research) will benefit from science input via modelling analysis using the framework under development by this CoP.

6) Concluding remarks

Our CoP negotiates research priorities, implements experiments, provides data and research results and facilitates development of and access to models. Through this, we constantly improve our current understanding of rice systems at plant, crop, farm and regional level. Through common modelling platforms, the data obtained and shared throughout our community helps to bridge the gap between chamber or plant-level understandings and field or regional-level observations. This helps to proactively plan and implement adaptation actions that are urgently needed to meet the increasing demand for rice. Ultimately, the CoP will provide the bases and platforms for developing climate robust rice production systems that are best adapted to their respective growing environments and socio-economic circumstances. Our research activities and approaches are a typical example of 'adaptation science', i.e. the process of identifying and assessing threats, risks, uncertainties and opportunities that generates the information, knowledge and insight required to effect changes in systems to increase their adaptive capacity and performance (Meinke et al., 2009) [3]. Table 2 summarises some of the key research activities that are currently underway. Many of these activities are collaborative efforts with institutions or scientists that do not actively participate in our CoP and who might not even be aware of our collaborative efforts. We herewith encourage their active participation.

¹ However, there is also mounting concern about the reliability of the Asian monsoon, which sustains vast areas of virtually rainfed production throughout Asia.

Table 2. Examples of current climate adaptation research activities by CoP partners (CC = climate change, CV = climate variability). NB: a) the list not comprehensive, b) listed activities do not necessarily represent specific projects, c) many of these activities involve other partners currently not listed as participants in our CoP.

Lead partners	Research topic or science question	Additional key words	Geographic focus
Crop physiology			
NIAES / IRRI	Understanding interactions between temperature and CO ₂	Physiology, microclimate, CC	Asia & Africa
IRRI / NIAES	Assessing heat stress of rice varieties under tropical conditions	Stress physiology, CC	Asia & Africa
CIRAD / WARDA	Methodologies to cope with CC in Sahel (rice: Senegal; sorghum: Mali)	High temp stress	West Africa
CIRAD / IRRI	Model assisted phenotyping for genetic diversity	Drought / heat stress	Global
IRRI	Modelling submergence effects on rice	Model development	Asia
WUR / Embrapa	Modelling phenology of different rice cultivars	Model development, CV, CC	Global
WUR / IRRI	<i>In silico</i> assessment of the field level value of C4 photosynthesis pathways for rice	Photosynthesis, impact assessment	Global
WARDA / WUR / CIRAD	Breeding for heat and cold tolerance in rice	Stress physiology, breeding	Africa
GHG Emission modelling			
IRRI / NIAES	Improving DNDC model for rice production for water saving techniques	Soil science, CC, emissions	Global
Resource use modelling			
WUR	Quantifying resource-use efficiency of aerobic rice varieties in Pakistan's wheat/rice rotations	Cropping systems, physiology, CV, CC	Pakistan
WUR / CAU / IRRI	Quantitative assessment of opportunities for a transition towards aerobic rice systems	Cropping systems design, CV, CC	China
IRRI	Regional scale hydrological water balance modelling	Water resources modelling, CC	Asia
CSIRO	Understanding alternative water mgt systems / production / cost : benefit analysis	Systems mgt, emissions, economics CC	Australia
CSIRO/IRRI/ACIAR	Understanding climate change adaptation options in SE Asia	System mgt, economics, social imperatives, climate change	Bangladesh, India, Cambodia, Laos
NIAES	Impact assessment on yield and water resource availability in S/SE Asia	Water use efficiency, CC	Asia
Embrapa / WUR	Performance of integrate upland rice in no tillage system	cropping systems, fertility, CC	Brazil
Embrapa / WUR	Environmental characterization of upland rice production area.	Environment, impact assessment, global change	Brazil
Crop health			
IRRI	Measurements and modelling of resistance (components) to plant diseases	Epidemiology of plant diseases	Asia
IRRI	Quantify the effect of CC on plant health	Ecosystems responses, CC	India, China Philippines
WUR / WARDA	Managing parasitic weeds in a changing environment	food security, CV, CC	Africa
Model platform development			
CSIRO / IRRI / WUR	Further integration of ORYZA into APSIM	Building model infrastructure	Global
WUR / CIRAD / CSIRO	Linking function with structure (3-D modelling)	Crop physiology, model development	Global
IRRI	Modelling submergence effects on rice	Model development	Asia
WUR	Modelling phenology of different rice cultivars	Model development	Global

References

- [1] Von Grebmer, K., Fritschel, H., Nestorova, B., Olofinbiyi, T., Pandya-Lorch, R. and Yohannes, Y., 2008. Global Hunger Index. The Challenge of Hunger 2008. Bonn, Washington D.C., Dublin, October 2008.
- [2] Mukherji, A., Facon, T., Burke, J., de Fraiture, C., Faures, J.M., Füleki, B., Giordano, M., Molden, O. and Shah, T., 2009. Revitalizing Asia's irrigation: to sustainably meet tomorrow's food needs, Colombo, Sri Lanka; International Water Management Institute; Rome, Italy; Food and Agricultural Organization of the United Nations.
- [3] Meinke, H., Howden, S.M., Struik, P.C., Nelson, R., Rodriguez, D. and Chapman, S.C., 2009. Adaptation science for agricultural and natural resource management – Urgency and theoretical basis. *Current Opinion in Environmental Sustainability*, in press, DOI: 10.1016/j.cosust.2009.07.007.
- [4] Pielke, R. Jr, Prins, G., Rayner, S. and Sarewitz, D., 2007. Lifting the taboo on adaptation, *Nature*, 445: 597-598.
- [5] Barnaby, W., 2009. Do nations go to war over water? *Nature*, 458: 282-282.
- [6] Rodell, M., Velicogna, I. and Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. *Nature advance online publication* 12 August 2009, doi:10.1038/nature08238.
- [7] Wassmann, R., Jagadish, S.V.K., Sumfleth, K., Pathak, H., Howell, G., Ismail, A., Serraj, R., Redona, E., Singh, R.K. and Heuer, S., 2009. Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation, *Advances in Agronomy*, 102: 91-133.
- [8] Tubiello, F.N., Donatelli, M., Rosenzweig, C., Stockle, C.O., 2000. Effects of climate change and elevated CO₂ on cropping systems: model predictions at two Italian locations. *European Journal of Agronomy*, 13: 179-189.
- [9] Shimono, H., Okada, M., Yamakawa, Y., Nakamura, H., Kobayashi, K., Hasegawa, T., 2007. Lodging in rice can be alleviated by atmospheric CO₂ enrichment. *Agriculture, Ecosystems and Environment*, 118: 223-230.
- [10] Wilbanks, T.J. and Kates, R.W., 1999. Global change in local places: How scale matters, *Climatic Change*, 43: 601-628.
- [11] WMO, 2009 - http://www.wmo.int/pages/prog/wcp/wcasp/documents/El_Nino_Jun09_Eng.pdf
- [12] Cane, M.A., 2004. The evolution of El Niño, past and future, *Earth and Planetary Science Letters*, 230: 227-240.
- [13] Guilyardi, E., 2005. El Niño – mean state–seasonal cycle interactions in a multi-model ensemble, *Climate Dynamics* (2006), 26: 329-348.
- [14] Krishna Kumar, K., Rajagopalan, B., Hoerling, M., Bates, G. and Cane, M., 2006. Unraveling the Mystery of Indian Monsoon Failure during El Niño, *Science* 314: 115-119.
- [15] Schneider, K., 2009. A Rice Town's Cry, *Circle of Blue Water News*, 9 March 2009.
- [16] Hammer, G.L., Kropff, M.J., Sinclair, T.R. and Porter, J.R., 2002. Future contributions of crop modelling — from heuristics and supporting decision making to understanding genetic regulation and aiding crop improvement, *European Journal of Agronomy*, 18: 15-31.
- [17] Bouman, B.A.M. and van Laar, H.H., 2006. Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions, *Agricultural Systems*, 87: 249-273.
- [18] Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation, *European Journal of Agronomy*, 18: 267-288.
- [19] Zhang, X., Meinke, H., deVoil, P., van Laar, G., Bouman, B.A.M. Abawi, Y., 2004. Simulating growth and development of lowland rice in APSIM, *Proceedings of the 4th International Crop Science Congress*, 26 Sep – 1 Oct 2004, Brisbane, Australia.
- [20] Gaydon, D.S., Buresh, R.J., Probert, M.E. and Meinke, H., 2009. Simulating rice in farming systems – modelling transitions between aerobic and ponded soil environments in APSIM. In: B. Anderssen et al. (eds) /18th IMACS World Congress - MODSIM09 International Congress on Modelling and Simulation/, 13-17 July 2009, Cairns, Australia.
- [21] Dingkuhn M., Miézan K.M., 1995. Climatic determinants of irrigated rice performance in the Sahel. II. Validation of photothermal constants and characterization of genotypes. *Agricultural Systems*, 48 : 411-434.
- [22] Luquet D, Clément-Vidal A, This D, Fabre D, Sonderegger N, Dingkuhn M (2008) Orchestration of transpiration, growth and carbohydrate dynamics in rice during a dry-down cycle. *Functional Plant Biology* 35, 689-704.
- [23] Matsui, T., Kobayashi, K., Yoshimoto, M. and Hasegawa, T., 2007. Stability of rice pollination in the field under hot and dry conditions in the Riverina region of New South Wales, Australia, *Plant Production Science*, 10: 57-63.
- [24] Luquet, D., Dingkuhn, M., Kim, H.K., Tambour, L. and Clément-Vidal, A., 2006. EcoMeristem, a model of morphogenesis and competition among sinks in rice. 1. Concept, validation and sensitivity analysis, *Functional Plant Biology*, 33: 309-323.
- [25] Hasegawa, T., Sawano, S., Goto, S., Konghakote, P., Polthanee, A., Ishigooka, Y., Kuwagata, T., Toritani, H., Furuya, J., 2008. A model driven by crop water use and nitrogen supply for simulating changes in the regional yield of rain-fed lowland rice in Northeast Thailand. *Paddy Water Environ.*, 6: 73-82.
- [26] Dingkuhn, M., Luquet, D., Clément-Vidal, A., Tambour, L., Kim, H.K., Song, Y.H., 2007. Is plant growth driven by sink regulation? Implications for crop models, phenotyping approaches and ideotypes. In 'Scale and Complexity in Plant Systems Research: Gene-Plant-Crop Relations'. Ed. P.C.Struik, H.J. Spiertz, H.H. van Laar. pp. 157-170: Wageningen, Netherlands
- [27] Dingkuhn, M., 1995. Climatic determinants of irrigated rice performance in the Sahel. III. Characterizing environments by simulating crop phenology. *Agricultural Systems*, 48: 435-456.
- [28] Baron, C., Sultan, B., Balme, M., Sarr, B., Traoré, S.B., Lebel, T., Janicot, B., Dingkuhn, M., 2005. From GCM grid cell to agricultural plot: Scale issues affecting modelling of climate impact. *Philosophical transactions of the Royal Society of London. Biological sciences* 360; 2095-2108.
- [29] Van Oort, P.A.J. and Meinke, H., 2009. Phenology modelling in ORYZA2000: issues and prospects. These proceedings.
- [30] Fujita, D., Santos, R.E., Ebron, L., Yanoria, M.J.T., Kato, H., Kobayashi, S., Uga, Y., Araki, E., Takai, T., Fukuta, Y. and Kobayashi, N., 2007. Genetic and breeding study on near isogenic lines of IR64 for yield-related traits—QTL analysis for days to heading in early heading lines, *Breed. Sci.*, 9: 114.

- [31] Kumar, J. and Abbo, S., 2001. Genetics of flowering time in chickpea and its bearing on productivity in the semi-arid environments, *Adv. Agron.*, 72: 107–138.
- [32] Nguyen, H.T., Babu, R.C. and Blum, A., 1997. Breeding for drought resistance in rice: Physiology and molecular genetics considerations, *Crop Sci.*, 37: 1426–1434.
- [33] Hsiao, T.C., O'Toole, J.C., Yambao, E.B. and Turner, N.C., 1984. Influence of osmotic adjustment on leaf rolling and tissue death in rice (*Oryza sativa* L.), *Plant Physiol.*, 75: 338–341.
- [34] Tripathy, J.N., Zhang, J., Robin, S., Nguyen, T.T. and Nguyen, H.T., 2000. QTLs for cell-membrane stability mapped in rice (*Oryza sativa* L.) under drought stress. *Theor. Appl. Genet.*, 100: 1197–1202.
- [35] Ludlow, M.M. and Muchow, R.C., 1990. A critical evaluation of traits for improving crop yields in water-limited environments, *Adv. Agron.*, 43: 107–153.
- [36] Richards, R.A., Rawson, H.M. and Johnson, D.A., 1986. Glaucousness in wheat: Its development, and effect on water-use efficiency, gas exchange and photosynthetic tissue temperatures, *Aust. J. Plant Physiol.*, 13: 465–73.
- [37] Henson, I.E., 1985. Modification of leaf size in rice (*Oryza sativa* L.) and its effects on water stress-induced abscisic acid accumulation, *Ann. Bot.*, 56: 481–487.
- [38] Sandquist, D.R. and Ehleringer, J.R., 2003. Population- and family-level variation of brittlebush (*Encelia farinosa*, Asteraceae) pubescence: Its relation to drought and implications for selection in variable environments, *Am. J. Bot.*, 90: 1481–1486.
- [39] Atlin, G.N., Lafitte, H.R., Tao, D., Laza, M., Amante, M. and Courtois, B., 2006. Developing rice cultivars for high-fertility upland systems in the Asian tropics, *Field Crops Res.*, 97: 43–52.
- [40] Manschadi, M., Hammer, G.L., Christopher, J.T. and deVoil, P., 2008. Genotypic variation in seedling root architectural traits and implications for drought adaptation in wheat (*Triticum aestivum* L.), *Plant Soil*, 303: 115-129. DOI 10.1007/s11104-007-9492-1
- [41] Matsui, T., Kobayasi, K., Kagata, H. and Horie, T., 2005. Correlation between viability of pollination and length of basal dehiscence of the theca in rice under a hot and humid condition, *Plant Production Science*, 8: 109-114.
- [42] Mitchell, P.L. and Sheehy, J.E., 2006. Supercharging rice photosynthesis to increase yield, *New Phytologist*, 171: 688-693.
- [43] Yin, X. and Struik, P.C., 2008. Applying modelling experiences from the past to shape crop systems biology: the need to converge crop physiology and functional genomics, *New Phytologist* 179: 629-642.
- [44] Yan, J., Yu J., Tao, G.C., Vos, J., Bouman, B.A.M., Xie, G.H. and Meinke, H., 2009. Yield formation and tillering dynamics of direct-seeded rice in flooded and nonflooded soils in the Huai River Basin of China, *Field Crops Res.*, submitted.
- [45] Kouressy, M., Dingkuhn, M., Vaksman, M., Heinemann, A.B., 2008. Adaptation to diverse semi-arid environments of sorghum genotypes having different plant type and sensitivity to photoperiod. *Agricultural and Forest Meteorology*, 148: 357-371.
- [46] Satake, T., Yoshida, S., 1978. High temperature induced sterility in indica rices at flowering. *Japanese Journal of Crop Science*, 47: 6–17.
- [47] Yeo, A.R., 1999. Predicting the interaction between the effects of salinity and climate change on crop plants. *Scientia Horticulturae*, 78: 159-174.
- [48] Rodenburg, J., Riches, C.R., Kayeke, J.M., 2009. Addressing current and future problems of parasitic weeds in rice. *Crop Protection*, accepted.