Competing Claims for Natural Resources and the Need for System Transitions in Rice Cultivation

M.J. Kropff, P.S. Bindraban, and M.A. Slingerland

The world entered the 21st century facing many challenges, often in an agricultural context. Prominent is the concern for feeding an ever-growing population with safe and healthy food. A sustainable living environment and socioeconomic development are major issues as well. All these concerns are strongly related to the management of natural resources such as land, water, energy, and minerals and the distribution of the products. Many resources are limited (e.g., land and fresh water) and several resources are not renewable, such as oil. The Millennium Development Goals attempt to resolve these concerns, aiming to increase benefits from Earth's resources for people living in developing countries. Now, the political arena shows the dependency of the world on an oil-based economy, in which demand for oil increases rapidly due to economic growth and political instability, driving market prices up. Not surprisingly, demand for bio-based products, and especially bio-based fuel as a renewable resource, is booming. The strongly increasing demand for food and nonfood agricultural produce challenges our agricultural production capacity worldwide.

As many natural resources have multiple uses and multiple users, increasing demand can create constraints and be a trigger for conflicts at different scales, from local to international. To minimize these constraints, it is essential that current uses, increased demand, and resulting constraints at different scales be analyzed simultaneously to identify socially and economically viable options for local innovation in which the different objectives of a variety of stakeholders are met. Such options can be identified only through the involvement of these stakeholders, including scientists. When they work closely together, this may result in increasing space for solutions and co-innovation. Scientists can contribute in several ways in the policy-making process from problem identification to implementation. They can raise awareness of competing claims at different scale levels and identify options based on which stakeholders can make decisions about the way they want to deal with multiple uses of natural resources. In other words, the stakeholders who are responsible have to set goals. Of course, scientists have to continue their contributions to new technology development at different scales based on clearly defined questions.

This technology should focus on a major increase in resource-use efficiency and expand the scope for solutions. In this way, we move from a technology push to a technology pull strategy and we need close interaction between social and natural scientists.

This paper discusses the challenge we face, which is to address the increase in different and often conflicting claims by transforming our systems, with specific attention to rice production systems. While transition in production systems calls for adjustments in socio-political conditions, the drastic transformations required cannot be achieved without technological breakthroughs using our best technical knowledge and means.

At the dawn of the 21st century, we realize that the increasing demand for virtually all commodities to meet human needs puts enormous pressure on the global resource base. With reducing availability of and access to resources, social tension and conflicts may arise, the divide between rich and poor might increase, and ecosystems may become overexploited.

The major concern still is the fact that more than 800 million people suffer from hunger and malnutrition and more than a billion people earn less than 1 dollar a day. For these people to escape these conditions, a sustainable living environment should be created that provides opportunities to also benefit from socioeconomic development. Inadequate access to food and production factors because of a lack of purchasing power and decreased productivity due to malnourishment causing health problems lead to a negative spiral into poverty that has to be broken. Some of the elements to help solve these problems are the production of more food and better food products, improved nutrition with the right balance of components, a better distribution of and access to food and natural resources, and sufficient education for people to make sensible choices.

These concerns are expressed in the Millennium Development Goals, which seek more equitable sharing of the limited resources to reduce hunger and poverty and to improve health, which compel us to make more efficient use of these resources for a sustainable environment, which call for better education to allow people to make informed choices, and which stress the need to stimulate partnerships in seeking development solutions (www.unmillenniumproject.org).

Many of these challenges in development have an agricultural background in a development context and relate to the management of natural resources, including land, water, minerals, energy, and products derived from them. Several resources have a limited capacity and are fragile, such as land and fresh water, and others are not renewable such as oil. The pressure on these resources is high indeed as described below, but humankind has faced such difficulties before and turned them into challenges. Dramatic food shortages as forecast by Ehrlich in the 1960s (Ehrlich 1971), for instance, have not become a reality, nor has the depletion of our energy sources as was predicted by The Club of Rome (Meadows et al 1972), but we cannot become complacent and should continue to tackle the challenges.

Land use is changing rapidly worldwide as a result of the growing population and urbanization, expansion for agricultural lands, as well as the need to conserve natural ecosystems. The fertility of agricultural land is continuously under pressure due to overexploitation resulting from the lack of inputs to sustain nutrient balances, in particular in sub-Saharan Africa (e.g., Sheldrick and Lingard 2004). Also, the claim on land for urbanization or wildlife conservation pushes poor people into marginal and vulnerable areas. Land degradation is often the result of timber harvesting in former forest zones, on slopes, or on fragile soils (Oldeman 1999).

The struggle for sufficient water for drinking and food production sets social groups and nations against each other, even leading to conflict. Major problems arise for farmers facing drought they cannot escape, such as in the south of India and in Africa. On the other hand, excessive water consumption by agriculture, for instance, in flooded rice production systems, contributes to decreased water availability for other sectors in society.

Some nutrients needed for plant growth, such as phosphorus, are available in limited quantities only. This essential nutrient is needed to realize the urgently required increase in crop productivity in Africa. Currently, a local lack of availability hampers production, while absolute shortages might become a threat in the long term.

Within a shorter period of a couple of decades, our major sources of energy, economically exploitable oil and gas, will be depleted. Although oil companies indicate having reserves to suffice for several decades, the costs of exploitation will increase. Our oil-based economy already reveals its severe energy dependency by suffering from large fluctuations in prices due to limited production capacity and geo-political issues. The current energy crisis has triggered politicians to seek alternatives. The demand for bio-fuels, for instance, is soaring because of requirements set by governments such as the European Union and the United States. By 2010, 5.75% of the diesel for transport should have a biological origin, creating an enormous, though artificial subsidy-driven, market. As the maximum energy efficiency of crops is 3% only (for C_3 crops), vast cropping land area will be required to provide the energy for our cars, especially if the fuel is to be derived from oilseeds (and sugar), that is, first-generation bio-fuel. Interestingly, developments are under way to produce second-generation bio-fuels, that is, ethanol produced from materials such as straw. We should realize, however, that materials such as straw are very important for soil improvement in many soil types. The massive use of straw for bio-fuel would create a problem there. So, bio-based fuel is an opportunity for agriculture (as its demand may push prices up) but also a threat to food production.

Economic development increases claims on natural resources and associated increases in income directly affect demand for agricultural produce because of rising meat consumption. As the production of 1 kg of meat requires many more kilograms of plant material, a meat consumer requires more agricultural produce than a vegetarian.

Large and sudden changes in the global system, either political or natural, are likely to occur more frequently, as we are stretching our global ecosystems toward their limits to provide us with the necessary goods. The increasing frequency of extreme events, such as floods, drought, heat, and typhoons, is perceived as adverse effects of climate change and these alarm nations to take adaptive measures and reduce emissions. Several local disputes are about the control and benefit of valuable resources such as the conflict in Nigeria about oil and, for instance, in 2005, the conflict between crop growers and livestock keepers in Kenya about water when the country was hit by a drought.

In this paper, we discuss the implications of these global changes for local systems. We will discuss them from an agricultural perspective as the production of sufficient, safe, and healthy food is a basic requirement for all development scenarios and, in addition, agriculture needs to provide biomass for fuel and feed. We first stress the need to examine these issues at different levels of scale and share our views on the changing role for scientists to provide new options to overcome any problems. The increasingly complex dynamics of global developments requires policy-driven transformation processes, leading to local solutions with relevance at all scale levels. The required development of technological options to increase resource-use efficiency is placed in this context. We illustrate the relevance of the various components of transformation processes as much as possible from a perspective of rice. We will mention some options as to how rice-based systems could be (re-)designed to meet future challenges.

THE ROLE OF SCIENCE AND DEVELOPMENT IN AN AGRICULTURAL CONTEXT

Concerted actions of decisive policies, potent institutions, and technological breakthroughs led to the Green Revolution during the 1960s and 1970s. From a technological perspective, the real breakthrough was achieved by raising the harvestable proportion of major cereal crops in combination with agronomic practices (irrigation, pesticides, and fertilizer) that allowed the new varieties to express their yield potential. Along with the accompanying policies that created the appropriate institutional and market conditions, a process of change was realized. Hence, a combination of actions and a multitude of actors were involved in carrying out the transformation of the agricultural sector. However, in Africa, to date, technological breakthroughs have not been implemented due to a lack of coordination of these multiple conditions (InterAcademy Council 2004).

Following this period of technological breakthroughs, the productivity of the major cereals and other crops per unit of land and unit of nutrient input has constantly been improved to comply with changing demands that moved from increased needs for food toward the prevention of adverse environmental impact. Resistances to pests and diseases and location-specific adjustments maintained the performance of varieties, while fine-tuning in time and space of input applications minimized their requirements and reduced adverse side effects.

Systems approaches have been developed to support these interdisciplinary studies (e.g., Kropff et al 2001). They can be applied at different scale levels: plot, farm, watershed, region, country, continent, world. In general, the approaches can be described as the systematic and quantitative analysis of agricultural systems, and the synthesis of comprehensive, functional concepts underpinning them. The systems approach uses many specific techniques, such as simulation modeling, expert systems, databases, linear programming, and geographic information systems (GIS). However, these tools have a biological/technological basis. For system improvement, socioeconomic aspects have to be included in the overall process.

TOWARD A NEW FRAMEWORK FOR THE ROLE OF SCIENCE IN AN AGRICULTURAL CONTEXT

For the coming decades, incremental improvements alone are no longer likely to suffice to meet drastically changing global demands. The magnitude of these demands urge for complete transformations of production systems in their local context while accounting for global issues as well. We should thereby address the competing claims by transforming our production systems to minimize trade-offs and to exploit any thinkable synergy. Figure 1 shows the sustainability triangle with its major components related to the environment, development, and equity. We could to a certain extent aim for a more efficient distribution of resources over the ever-increasing claims or sustainability domains. This leads to shifts in the interior of the small triangle in Figure 1. Yet, at a certain moment, technological innovations will be needed to increase resource-use efficiency for all resource uses, thereby enlarging the space for sustainable development. This is represented by the larger triangle.

One might also say that technological innovations widen the window of opportunities. For example, better nutrient-use efficiency, better land-use efficiency through higher production per hectare, and improved labor productivity through mechanization, etc., are essential technological developments for further agricultural development.

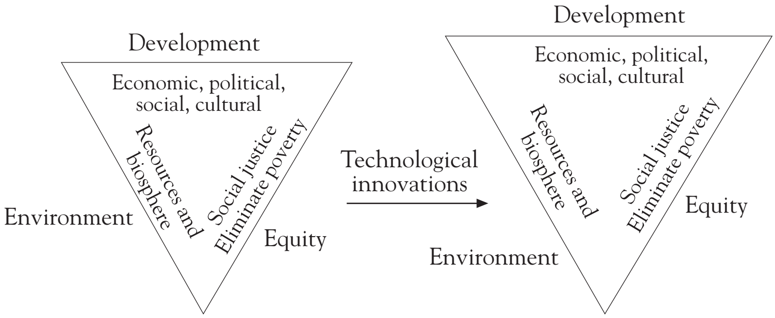

Fig. 1: Increasing the surface of the triangle of sustainability through technological innovations.

At the field level, the optimization of resource use is a key component to achieve the different goals with respect to food supply, income, and protection of the environment. That requires the understanding of genotype × environment × management interactions to better adjust genotype selection and management options to specific local conditions and objectives. Systems approaches are now being used to increase the efficiency of breeding efforts, to determine yield potential in different environments, to optimize water and N use at the field level, and to improve crop protection (through prevention and the use of natural enemies to minimize pesticide requirements (Kropff et al 1997).

C.T. De Wit introduced a forceful theory on resource-use efficiency in agriculture (De Wit 1992). The basis of the theory is the law of diminishing returns when availability of a single resource is increased. De Wit postulates that "most production resources are used more efficiently with increasing yield levels." De Wit also pointed out that higher input-use efficiency reduces the risk of environmental pollution and improves economic performance by lowering the cost:benefit ratio. This law of increasing returns indicates that all resources are most optimally used when the others are close to their maximum as well. Interestingly, it seems that this theory also holds for negative side effects of our systems. Denier van der Gon et al (2002), for instance, show a linear reduction in methane (greenhouse gas) emissions with increasing yield of rice in a specific environment when resources are optimized, confirming the concept of De Wit. The theory and the example point clearly to the possibility of synergy creating a larger triangle at both the development (yield) and the environment (less methane) axis by using resources at the optimum level.

In (re-)designing our systems, many dimensions have to be considered (Fig. 2). Food production systems can be designed at the field scale, while maintenance of nature and wildlife necessitates land-use system designs at the regional scale. Whereas changes at the field scale can be introduced in days

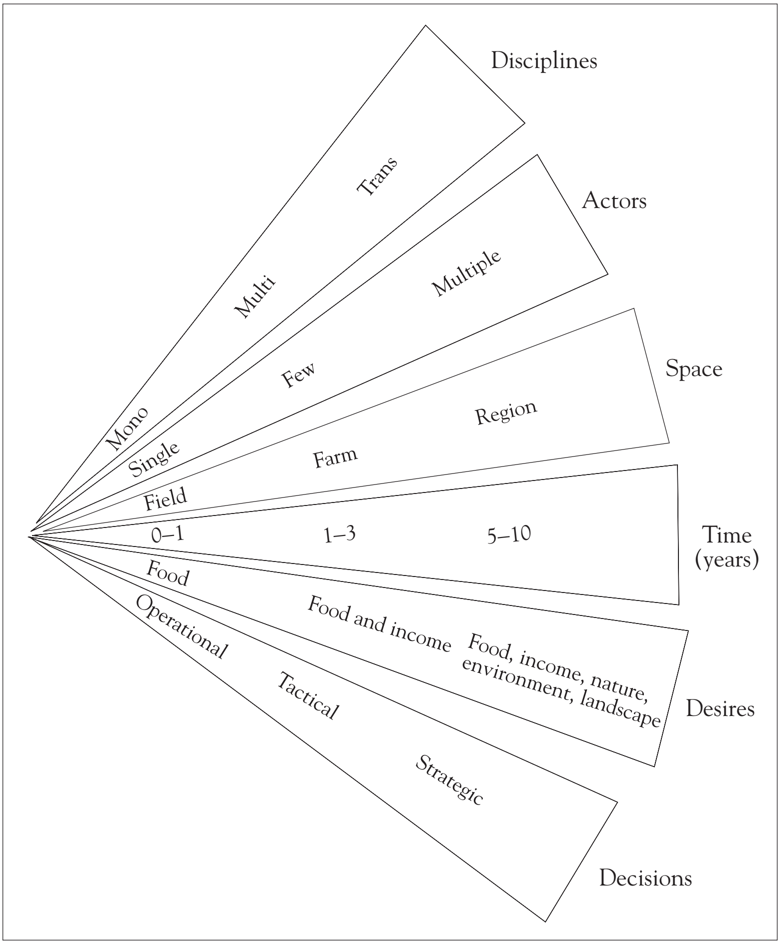

Fig. 2: Multiple dimensions that should be considered in systems design and in transformation processes.

as they concern operational decisions, changes at the farm level are generally of a tactical nature and may take one or more years. To alter the design of a region in order to combine various functions, strategic choices have to be made that may take up to 5 years or more. And finally, operational decisions at the field scale can be made by the farmer alone, and single disciplinary solutions can suffice in addressing occurring field problems. At the regional scale, however, many actors have a stake in the developments and several disciplines should address the complexity of problems.

Methodologies and technologies are generally developed at a specific scale or to link two specific scales. Bouma et al (2006) describe the different phases in the policy cycle that basically apply at all scales: signaling, design,

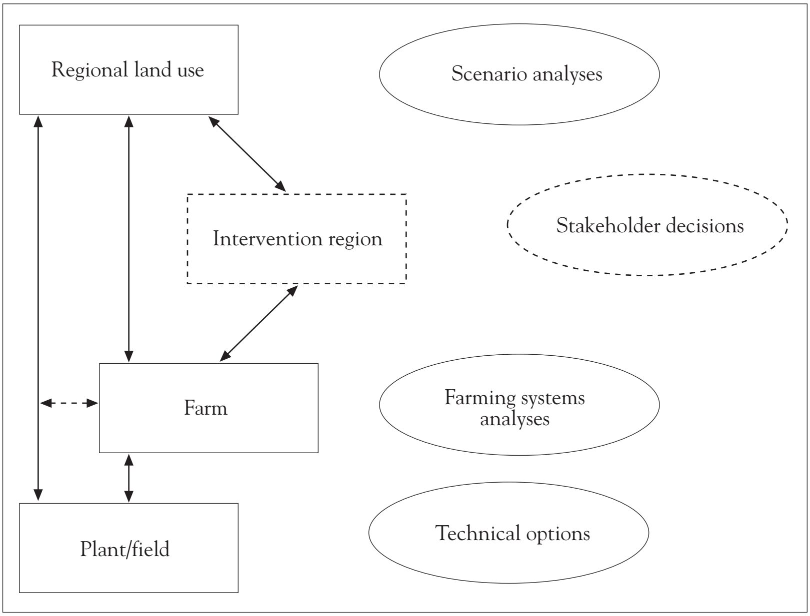

Fig. 3: The missing link in our approaches to enhance the impact of science.

decision, implementation, and evaluation. In all these phases, long-term joint-learning processes are required in which stakeholders and scientists cooperate. Each stakeholder, including the scientists, has a different role in the different phases. Technological solutions are developed based on clear questions to ensure that they will fit in the socioeconomic context in which they will be used. At higher levels of scale, new tools become available that help to explore spatial and temporal opportunities for development assuming specific goals (Bouma et al 2006). Especially when large land reform programs are carried out, a multitude of objectives at various scale levels have to be addressed simultaneously. Also, solutions at one level of scale may not work out when they are applied at a larger scale. A process of transition should be stimulated through the participation of relevant stakeholders from several sectors and administrative scales and, in addition, a systematic search for technological breakthroughs is needed.

Schematically, the scientific analyses at the various scales can be presented as in Figure 3. We develop technological options at the plant and field scale and assess farm livelihood strategies at the farm level considering biophysical and socioeconomic aspects. Scenario analyses for regional land use in fact aggregate field-scale parameters, ignoring the socioeconomic complexity of farming systems and configurations. In some methods, information at the farm level is incorporated through constraints or objectives, but the interaction between farm and region remains minimal.

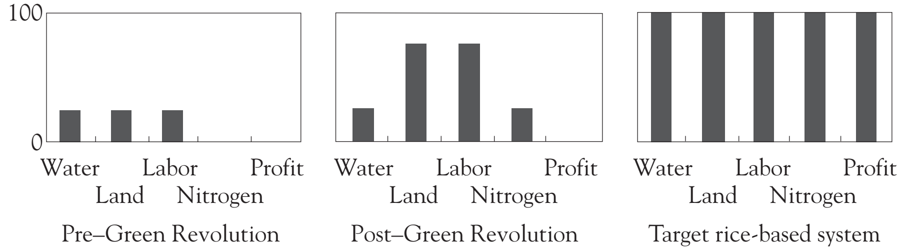

Fig. 4: Schematic evolution in relative resource productivity and profitability of rice-based systems. The latter is derived from the ability to diversify rice-based systems (derived from Bindraban et al 2006).

The missing link in our current approaches is the dashed levels and relations that indicate the actual level of intervention beyond the farm scale, where the farmer has the final decision to act, and below the options given in scenario analyses at the regional scale. Embedding production systems in its landscape calls for interventions that affect multiple actors, the need to integrate multiple objectives, etc. This coincided with the outer spheres of the fan of Figure 2.

Actual implementation of options at the regional scale calls for "postmodern science approaches," with a direct involvement of scientists in the process of transition. Here, technical scientists are supposed to design options that comply with various goals, and social scientists are assumed to take an active part in shaping the process, rather than only studying the process. Likewise, politicians should not only set theoretical conditions that provide the scope and limits to operate but should also actively participate in the process. At the farm level, approaches as used in farmer field schools or practical networks are means to involve farmers in co-innovation at the field level and decision processes at larger-scale levels.

In the following section, we will elaborate on some of these approaches at various scales for the specific case of rice and discuss our achievements so far and challenges ahead.

NATURAL RESOURCE MANAGEMENT AND RICE-BASED SYSTEMS: SCIENTIFIC CHALLENGES AT DIFFERENT SCALES

Resource-Use Efficiency in Rice Systems

In the case of rice, enlarging the surface of the sustainability triangle calls for increasing the use efficiencies of resources that are low compared with those of other crops (Fig. 4). Between 2,000 and 10,000 liters of water are needed to produce 1 kilogram of rice (Bouman and Tuong 2001) compared with 700–1,000 liters for wheat (Rockström 2001). Nitrogen losses in rice fields are high, with efficiencies as low as 30%, whereas efficiencies for wheat can be as high as 70%. The global average yield of rice and wheat per hectare is within the same range, but the inundated cultivation practices of rice hamper the growth of subsequent nonrice crops as a result of poor soil structure after puddling. This strongly limits the ability of farmers to diversify their activities and secure income. Labor demand for rice is as much as 50 to 100 times higher in most systems than for mechanized wheat or rice cultivation.

Maintaining the balance between the sustainable development parameters of rice-based systems seems particularly fragile. They are challenged by the simultaneous demand for increased land and labor productivity, the contribution to poverty alleviation, reduced environmental impact, and increasingly for lower water use. For the coming two decades, rice production volume should increase by 25% to keep up with growing rice consumption, which should be realized on the same and preferably less land area. More stringent is the need to enhance labor productivity. Labor-intensive operations in rice cultivation are under pressure due to the rapid expansion of the nonagricultural sector, stimulating migration of the rural population to urban areas, reducing labor availability, and increasing rural wage rates. Some farmers are seeking to diversify their activities by introducing nonrice crops to stabilize and increase income. Others may continue rice cultivation by minimizing labor input to peak activities only and generating off-farm income during the crop growth period. For the past two decades, high inputs of nutrients and biocides have raised concerns about the environmental impact of intensively managed systems. More recently, the worldwide decline in availability of water resources urges a drastic reduction in the amount of water used for rice production.

For the coming decades, designing rice-based systems requires reconciliation of different and possibly conflicting objectives, within and outside the systems. In the search for rice cultivation practices with higher productivity of water, nutrients, land, labor, and capital, and with safe and nutritious produce, while well embedded within the landscape, dramatic changes in the system should not be disregarded. The largest gains can be expected in current high production areas as the use efficiency of inputs will increase. An array of rice cultivation systems will probably be required, ranging from inundation under monsoon conditions to rice grown as any other irrigated cereal crop elsewhere. In current low-input systems, such as rainfed rice, use efficiencies can be increased strongly only when all other resources are optimized as well. Policy measures that assure proper conditions to enhance the use of inputs in the systems should be developed. The more remote the transformed system will be from current practices, the larger the ecological, economic, and socio-institutional implications and the more pressing the research agenda to support the transformations.

Options to Increase Resource-Use Efficiency in Rice

For various reasons, rice has been predominantly cultivated under inundated conditions for more than 5,000 years. Inundation strongly reduces weed pressure, while the rice plant thrives well. Standing water serves as a buffer for periods of low and unreliable water supply, in particular for rainfed rice systems and for rice grown in poorly managed irrigation systems. Water entering the field carries nutrients, while inundated conditions further increase the availability of other nutrients, especially phosphorus, because of the dissolving effect and the lack of oxygen in the soil (De Datta and Patrick 1986). Under inundated and shaded conditions in rice fields with elevated CO_2 concentration in the water and high availability of phosphate, biological nitrogen fixation may provide up to 100 kg N ha^{-1} per year. In the prefertilizer era, this was the main nitrogen source explaining the sustainability of this ancient cultivation practice; however, yield often did not exceed 2 tons ha^{-1} per year. Land preparation, that is, puddling of heavy soils, was made feasible by animal traction. Finally, soil-borne pathogens such as nematodes were suppressed (George et al 2002).

In the pre–Green Revolution, the production in kg rice per unit of resource was very low, but satisfied the needs and technical possibilities then. Some of the reasons became obsolete after the introduction of high-yielding varieties, chemical fertilizer, biocides, and improved irrigation as part of the Green Revolution. As a consequence, land productivity at the global scale has tripled, with rice yields averaging almost 4 t ha^{-1} today, while in some countries such as China national average yields exceed 6 t ha^{-1}. This increase in land productivity and the associated improvement in labor productivity were realized through an increased use of external inputs, yet water and nitrogen are still not efficiently used.

The interventions in rice systems so far have not changed the basic principle of inundated cultivation of rice, that is, water use as a dominant factor remained untouched. Similarly, other pressing concerns such as labor requirement and cost reduction have not been strongly considered apart from high-tech systems in the United States and Australia. Clearly, rice cultivation systems are resistant to many external influences or absorb them by adaptations within the existing system. However, when pressure increases further as currently is the case, the resilience of the system may be affected and even a small intervention may lead to a drastic change. Scheffer et al (2001) show different stages of systems that may start with gradual changes over time, evolving toward a status of turmoil pushing the system toward a new equilibrium. In terms of Scheffer and colleagues, we may be looking at a rice system that has reached a stage where it is likely to make sudden changes to another state.

In the following sections, we will describe some biological/technological options to modify rice-based systems, illustrated by examples from rice as well as other crops and systems. We thereby incorporate the role of various technical tools, such as crop modeling, information and communication technology, and biotechnology, to support research and we will look at several scale levels from a systems perspective.

Redesigning the Rice Plant

The largest scientific gains in rice have been achieved through the increase in the harvestable portion of the plant and the increased resistance to pests, diseases, and weeds. Further adjustments in plant design may be necessary to better use resources. The penetration ability of rice roots may have to be increased, while the transpiration rate needs to decrease when the crop is grown under drier conditions. Other options are the elongation of the grain-filling period, morphological adjustments, targeting genotypes for specific environments, etc. (e.g., Boote et al 2000, Kropff et al 1997). New tools will be needed in research linking different scales such as systems biology (Yin et al 2004).

The photosynthetic capacity of plants has not been modified so far. Photosynthesis in rice, a C_3 plant, is less efficient than that of C_4 plants such as maize that use an extra chemical process for capturing carbon dioxide. C_4 plants are 50% more efficient at turning solar radiation into biomass. Biotechnology provides the means to increase the photosynthetic rate of the C_3 species by incorporating mechanisms from C_4 crops, for instance (Surrigde 2002). Transforming rice into a C_4 plant would require major morphological and physiological changes in the rice plant, but this is attractive as it might lead to 50% higher yields. Nitrogen-fixing characteristics could be introduced to reduce fertilizer requirements of nonfixing species, and symbiotic relations with bacteria could facilitate the uptake of nutrients such as phosphorus. Also, bacteria can form plant-bacteria associations that protect crops against losses from diseases. Modification of the biochemical processes of the rice plant should be looked into for achieving new system breakthroughs.

Drought and salinity are major abiotic stresses to crop production, also in rice. About 7% of the world's total land area is affected by salt, as is a similar percentage of its arable land (Ghassemi et al 1995). The area is still increasing as a result of irrigation or land clearing. Molecular markers are particularly useful for identifying different traits for salt tolerance (Flowers et al 2000), and other accompanying stresses, such as drought or waterlogging. QTLs (quantitative trait loci) for salt tolerance have been described in several cereal species, including rice (Flowers et al 2000). When salt tolerance and drought resistance could be bred into highly productive rice varieties, the area for rice cultivation could be expanded to marginal areas that currently suffer from salt stress or drought.

Worldwide, more than 2 billion people suffer from anemia and stunted growth due to Fe and Zn deficiency and another 500 million from blindness due to vitamin-A deficiency. Nearly all of the widely grown Green Revolution varieties have similar densities, with iron at about 12 mg kg^{-1} and zinc at about 22 mg kg^{-1}. The potential exists for developing improved rice varieties with enhanced beta-carotene, iron, and zinc in the grain. Because a large part of the diet of the poor in South and Southeast Asia consists of rice, these added micronutrients would have a meaningful impact on human nutrition and health, especially for anemic women and children. Breeding for micronutrients would thus increase solutions for the health-care sector. Certainly, diversifying the diet may have a similar impact, but this requires alternative, more socioeconomic measures such as an increase in income, availability of markets, etc.

The implications of these changes for both plant design and biochemical plant processes would be impressive in terms of natural-resource use, the design of rice-based systems, and land use. Enhanced radiation absorption through optimized morphology and increased photosynthetic rate would potentially reduce the need for land expansion because of higher yields. Nitrogen fixation would lower the need for fossil fuels because of less need for fertilizers, while drought and salt tolerance would allow the cultivation of currently marginal lands. Improved nutritive value of rice through increased micronutrients could solve health problems. Here, the role of technology is prominent.

Redesigning the Rice-Based System

At present, farmers are already modifying their rice cultivation practices to meet their immediate needs. Also, several changes are introduced to farmers from external sources. Although some ways have been found by researchers and other groups to enhance the productivity of land, labor, and water, farmers are not inclined to adopt such practices if these do not fit their economic and social considerations. To prevent the proliferation of unrealistic claims and derailing of the system with strong social implications, more systematic research support is required to truly initiate a process of transition based on co-innovations through the involvement of multiple stakeholders. Sound science should be underlying new technologies and claims should be carefully tested in interaction with farmers.

As the extremely low water-use efficiency of paddy rice systems is a major problem, scientists have been looking for systems to reduce water use, for example, by alternate wetting and drying and systems without standing water. However, a major reduction in water use can be expected only when rice is grown in a dryland system. Such dryland systems exist as upland rice systems in subsistence farming systems with extremely low yield levels. However, it must be possible to reach the same productivity in rice in a dryland situation as in a paddy system. Recent studies on so-called aerobic rice show that this is not yet possible with the current varieties. So far, results are promising in that water use can be reduced by approximately half without a loss in rice yield (Bindraban et al 2006, Bouman et al 2002). In order to lower water use toward that of dry systems such as wheat, modifications in plant design will be necessary, in particular tolerance of drought.

A telling example of a redesigned rice system is the mixed cultivation of various lines. Rice suffers from severe yield losses due to many diseases. Improved varieties respond well to inputs and are generally resistant to major diseases such as blast. However, consumers pay high prices for glutinous rice produced by traditional varieties that lodge and are sensitive to blast. Farmers in Yunnan, China, were exploring the interplanting of traditional glutinous rice together with modern hybrid rice. It was found that yields in carefully co-designed mixtures were higher and blast was not able to infect the glutinous rice plants. Successful proof of principle turned the target location into a demonstration location to disseminate the “new” technology and knowledge. Practical success led to rapid adoption by many farmers.

Planning at the Farm and Regional Level: Options for Decision Making by Stakeholders

At the farm level, many decisions need to consider the trade-offs between different biophysical and socioeconomic objectives. Integrated approaches for farm-level decision support have been developed that consider both biophysical and socioeconomic approaches (e.g., Kropff et al 1997).

At the regional level, methodologies have been developed for ecoregional studies in which the use of systems models converts huge databases into valuable information that can be geographically visualized using GIS for easy interpretation. Scaling issues play a role here and novel approaches have been developed in an ecoregional research program (Bouma et al 2006). Different stakeholders have contrasting ideas and there is not a single truth. The way in which science should deal with this has been studied intensively (e.g., van Ittersum et al 2004). The identification of windows of opportunity can improve the decision-making process of policymakers. Scientists should be involved at all phases in the policy cycle as defined before, by contributions as mediators, facilitators, and suppliers of scientific information in the debate. So, not only in the design phase are scientists needed but also in the evaluation phase to generate new scientific insight based on observations of the processes. One of the cases of the ecoregional program deals with rice-based systems in Southeast Asia. The SYSNET project examined post–Green Revolution issues such as stagnating crop yields in India, Vietnam, and the Philippines (Roetter et al 2005). This prospect developed a Land-Use Planning and Analysis System (LUPAS), which is a modeling framework using multiple-goal linear programming as an integrative component for identifying land-use options that fit best to specific scenarios and policy choices. It presents land-use maps based on these scenarios. For example, in the Philippines in Ilocos Norte Province, the effect of better sharing of irrigation water making water use more efficient would lead to major land-use changes and a farmers' income increase of 16%. All examples from the ecoregional studies reviewed by Bouma et al (2006) show that new methodologies are becoming available but that the main issue is the involvement of the different stakeholders and scientists simultaneously to ensure that scientific information is used effectively in the different phases in the policy-making process.

CONCLUDING REMARKS

The major challenges we face today are related to natural resources in an agricultural context. Especially, the increasing energy demand and strong reduction in fossil fuel resources increase the interest in biological production of fuel. That will cause major changes in agricultural systems, with strong effects on food and feed production and prices as a result of competing claims for natural resources (land, water, minerals), labor, and energy. A major key to addressing these concerns is enhanced resource-use efficiency at different levels of scale. Several examples from rice production systems show that the range of options to enhance resource-use efficiency can be enlarged by biological/technological breakthroughs ranging from new stress-resistance genes to completely new production technologies such as highly productive dryland rice ecosystems. Scientists have to keep on developing new technologies to enhance resource-use efficiency to cope with the reduced availability of many resources in the future.

However, the development of new technology may not automatically lead to adoption or implementation (e.g., absence of a Green Revolution in Africa). And, even successful adoption and implementation such as the Green Revolution in rice systems in Asia may have negative consequences for several groups in society. These problems have to be tackled by new approaches in which problem definition, analysis, design, and implementation of new technologies are conducted in a participatory manner. In this way, technological solutions fit the socioeconomic context in which they can be used. In social sciences, this process is defined as mode-2 science or postmodern science. We call it co-innovation. At the farm level, approaches such as those used in farmer field schools or practical networks can be applied for this purpose of co-innovation. However, the number of issues that should be considered in the process is scale dependent and may even be interrelated. Especially when large land reform programs are carried out, a multitude of objectives at various scale levels have to be examined simultaneously. Also, solutions at one level of scale may not work out when these are applied at a larger scale. To take into account the multitude of issues, objectives, and interests, a process of transition should be stimulated through the participation of relevant stakeholders from several sectors and administrative scales, including a systematic search for technological breakthroughs.

The mode of operation of researchers and research institutions will have to change drastically. Today, most scientific projects are carried out separately from the large-scale development programs in which systematic use of new insights from science could be beneficial. Researchers should participate in platforms of multiple stakeholders for a more effective articulation of their research questions. These regular contacts will also facilitate a more effective implementation of research findings. However, not all responsibility for effective demand articulation or implementation lies with researchers. Embedding the research effort in mega implementation projects such as those being undertaken by development banks and governments should be facilitated by policymakers. A current water reformation program being implemented in Indonesia, for instance, could benefit from ongoing research on growing rice with less water. Vice versa, the research community could formulate its research questions much more effectively. We have illustrated, though for rather small projects, that participatory processes for systems innovations are feasible and are currently being implemented. However, better interaction between scientists and other stakeholders is an essential component to make science for impact possible.

We realize the need for researchers and other stakeholders to actively engage in development processes. The reality is, however, that such processes are not easy to implement. We are still far away from proven examples of the missing link as indicated in Figure 3 where actual implantation of change takes place at scale levels going beyond the farm. Examples show that participatory research linked to explanatory biological/technological research may help to understand and optimize the system. Similarly, integrated pest management programs operated at the level of farm decision making, though implemented at a regional scale, enhanced the impact of reduced pest and disease incidence.

The number of examples to illustrate successful interventions at higher scale levels is scarce. At these higher scale levels, a multitude of system components such as farms, infrastructure, nature areas, urban centers, markets, factories, etc., are present, holding complex relations with each other. These components and relations tend to resist change as the change of one requires the change of all. It is therefore a challenge to achieve an impact of scientific findings through deliberate and coherent policy to change agricultural systems at the regional scale.

The rice system faces a multitude of challenges that should be addressed simultaneously and at various scale levels. We have to realize that the drastic socioeconomic and ecological disturbance of the conventional system of inundated and transplanting cultivation of rice may have positioned it in a stage that could lead to sudden large-scale changes as described in the theories of Scheffer et al (2001). Scientists should be alert to this situation and look for innovative and realistic options and rewarding synergies with developments at other scale levels. The proliferation of unfounded recommendations to change the system may find its roots in the susceptibility of farmers to jump into solutions because of pressing conditions, but may lead to unforeseen side effects, only temporary incremental change, and disappointments. We should not just look at mitigating adverse side effects or at better distribution of resources within the existing triangle, but we should provide technological innovation to increase the solution space by increasing resource-use efficiency for all resource uses. To facilitate a process of fundamental change, we need to develop options that comply with production ecology principles (De Wit 1992), we need systems approaches, and we need co-innovation at all scale levels. We will not be able to realize these drastic transformations that are required without technological breakthroughs using our best technical knowledge and means. We should at the same time realize that any transition of production systems calls for adjustments in socio-political conditions and may come with severe socioeconomic and political implications, yet these adjustments will be utterly necessary. A closer relation between science and policy will therefore be needed to marry technological innovation and socioeconomic well-being.

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