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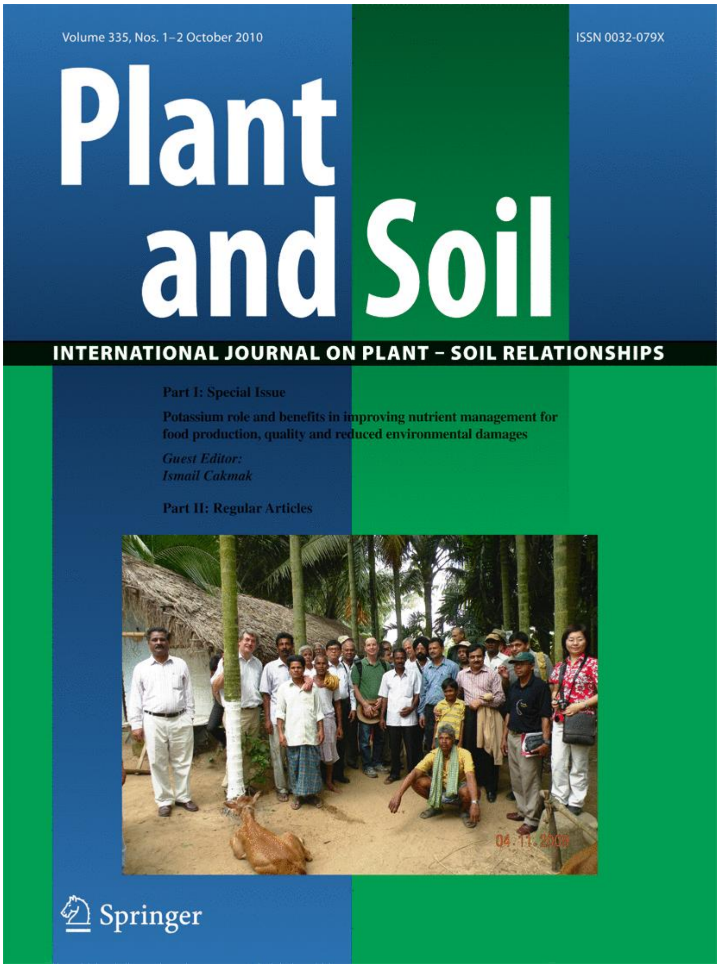

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Potassium role and benefits in improving nutrient management for food production, quality and reduced environmental damages

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REGULAR ARTICLE

Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management

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Abstract Rice (*Oryza sativa* L.) and maize (*Zey mays*) are grown in 3.5 million hectares (Mha) in Asia that includes 1.5 Mha in South Asia. These crops are grown in sequence on the same land in the same year either in double–or triple-crop systems to meet the rice demand of a rapidly expanding human population and maize demand of livestock and poultry. The objective of this review is to provide a comprehensive overview of the current state of technical knowledge on agro-ecosystems and adaptation, area and distribution, yield potential and yield gaps, and nutrient management for rice-maize (R-M) systems in South Asia. Rice-maize systems are emerging all around South Asia but in particular are developing quite rapidly in Bangladesh and South and North India. Yield potential of rice and maize, as estimated by ORYZA2000 and Hybrid Maize models, reaches up to 15 and 22 t ha^{-1}, respectively. However, data from several environments in India reveal gaps between potential and attainable yields of maize of upto 100% and between attainable and actual yields of upto 25–50%. Nutrient demand of R-M system is high due to high nutrient removal by high-yielding maize. Nutrient balance studies for these highly–productive and nutrient-extractive systems are scarce in South Asia. The review outlines principles of nutrient management for R-M systems, and identifies development, refinement, and dissemination of the integrated plant nutrition system technologies based on site-specific nutrient management principles as priorities for future research to increase yield, profitability, and sustainability of R-M systems.

Keywords Rice-maize · Yield potential · Yield gaps · South Asia · Integrated plant nutrition system · Site-specific nutrient management

Introduction

Rice, maize, and wheat are major cereals contributing to food security and income in South Asia. These crops are grown either as a monoculture or in rotations in tropical and sub-tropical environments of South Asia. In the irrigated and favorable rainfed

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lowland areas, rice-rice (R-R), rice-wheat (R-W), and rice-maize (R-M) are the predominant cropping systems. Rice-rice is common in tropical climate with distinct dry and wet seasons such as in South India, and in sub-tropical areas with mild cool winter climate such as in Bangladesh, Eastern India, and Eastern Nepal. Rice-wheat systems are extensive in the sub-tropical areas of the Indo-Gangetic Plains (IGP) of Bangladesh, India, Nepal, and Pakistan (Timsina and Connor 2001) while R-M systems exist in all climate ranging from tropical to sub tropical to warm temperates (Timsina et al. 2010). Rice-maize systems, however, are less extensive as compared to R-W or R-R if total area under these cereal systems is considered. There are mainly three cropping seasons in S. Asia: summer or *kharif* or *monsoon* (or called *kharif-II* or *aman* in Bangladesh) from June/July to Sept/Oct, *rabi* or winter from Oct/Nov to Feb/Mar, and spring or *pre-kharif* or *pre-monsoon* (or *kharif-1* in Bangladesh) from Mar/Apr to May/June. Rice (called transplanted aman or T. *aman* in Bangladesh) is the main crop in summer while a wide range of crops, including rice (called *Boro* in Bangladesh, eastern India and eastern Nepal), wheat, maize, winter pulses (chickpea, lentil, field peas), potatoes, and mustard are grown in *rabi* or winter season. In the *kharif-1* or spring season, short-duration crops such as maize, pulses (mungbean, cowpea), and rice (called *aus* in Bangladesh) are grown. All the three major double-crop systems (R-R, R-W, R-M) often include an additional crop such as potato, lentil, chickpea, mustard, etc. in *rabi*, and jute, maize, rice, mungbean, cowpea, etc. during *kharif-1* or *spring* season (Table 1).

Table 1 Area (Mha) under major cropping systems in four south Asian countries (Source: modified and updated from JK Ladha, unpublished data)

Cropping system	Area (Mha)			
	Bangladesh	India	Nepal	Pakistan
Rice-rice	4.50	4.70	0.30	
Rice-rice-rice	0.30	0.04		
Rice-wheat	0.40	9.20	0.57	2.20
Rice-maize	0.35	0.53	0.43	NA[a]
Maize-wheat		1.80	0.04	1.00
Rice-pulses		3.50		
Rice-vegetable		1.40		
Millet-wheat		2.44		
Rice-potato	0.30	NA		
Cotton-wheat		NA		3.10

[a] Areas exist but data not available

Much is known about rice and maize production systems separately in South Asia. Also, the other two important systems, R-R and R-W, have been researched and reviewed rigorously (for example, see Timsina and Connor 2001 for a comprehensive review of R-W system). Research on R-M system, on the other hand, did not receive any priority until recently. Consequently, there are only a few published papers in scientific journals, and no critical review papers on any aspects of the R-M systems.

Rice-rice systems differ completely from R-W or R-M systems because in the former both crops are grown under flooded conditions, so root development and water and nutrient dynamics would be similar to both rice crops. In contrast, due to similar growing conditions and altered soil hydrology from flooded rice to non-flooded wheat or maize, R-M and R-W systems would face similar soil physical environment as both wheat and maize roots could break plow pans and roots could grow deeper in the profile. Hence, the soil physical and structural properties under R-M system would be fairly similar to that under R-W system. Timsina and Connor (2001) have critically reviewed the soil physical and chemical properties and associated management for alternating wetting and drying environments of R-W system that could be well applied to R-M system as well. However, in contrast to wheat which is grown only in rabi season, maize is also grown during pre-kharif or kharif-1 (spring) and kharif (summer) seasons, especially under rainfed situation. While kharif maize is generally grown in uplands or higher landscape fields kharif-1 maize is grown in low-lying rice fields. Hydrology and transient waterlogging of maize would vary between rabi and the two kharif seasons. In rabi maize the risk of waterlogging occurs during emergence and seedling establishment while during kharif-1, waterlogging risk due to pre-monsoon rainfall occurs during reproductive stage. In addition, kharif-1 crops could also be damaged by heavy storms accompanied by the pre-monsoon rainfall. Transient waterlogging due to heavy rainfall and heavy storms could be more damaging then transient waterlogging during establishment of rabi maize. Both waterlogging events could, however, alter soil hydrology and nutrient dynamics both during waterlogging and during drying following waterlogging. Such altered hydrology could also bring changes in soil-borne diseases and insects and weed ecology and weeds abundance. Breeding for tolerance to transient waterlogging for maize would be necessary for successful growing of maize in both rabi and kharif-1 seasons. Conservation agriculture (CA) based agronomic practices such as raised beds and reduced tillage would be potential options help alleviate the risk of waterlogging in both seasons.

One aspect of R-M system that is different from R-W or R-R system is that the nutrient extraction and nutrient drawdown from R-M system would be much greater due to higher yield of maize. High-yield maize crops would require higher amounts of nutrients than that would be required for rice or wheat. Hence, if fertilizers are not added as per the requirements for high target yield of maize there is a possibility of nutrient mining. Realistic nutrient drawn (especially P and K) factors could be derived for each soil and crop growing environments whereby yield could be optimized and profit could be maximized without substantial mining of nutrients from the soil (Buresh et al. 2010). At present, there are no literatures on these aspects of R-M systems. Research is required to understand the various aspects of R-M systems that would improve the productivity, profitability, and sustainability of these systems in South Asia.

The magnitude and intensity of R-M systems in the region depend in part upon soil and climate but, more importantly, on the socio-economic circumstances of the farmers, demand of maize by livestock (especially poultry) sector, and domestic and international markets of maize for food, feed and fuel industries. It should also be noted that the R-M systems are also prevalent in Indonesia and common in China and Vietnam but published literatures are lacking. The objective of this review is to provide the comprehensive overview of the current state of technical knowledge in relation to agro-ecosystems and adaptation, area and distribution, yield potential and yield gaps, and nutrient management of R-M systems in South Asia. The review is based on the existing, limited published and unpublished literature on R-M systems, focusing on nutrient management. The review highlights the issues and priorities for future research on R-M systems in general, and for nutrient management in particular. Separate reviews could be justified for R-M systems in East and Southeast Asia as well as on the socio-economic issues and value chain analysis of rice and maize in relation to nutrient and fertilizer management for these systems.

Distribution of R-M systems and fertilizer use in South Asia

Rice-maize systems are distributed all over South Asia but more particularly in Bangladesh, India, Nepal, and Pakistan (Timsina et al. 2010). Dynamics of the area and productivity of R-M systems in different countries depend on the dynamics of area and yield per hectare of rice and maize in those countries. FAO statistics indicate small increases in rice area in the above four south Asian countries from 1976 to 2006 but the rice production more than doubled due to increase in average yield over the same period. Maize area increased dramatically in Bangladesh, Nepal, and Pakistan but slowly in India. However, production in all countries increased substantially due to increase in area as well as yield per hectare with the use of maize hybrids (www.faostat.fao.org). FAO statistics for fertilizer use for the three major cereals (rice, maize, wheat) over the same period reveal that the trend in consumptions of N fertilizer is highest followed by P and K fertilizers. Fertilizer consumption in India and Bangladesh increased steadily since 1961 until recently but that in Nepal and Pakistan was variable (www.fao.org/site/575/default.aspx). There are common concerns of imbalanced fertilizer use (i.e., very high use of N, less use of P, and negligible use of K, S, and micronutrients), soil nutrient mining, and soil organic matter and soil fertility decline (FAO 2006) in all the four countries.

Yadav and Rao (2001) identified the main maize-based cropping systems in irrigated and rainfed conditions in different agro-climatic regions of India. Cropping systems with rice and maize together in the system are presented from their study in Table 2. The Planning Commission of India has delineated country in 15 broad agro-climatic regions based on physiography and climate, and R-M systems are prevalent in all agro-climatic regions, especially in the IGP (Pandey et al. 2008; Gill et al. 2008a, b). Pandey and Sud (2007) and Singh et al. (2008) also showed prevalence of maize in potato–and rice-based systems

Table 2 Main cropping systems involving rice and maize in different ago-climatic zones of India (Source: Modified from Yadav and Rao 2001)

Agro-climatic region	Cropping system	
	Irrigated	Rainfed
Eastern Himalayan region	Summer rice-maize-mustard	Sesame-rice + maize
Lower-Gangetic Plain region	Autumn rice-maize Jute-rice-maize	Rice-maize
Upper-Gangetic Plain region	Rice-potato-maize	
Eastern Plateau & Hills region		Rice-potato-maize
Southern plateau & Hills region	Maize-rice Rice-maize	
East Coast Plain and Hills region	Rice-maize-pearl millet Maize-rice Rice-maize Rice-rice-maize	Rice-maize + cowpea
West Coast Plain and Hills region	Rice-maize	Rice-maize
Gujarat plains and hills region		Rice-maize
Island region	Rice-maize	Maize-rice Rice-maize + cowpea Rice-maize-urdbean Rice-rice-maize

in different agro-ecological regions of India. Likewise, R-M systems have been highly intensified and diversified all over Bangladesh. Even within a small district of Bogra in northern Bangladesh, for example, several forms of R-M systems exist with the use of diverse maize hybrids (Ali et al. 2008, 2009).

Rice-maize agro-ecosystems in Asia

Timsina et al. (2010) have identified four main R-M agro-ecosystems with four broad climates in Asia, of which three exist in South Asia (Table 3). The first agro-ecosystem (tropical, warm, semi arid, no winter) includes locations in southern India with tropical monsoon with a longer dry season. In this agro-ecosystem, both rice and maize are not limited by low temperature and can be grown all year round. Here either the fallows after rice are replaced by a maize crop, or the existing areas under rice-rice-maize and rice-maize-maize systems are increasing in acreage. The second agro-ecosystem (sub-tropical, sub-humid, warm summer, mild cool winter) includes locations in Bangladesh, Nepal, and northern India. In this agro-ecosystem, winter is mild cool so rice maybe limited by low temperature. Maize, however, will perform well due to mild cold winter and long grain-filling period and can replace wheat or *Boro* rice. The third agro-ecosystem (sub-tropical to warm temperate, sub-humid, warm summer, mild to severe cold winter) has been classified into 2 sub-classes, and includes areas in north and northwest India, Terai and hills of Nepal, and Punjab and Sindh provinces in Pakistan. In this agro-ecosystem, both rice and maize can be limited by low temperature and hence can not be grown for sometime in winter. In all the agro-ecosystems, due to decreased availability of irrigation water, some areas under rice, cotton, and sorghum in summer are already or will likely be replaced by a summer maize crop.

Why R-M systems are important in South Asia?

Excluding China and Pakistan for which exact data for R-M area are not available, R-M systems currently occupy approx. 3.5 Mha in Asia (Timsina et al. 2010). Excluding Pakistan, area under R-M systems is 1.31 Mha in South Asia (Table 4). The highest acreage is in India followed by Nepal. The absolute area under R-M system is less in Bangladesh compared to other south Asian countries but it is

Table 3 Key emerging R-M agro-ecosystems in South Asia (Source: modified from Timsina et al. 2010)

Key features	Current systems	Emerging systems	Key examples
1. Tropical, warm, semiarid, no winter			
Tropical monsoon with longer dry season; both rice and maize not limited by low temperatures and can be grown all year round	Rice-rice Rice-rice-pulses	Rice-maize	Cauvery Delta (Tamil Nadu), Karnataka and A.P., India
2. Sub-tropical, subhumid, warm summer, mild cool winter			
Sub-tropical monsoon with cool winter and summer rainfall; rice but not maize maybe limited by low temperatures	Rice-wheat	Rice-maize	Central, western, and NW Bangladesh;
	Rice–*Boro* rice	Rice-rice-maize	
			Eastern Terai, Nepal;
		Rice-potato-maize	West Bengal, eastern UP and Bihar, India
3. Sub-tropical to warm temperate, subhumid, semiarid, warm summer, mild to severe cold winter			
3.1. Sub-tropical monsoon with cold winter and summer rainfall; both rice and maize limited by low temperatures and can't be grown for some time in winter	Rice-wheat	Rice-maize	North and NW India; Central and western Terai and mid-hills, Nepal
3.2. Sub-tropical to warm temperate, semiarid, with hot summer and cool to cold winter; very low rainfall; both rice and maize limited by low temperatures and can't be grown for some time in winter	Rice-wheat Cotton-wheat Sorghum-wheat	Rice-maize Rice–potato- maize	Punjab and Sindh, Pakistan

increasing rapidly over the past 5-6 years (Ali et al. 2009). Rice-maize systems are practiced mostly in the south (Andhra Pradesh, Tamil Nadu, and Karnataka) and in the northeast (Bihar and West Bengal) parts of India with an acreage of more than 0.5 Mha (Table 5). Andhra Pradesh has the highest acreage under R-M system in South India where this system is rapidly increasing under resource-conserving technologies, mostly zero tillage (Jat et al. 2009). Of the four south Asian countries, R-M systems are rapidly spreading in South India and Bangladesh, driven by the rising demand for maize, especially by poultry sector, and tightening world export-import markets. The recent development of short-duration rice varieties and maize hybrids with improved drought tolerance is also providing opportunities for the expansion of R-M systems into areas of South Asia with insufficient irrigation or rain for continuous rice cultivation.

Table 4 Current areas (Mha) under R-M systems in South Asia (Source: Modified from Timsina et al. 2010)

Country	Area (Mha)		
	Rice	Maize	R-M
India	43.4	7.80	0.53
Bangladesh	10.5	0.38	0.35
Nepal	1.6	0.90	0.43
Total	55.5	9.08	1.31 (exc. Pakistan)

Table 5 Estimates of acreage (ha) under R-M system in India (Source: ML Jat 2009, unpublished data)

State	Area (ha)
Andhra Pradesh	250,000
Tamilnadu	30,000
Karnataka	20,000
Bihar	120,000
West Bengal	60,000
Orissa	20,000
Other states	25,000
All India	525,000

Drivers of change from other systems to R-M systems

Among the three competitive crops (*Boro* rice, maize, wheat) in the *rabi* season in Bangladesh, maize has clear superiority over the other two crops. Though hybrid maize requires high input, especially nutrients, it has a very high output that makes it over twice more profitable than wheat or *Boro* rice (Ali et al. 2008, 2009). Maize also requires far less water than *Boro* rice and produces consistently much higher yield than *Boro* rice and wheat. In particular, wheat is often vulnerable to temperature fluctuation resulting in shriveled grains and poor yield. Besides, maize has fewer pest and disease problems than *Boro* rice and wheat.

Maize needs around 850 l water per kg grain production (with 2–4 irrigations) compared to 1,000 l/kg wheat grain (1–3 irrigations) and over 3,000 l/kg rice grain (with 20–35 irrigations) for *Boro* rice (Ali et al. 2009). The high financial and environmental costs of irrigating *Boro* rice from electric or diesel pumps is an increasing concern. There are increasing evidences from Bangladesh that arsenic (As) moves along with irrigation water from soil to the plant and then to the grain. Thus, there is a greater chance of As accumulating into the soil, its uptake by the plant, and entering into the food chain through *Boro* rice cultivation (Duxbury and Panaullah 2007). Thus, growing *rabi* maize may be environmentally safer due to less water requirement and less chance of As accumulation in soils and plants and its subsequent transport to food chain. Where soils are already contaminated with As, maize can be grown instead of *Boro* rice as an As management option.

Similarly maize is considered to be a better alternative to wheat or *Boro* or rabi rice due to several reasons: (a) wheat encounters several biotic stresses, and most importantly, abiotic stresses due to terminal heat stress in the IGP, (b) evidences of declining yield of *Boro* rice in West Bengal and Orissa, and (c) water scarcity in peninsular India affecting yield of *rabi* rice in Andhra Pradesh and Tamil Nadu. Peninsular India and Bangladesh are considered to be neutral environments where maize can be cultivated in all seasons and this is emerging as a potential driving force for diversification from the existing cropping systems to a R-M system. A recent study by National Centre for Agricultural Economics and Policy Research (NCAP) in India has also shown an increasing demand for maize by the industry sector which caters to consumer needs like textiles, paper, glue, alcohol, confectionery, food processing, and pharmaceutical industry, etc. (Dass et al. 2008a). Therefore, in the changing farming scenario in South Asia, maize is emerging as one of the potential crops in rice-based systems that can favorably address several issues like food and nutritional security, climate change, water scarcity, farming systems, bio-fuel demand and other industrial requirements.

Yield potential of rice and maize in R-M systems in South Asia: a modeling analysis

Yield potential (Yp) of any crop cultivar/hybrid for a site (called site Yp) and for a given planting date is the yield achieved when grown in environments to which it is adapted, with nutrients and water non-limiting and pests and diseases effectively controlled (Evans and Fischer 1999). Yield potential will be different for different varieties and for different planting dates. Attainable yield (Yat), generally set at 80–90% of Yp, is average grain yield in farmers' fields with best management practices and without major limitations of water and nutrients. Attainable yield can be limited by variety, planting density, water and nutrient management, soil-related constraints (acidity, alkalinity, salinity, etc.), and climate-related constraints (flooding, drought, etc.). Actual yield (Yac) is the yield farmers receive with their average management under all possible constraints. Yield potential of any crop species or varieties can be estimated by use of crop simulation models. A detailed study on Yp of rice and maize for R-M systems was done by Timsina et al. (2010) who used the ORYZA2000 (Bouman et al. 2001) and Hybrid Maize (Yang et al. 2004) models and long-term National Aeronautics and Space Administration (NASA) climate data to estimate Yp for several sites in nine Asian countries, including the four south Asian countries reviewed here. In that study, four generic rice varieties differing in maturity (extra short-, short-, and long-duration) were created by calibrating the DVRJ (development rate during juvenile phase), DVRI (development rate during photoperiod sensitive phase), DVRP (development rate during panicle development phase) and DVRR (development rate during reproductive phase) coefficients used in the model. Coefficients for an intermediate maturity type as used for IR72 were adapted from Bouman et al. (2001). The growth durations for extra short-, short-, intermediate-, and long-duration varieties in the four south Asian countries ranged from 75 to 110 days, 90 to 125 days, 110 to 150 days, and 130 to 180 days, respectively. Mean Yp of extra short, short, intermediate, and long-duration rice varieties across R-M agro-ecosystems, as predicted by ORYZA2000, ranged from 0.6 to 9.0, 0.7 to 10.8, 0.6 to 12.8, and 0.7 to 17.6 t ha^{-1}, respectively (Table 6). There were large differences in Yp amongst sites within a country, amongst the countries, as well as amongst planting dates at each site (Timsina et al. 2010). For each site, Yp was highest for long and lowest for extra short-duration varieties. The large ranges in Yp for different varieties were associated with large variations in growth duration, total intercepted solar radiation, and growing season mean temperature leading to differences in grain-filling period. In the tropical to sub-tropical climate, Yp was highest for Dinajpur in Bangladesh and Begusarai in Bihar followed by Bogra in Bangladesh. In the sub-tropical to warm temperate climate, Yp was highest in Punjab in India followed by Chitwan in Nepal. Yield potential in Pakistan was intermediate.

For maize, four hybrids differing in growing degree days (GDD), defined as cumulative degree days from seeding to physiological maturity, ranging from 1,300 to 1,800 GDD, were used. Yield potential of the four hybrids ranged from 7.1 to 19.7 t ha^{-1} in India (with 1,400 to 1,800 GDD), from 8.7 to 20.4 t ha^{-1} in Bangladesh (with 1,500 to 1,800 GDD), from 5.8 to 22.4 t ha^{-1} in Pakistan (with 1,300 to 1,700 GDD), and from 11.1 to 32. 7 t ha^{-1} (with 1,500 to 1,800 GDD) in Nepal (Table 6). Planting during August to November gave exceptionally high yields due to low temperature during grain filling, long growth duration, and large receipts of solar radiation (Timsina et al. 2010). Thus for rabi planting of maize after rice in South Asia, October and November would provide high Yp and would help in successful intensification and diversification of the rice-based systems. Likewise, for *kharif-1* or *pre-monsoon* season, late March to early May planting would result in reasonably high Yp and the maize crop would fit easily into the rice-based systems. Very long growth duration in warm temperates of Chitwan, Nepal, and two sites in Pakistan resulted in unrealistically high yields due to larger receipts of solar radiation. The Hybrid Maize model needs to be further tested and refined for warm temperate region of South Asia.

Attainable and actual yields of maize in India

The difference between attainable yield (Yat) and actual yield (Yac) of crop species and varieties can be quite large. Attainable yield of maize in farmers' fields, achieved under optimal conditions, can vary significantly across the agro-ecologies mainly due to genotype x environment interactions but also due to confounding influence of biotic and abiotic stresses and agronomic management.

Dass et al. (2008b) reported Yat and Yac of maize from experiments conducted in 13 representative locations in various agro-environments for 9 years (1995–2003) under the All India Coordinated Research Project (AICRPM) on maize. The selected locations were first divided into two categories: locations having lower productivity than the national average (Banswara, Udaipur, Godhra, Varanasi, Kanpur and Chhindwara) and locations (Mandya, Arbhavi, Ludhiana, Dhaulakuan, Bajaura, Dholi and Hyderabad) having greater productivity as compared to national average. Data indicated that the Yac is always less than Yat under all the agro-environments due to limited availability of agronomic inputs and their scheduling. Potential for improving Yat was more at the locations of the first group as compared to the locations of the second group. Except Banswara, other locations of the first group showed the potential for achieving Yat of 4–6 t ha^{-1}, while Yac at all the locations of this group was less than half (1-2 t ha^{-1}) of the Yat. It has also been reported that present average Yac at farmers' fields is only about 50% of the Yat, which could be increased through adoption of improved technology. On the other hand, Yat for most locations was about 4.0 t ha^{-1} except for Arbhavi (5.9 t ha^{-1}) in the high productivity group, whereas, Yac at most of the locations of this group was more (1.2–3.4 t ha^{-1}) as compared to the low productivity group (Dass et al. 2008b).

Data from multi-location trials in India in 2007 and 2008 on integrated nutrient management in hybrid

Table 6 Yield potential (Yp, t ha^{-1}) of rice varieties and maize hybrids for several locations in four south Asian countries (Source: Modified from Timsina et al. 2010)

Country	Location	Rice		Maize	
		Variety	Yp (t ha^{-1})	Hybrid	Yp (t ha^{-1})
Bangladesh	Bogra	Extra short	4.4–8.1	1,500	8.8–12.6
		Short	5.2–9.6	1,600	9.8–16.8
		Intermediate	6.4–11.0	1,700	10.9–18.3
		Long	7.8–11.5	1,800	12.0–19.6
	Dinajpur	Extra short	4.5–9.0	1,500	9.0–16.5
		Short	5.1–10.2	1,600	10.2–18.1
		Intermediate	6.1–12.3	1,700	11.2–19.3
		Long	6.2–14.5	1,800	12.2–20.4
	Jessore	Extra short	4.3–7.5	1,500	8.7–14.2
		Short	5.5–9.0	1,600	9.7–16.0
		Intermediate	7.0–10.4	1,700	10.7–17.7
		Long	8.2–12.9	1,800	11.8–19.0
India	Begusarai	Extra short	4.6–8.9	1,500	8.1–14.9
		Short	5.5–9.9	1,600	9.2–16.9
		Intermediate	7.4–11.5	1,700	10.4–18.5
		Long	6.2–14.8	1,800	11.4–19.7
	Aduthurai	Extra short	4.0–6.3	1,500	9.1–11.2
		Short	5.4–7.7	1,600	10.2–12.5
		Intermediate	6.5–9.7	1,700	11.2–14.0
		Long	8.4–11.9	1,800	12.3–5.0
	Thanjavur	Extra short	4.1–6.1	1,400	9.2–11.1
		Short	5.1–7.5	1,500	10.2–12.4
		Intermediate	6.9–9.4	1,600	11.1–13.6
		Long	8.7–11.5	1,700	12.2–14.7
	Bangalore	Extra short	6.4–7.7	1,400	10.0–13.3
		Short	7.9–9.2	1,500	11.2–14.9
		Intermediate	10.0–11.5	1,600	12.3–16.4
		Long	12.2–13.8	1,700	13.6–17.6
	Nalgonda	Extra short	4.8–7.0	1,400	7.7–12.6
		Short	5.1–8.3	1,500	9.1–14.2
		Intermediate	6.1–10.6	1,600	10.0–15.8
		Long	8.2–12.6	1,700	10.7–17.0
	Ludhiana	Extra short	3.0–8.8	1,500	7.1–16.6
		Short	2.9–10.8	1,600	8.2–20.4
		Intermediate	3.0–12.8	1,700	9.0–23.7
		Long	2.6–17.6	1,800	9.8–26.0
Nepal	Chitwan	Extra short	1.6–8.7	1,500	11.3–27.4
		Short	1.7–9.3	1,600	13.1–29.7
		Intermediate	1.9–10.9	1,700	14.1–31.3
		Long	2.1–14.4	1,800	15.4–32.7
Pakistan	Larkana	Extra short	2.1–7.0	1,400	6.2–17.2
		Short	2.5–8.0	1,500	7.0–19.2

Table 6 (continued)

Country	Location	Rice		Maize	
		Variety	Yp (t ha^{-1})	Hybrid	Yp (t ha^{-1})
		Intermediate	2.8–9.5	1,600	7.8–20.7
		Long	3.8–11.5	1,700	8.6–21.9
	Okara	Extra short	0.6–4.7	1,300	5.8–17.7
		Short	0.7–5.6	1,400	6.7–18.4
		Intermediate	0.6–8.0	1,500	7.6–18.4
		Long	0.7–10.0	1,600	8.4–22.4

maize (HQPM-1) revealed linear yield increase, without any yield plateau, upto 150% of recommended N rate (150:60:40 kg N, P_2O_5 and K_2O/ha) together with 6 t ha^{-1} FYM, which indicates that more N will be required than the existing rates to achieve higher yield (unpublished data, ML Jat). Grain yield and grain and straw N uptake data on response of 6 hybrids under three nutrient levels (100:50:50; 150:65:65; 200:80:80 kg N, P_2O_5 and K_2O/ha, respectively), however, reveal highest yield from 150:65:65 treatment and varying responses of different hybrids to the three nutrient levels. Hybrids varied significantly in nutrient uptake indicating their differences in efficiency as well as nutrient requirements (unpublished data, ML Jat). The data reveal that Yat of maize can be quite large, and so yield gap between Yp and Yat, between Yat and Yac, and that between Yp and Yac can be minimized.

Nutrient management for R-M systems

Principles of nutrient management

Rice-maize systems extract large amounts of mineral nutrients from the soil due to large grain and stover yields. Proper nutrient management of exhaustive systems like R-M should aim to supply fertilizers adequate for the demand of the component crops and apply in ways that minimize loss and maximize the efficiency of use. The amount of fertilizer required depends on many factors including the indigenous supply of each nutrient which can be in appreciable quantities (Cassman et al. 1998). Phosphorus inputs from irrigation and rain waters are negligible (Dobermann et al. 1998) but 1,000 mm irrigation through surface water may provide up to 30 kg K ha^{-1} yr^{-1} (Dobermann et al. 1996, 1998) and up to 1,100 kg S ha^{-1} yr^{-1} (Pasricha 1998). In R-M areas where groundwater is used, K inputs may be much larger than 30 kg ha^{-1}. Thus, to achieve and sustain the high yields currently demanded of R-M systems, emphasis must be upon the nutrient requirements for target yields and nutrient supply by integrated use of indigenous sources, soil organic matter (SOM), farm yard manure (FYM), composts, crop residues, and increasingly, inorganic fertilizers. Fertilizer is the dominant source of nutrients and is required to increase yield of individual crops in R-M systems but should be applied in such a quantity that it becomes profitable and will have least adverse effect on environment. In the exhaustive R-M systems, it is necessary to attend to the distinct requirements and growing conditions of the individual crops. The inclusion of legumes or potato in the R-M system further increases the demand for the macronutrients (N, P, K, Ca, Mg, S) that they require in larger quantities than cereals.

Inorganic fertilizers

Timsina and Connor (2001) devised principles of fertilizer practice required to achieve high efficiency of use and high sustainable yield in R-W systems that could equally apply to R-M systems. Of all the nutrients, nitrogen (N), phosphorus (P), and potassium (K) remain the major ones for increased and sustained productivity. However, the development of high yielding R-M systems will likely exacerbate the problem of secondary and micronutrient deficiencies, not only because larger amounts are removed, but also because the application of large amounts of N, P, and K to achieve higher yield targets often stimulates the deficiency of secondary and micronutrients (Johnston et al. 2009).

Nitrogen management requires special attention so that potentially large losses can be minimized and efficiency can be maximized. During the growing season of rice, the aim of fertilizer management should be to reduce N loss through denitrification, volatilization and leaching by either deep placement or split applications to match crop demand and to increase N-use efficiency. At the end of the rice season, the return to aerobic conditions sees rapid nitrification of newly formed and existing ammonium. Once the maize crop is established, split applications of N fertilizer can supplement mineralization of SOM to meet the N requirement of the crop without undue loss, even under irrigation. Water availability during the dry winter period varies among R-M systems and will determine yield of the maize crop and hence its N requirement. Achievement of efficient use by the system requires that the maize crop leave little mineral N at the end of the season because that may either depress N fixation by a legume crop such as mungbean, or will be rapidly lost during puddling for rice (Buresh and de Datta 1991).

Phosphorus management principles developed for R-W systems by Timsina and Connor (2001) are applicable to R-M systems as well. Phosphorus tends to accumulate in the soil due to fixation by Fe and Al, especially in acidic soils. Over time, large amounts of P can be fixed in that way (Kirk et al. 1990) while contributing slowly to available P pool of the soil. Phosphorus, however, solubilizes immediately after flooding, leading to a flush of available P (Kirk et al. 1990) increasing its supply to rice. Subsequent drying, however, reduces its availability to maize for which strong crop responses to P fertilizer are expected (Willet and Higgens 1978; Willet 1979; Sah and Mikkelsen 1989; Sah et al. 1989a, b). In systems of low P fertility, the repeated dry-wet transition in R-M system increases P extraction, further lowering fertility. Finally, management of P fertilizer for R-M systems must take account of residue and organic amendments.

The increased concentrations of Fe(II), Mn(II), and ammonium in flooded soils during rice cultivation displace K from the exchange complex into the soil solution (Ponnamperuma 1972). This displacement, however, ceases on return to aerobic conditions. Despite often having relatively large total K content, the K nutrition of R-M systems grown on the soils of South Asia is not assured, because many heavy textured alluvial floodplain Terai soils of Nepal and northern and eastern India, and soils of Bangladesh contain vermiculite, illite, or other K-fixing minerals (Dobermann et al. 1996, 1998). Improved K management may have great potential for improving the overall productivity of R-M systems of South Asia, but will require special consideration on soils containing K-fixing minerals. As with P, it may seem appropriate to make differential applications of K to component crops in R-M systems on non-K fixing soils, again with least K applied to rice with the aim of preventing loss by leaching.

Finally, occurrence of K deficiency and response to applied K depend on yield level, K buffering capacity of the soil, straw management, and net K inputs from sources other than fertilizer. Clay mineralogy, texture, and K inputs from irrigation or rainwater need to considered (Dobermann et al. 1998) along with K inputs from sediments deposited from flood plains and flood water while formulating a rational K management strategy for R-M systems. Application of full maintenance rate of K (input = output) may not be profitable for rice and maize under situations where crop response to K is poor. In such soils, such as in Bangladesh, some K mining may be allowed by applying K below maintenance rate (Buresh et al. 2010). However, the extent of mining that could be allowed in a particular soil will require a complete understanding of the dynamics of K in the soil as well as the K input-output balance associated with the cropping system practiced.

Residue management

Soil puddling for rice with continuous soil submergence helps maintain SOM and sustain a supply of indigenous N originating from BNF and soil (Pampolino et al. 2008). The conversion from continuous rice cultivation with soil puddling and soil submergence to a R-M rotation with soil drying and tillage of aerated soil during land preparation for maize, however, can result in loss of SOM and soil fertility (Pampolino et al. 2010). Retention of crop residues after no or minimum tillage or on raised beds in R-W systems has increased yield and SOM in many experiments in South Asia (Humphreys and Roth 2008). In a 4-yrs experiment on a sandy loam soil in northern Bangladesh, SOM in surface soil layers of the permanent raised beds (PRB) had increased by 13–41% after 4 years (ie four rice + wheat + maize crop cycles) with straw retention (SR), with a greater increase with 100% recommended dose of fertilizers than 50% of the same. Soil organic C in PRB without SR was similar to the initial organic C prior to bed formation (Talukder et al. 2008) which might be due to lesser biomass formation in absence of appropriate fertilization. We hypothesize that the establishment of maize after rice with reduced or no tillage and retention of crop residues could help conserve SOM and maintain soil fertility provided improved nutrient management is practiced. Reduced or no-till practices can also facilitate fast turnaround between crops. Experiments are underway in South Asia, particularly in India and Bangladesh, comparing maize and rice under conventional, reduced, and zero tillage in R-M systems to standardize nutrient management practices under differing tillage practices.

Bijay-Singh et al. (2008) made a simplified decision tree to illustrate guidelines for managing residues in rice-based cropping systems. They proposed that for the systems in which residue from rice or a non-flooded crop (such as maize) is retained or incorporated to ensuing rice, the management of residue depends upon whether soil during the recipient rice crop has been puddled. For non-puddled rice production, they recommended a no-till system in which the residues are left on the surface as mulch. For puddled rice production where crop residue cannot readily be used as mulch, however, the residue of the preceding maize crop can typically be safely removed from the field without any loss in productivity or sustainability of the system. However, an appropriate increase in fertilizer addition, particularly K, will be required to compensate for nutrient removal in the residue. The removal of crop residue has the potential to reduce the detrimental environmental impacts arising with CH_4 emission from incorporating residue in flooded soils. For non-flooded rice or maize crop in rice-based system under reduced or no tillage, residue should be retained as mulch. Consistent residue removal for non-flooded crops with full tillage will result in loss of SOM and soil nutrient supplying capacity because of enhanced oxidation of SOM (Bijay-Singh et al. 2008).

Site-specific nutrient management in R-M systems

Existing fertilizer recommendations for rice and maize often consist of one predetermined rate of nutrients for vast areas of production. Such recommendations assume that the need of a crop for nutrients is constant over time and space. However, the growth and needs for supplemental nutrients of any crop can vary greatly among fields, seasons, and years as a result of differences in crop-growing conditions, crop and soil management, and climate. Hence, the management of nutrients for rice and maize requires an approach that enables adjustments in applying nutrients to accommodate the field-specific needs of the crop for supplemental nutrients. Site-specific nutrient management (SSNM), a plant-based approach, is used to address nutrient differences which exist within/between fields by making adjustments in nutrient application to match these location, or soil, differences. This approach for irrigated rice systems for Asia was developed in the 1990 s by IRRI in collaboration with national partners across Asia (Fairhurst et al. 2007; Witt et al. 1999, 2007) to address serious limitations arising from blanket fertilizer recommendation for large areas, as practiced in Asia. It focused on managing field-specific spatial variation in indigenous N, P, and K supply, temporal variability in plant N status occurring within a growing season and medium-term changes in soil P and K supply resulting from actual nutrient balance. The plant-based SSNM strategies for rice is well advanced but that for maize is under development and evaluation. Here we present a few examples from Bangladesh and India where experiments on SSNM in R-M systems have been initiated.

An omission plot SSNM experiment on R-M system was conducted in Hyderabad, India, using rice hybrid PA6201 and maize hybrid MQPM1. The treatments included (1) control with no fertilizer- T1 (2) state recommendation- T2 (3) recommendation based on AICRP results- T3 (4) Full N, P, and K (SSNM)- T4 (5) N omission- T5 (6) P omission- T6 and (7) K omission- T7 (Table 7). The nutrient levels for T4 to T7 treatments were calculated based on the QUEFTS model (Janssen et al. 1990) taking into

Table 7 Grain yield (t ha^{-1}) of rice and maize, maize equivalent yield of rice, and rice-maize system productivity in an SSNM experiment (Source: ML Jat, 2009, unpublished data)

Treatment[a]	Rice yield (t ha^{-1})	Maize yield (t ha^{-1})	Maize equivalent yield (MEY) of rice (t ha^{-1})[b]	R-M system productivity in terms of MEY (t ha^{-1})
T1	4.11	3.87	3.88	7.76
T2	4.98	6.53	4.70	11.23
T3	5.01	7.04	4.73	11.77
T4	5.76	8.06	5.44	13.50
T5	4.88	4.86	4.61	9.47
T6	5.01	6.52	4.73	11.25
T7	5.00	6.65	4.72	11.37
CD(P=0.05) (kg ha^{-1})	232.1	715.7		

[a] Maize equivalent yield (MEY) of rice = [Grain yield of maize (t/ha)* selling price of maize (Rs/t) + (grain yield of rice (t/ha)* selling price of rice (Rs/t)]/selling price of maize (Rs/t)]; price of rice: Rs. 850 t^{-1} ; price of maize: Rs. 900 t^{-1}

[b] T1 = control with no fertilizer; T2 = State recommendation; T3 = recommendation based on AICRP results; T4 = full N, P, and K; T5 = N omission; T6 = P omission; T7 = K omission

account organic carbon and available P and K in the soil as well as potential and targeted yields. Results from the experiment (Table 7) revealed that highest yields for both rice and maize and highest system productivity were obtained from the SSNM treatment (M. L. Jat, unpublished data). Omission of N from the optimum treatment reduced yield by about 1 and 3 t ha^{-1} in rice and maize, respectively. Yield loss in rice and maize (0.8 and 1.5 t ha^{-1}, respectively) was similar in P and K omission treatments. This suggests that N is by far the most limiting nutrient and greater response to applied nutrients is expected in maize than rice possibly due to a combined effect of higher yield potential in maize and change from puddled submergence condition in rice to a more aerobic ecology in maize.

Table 8 shows data from another set of SSNM experiments, in maize from India. The trials were conducted in 2 major maize-based cropping systems, i.e. maize-wheat at 8 locations (Delhi, Bajaura, Udhampur, Dholi, Ludhiana, Pantnagar, Banswara and Ranchi) and rice-maize at 3 locations (Jorhat, Banswara, Hyderabad) during *Kharif* 2008. Significantly higher yield of maize was recorded under SSNM compared to State recommendations at most of the locations. Omission plot yield data revealed differential indigenous nutrient supplying capacity of the study sites across locations (agro-ecologies). However, yield loss due to omission of N was higher as compared to P and K suggesting N as the major yield-limiting factor under all agro-ecologies. The response to applied nutrients varied from 1–5 t ha^{-1} for N to about 0.2–1.5 t ha^{-1} for P and K across locations. The results also suggest that response to applied nutrients must be included as a criteria to develop recommendations where nutrient application

Table 8 Effect of nutrient management practices on grain yield of maize (t ha^{-1}) at different locations in India (Source: ML Jat, unpublished data)

Nutrient management	Grain yield (t ha^{-1})							
	Delhi	Bajaura	Udhampur	Dholi	Ludhiana	Pantnagar	Banswara	Ranchi
State recommendation	7.78	5.69	4.06	3.65	6.76	4.44	5.93	3.69
SSNM	7.94	7.21	4.52	4.96	6.98	5.09	6.94	4.46
SSNM (-N)	4.46	2.76	2.26	3.21	5.87	3.11	1.72	2.78
SSNM (-P)	7.71	5.84	3.41	3.41	6.76	3.78	6.19	4.33
SSNM (-K)	7.36	5.87	4.41	3.69	7.33	5.22	6.41	3.89

rates should be fixed based on expected response and application of maintenance rate, calculated on the basis of off-take of the concerned nutrient after a cropping season, might be a more economical approach under no or limited response scenarios.

Table 9 summarizes grain yield data from SSNM trials on rabi maize under R-M systems in two districts in NW Bangladesh. The experiment consisted of seven treatments namely, 1) N omission with ample P and K, 2) P omission with ample N and K, 3) K omission with ample N and P, 4) low P with ample N and K, 5) low K with ample N and P, 6) ample N, P, and K, and 7) ample N, P, K, S and Zn. Yields under all treatments differed in the two sites, with highest yields for ample N, P, and K and N, P, K, S, and Zn treatments. Yields in the minus nutrient treatments varied widely across farmers' fields within a district and also differed in the two districts, indicating large variations in the indigenous nutrient supplying capacities of the soils. Yields in minus N treatment were quite low but in low P and low K treatments were quite close to ample N, P, and K treatment indicating high response to added N but low response to added P and K due to low indigenous N but high indigenous P and K in the soils (Table 10). Yields in all treatments were generally higher in Rajshahi than Rangpur due to differences in soil nutrient levels.

Table 9 Grain yield (t ha^{-1}) of *rabi* maize in 10 farmers' fields in an SSNM experiment at two districts in NW Bangladesh in 2008-2009 (Source: J. Timsina, 2010, unpublished data)

Treatments	Rangpur	Rajshahi
N omission	0.5–5.1	3.4–3.9
P omission	3.9–8.3	4.5–8.5
K omission	4.1–8.1	5.3–7.9
Low P	5.5–8.8	6.2–8.9
Low K	5.8–9.8	6.5–8.6
NPK	6.0–10.3	6.7–10.3
NPKSZn	6.0–10.4	7.2–10.8

Table 10 Soil nutrient levels (ranges) in ten farmers' fields in two districts in NW Bangladesh (Source: J. Timsina, 2010, unpublished data)

Parameters	Rangpur	Rajshahi
pH	4.0–5.7	5.2–6.8
Total N (%)	0.02–0.08	0.04–0.075
Available P (ppm)	3–56	6–35
Available K (meq/ 100 ml)	0.38–0.64	0.1–0.38
Zn (µg ml^{-1})	0.2–1.7	0.2–0.57

Soil test methods: Total N, Kjeldahl; Avail. P, Bray-1; Avail. K, 1 N NH4-acetate; Zn, DTPA-extractable

The above results from India and Bangladesh highlight the highly variable response to applied N, P and K across agro-ecologies suggesting the necessity of SSNM to improve the productivity of R-M systems. Very high yield losses in maize in the N omission plots might be associated with the loss of SOM due to dry tillage in aerated soil after rice cultivation under submergence (Pampolino et al. 2010) and may need serious consideration for reduced or zero-till cultivation of maize with residue retained from the previous rice crop. However, there is a distinct knowledge gap in terms of nutrient dynamics and subsequent indigenous nutrient availability in R-M systems where no- or reduced tillage is practiced with or without the retention of residues of previous crop. We anticipate that soils under reduced tillage with retention of residues will differ considerably from the conventional tillage without retention of residues as far as nutrient dynamics is concerned and may need separate set of strategies in terms of nutrient application rate and timing.

Estimating fertilizer needs for R-M systems

Continuous production of high yielding maize may lead to the rapid depletion of mineral nutrients from soil unless appropriate nutrient inputs are supplied and best management followed. Maize hybrids grown in the *rabi* season in South Asia have an attainable grain yield of about 10–12 t ha^{-1}, with similar amount of non-grain biomass. To obtain such high yields, for example in Bangladesh, maize plants take up around 200 kg N, 30 kg P, 167 kg K and 42 kg S ha^{-1} (BARC 2005). Farmers, on the other hand, apply imbalanced fertilizers, with high amount of N and low amounts of P, K, S, and micronutrients. In R-M system in Bangladesh, the apparent nutrient balances have been highly negative for N and K (-120 to -134 and -80 to -109 kg ha^{-1}, respectively), while the P balance has been positive (15 to 33 kg ha^{-1}) (Ali et al. 2008, 2009). Nutrient depletion-replenishment studies in R-

W systems have also shown negative balances for N and K and positive balance for P (Panaullah et al. 2006; Saleque et al. 2006; Timsina et al. 2006). Declining soil organic C, acid leaching of soils through CO_2-charged rainwater and consequent base (Ca, Mg) removal, and micronutrient deficiencies (e.g. Zn and B in calcareous and coarse-textured soils) may be associated with this (Ali et al. 2008, 2009). One recent estimate shows that about 200 kg ha^{-1} yr^{-1} N + P + K applied as fertilizers remain unutilized by the crops in these systems, mainly due to improper management practices such as imbalanced fertilizer doses, inappropriate time of fertilizer application, and inappropriate timing and amount of irrigation (BARC 2005).

Fertilizer N, P and K needs by crops, as determined with the SSNM approach, are directly related to Yat levels. It is thus important to know the Yat targets for crops when assessing probable opportunities for future crop production and the associated needs for fertilizers in intensive cropping systems such as emerging R-M systems. Buresh and Timsina (2008) illustrated how crop simulation models for rice and maize can be used to estimate attainable yield (Yat) targets with best crop management practices for Sadar Upazilla of Kushtia District in Bangladesh. In Sadar Upazilla, R-R and R-W were formerly the main cropping patterns. Starting in about 1990, maize was introduced during the *rabi* season to be grown after the harvest of rice. The area of maize production subsequently expanded rapidly and replaced *Boro* rice and wheat. The cultivation of *Boro* decreased by about 40–50% and wheat cultivation is now almost non-existent. Rice-rice and R-M are now the two predominant cropping systems. Based on interviews of farmers in January 2008 by the first author, the average yield of maize in this area is about 8 t ha^{-1}.

Buresh and Timsina (2008) used ORYZA 2000 and Hybrid-Maize to estimate climatic and genetic yield potential (Yp) of rice and maize using 20 years of satellite-derived historical weather data from NASA for Sadar Upazilla. Farmers generally transplant *Aman* rice from mid-July to mid-August and *Boro* rice from mid-January to mid-February. The Yp of rice was consequently determined for intermediate duration rice (about 110 to 130 days from seed to seed) with transplanting on 1 August for *Aman* and on 1 February for *Boro*. Farmers generally plant maize from November to mid-January. The Yp for maize was determined for a hybrid with duration of 1,800 GDD and planting on 1 December. Simulation results showed that Yp for rice was higher for *Boro* than *Aman*, and Yp for maize was much higher than for rice (Table 11). Maize captured more solar radiation during the growing season and also experienced cool environment during the grain-filling period, resulting in high yield. The Yat for high financial return through use of best crop and nutrient management practices was set at 80% of the Yp (Witt et al. 2007). The Yat of maize established through this technique (11.1 t ha^{-1}; Table 11) was markedly higher than the currently reported average farmers' yield of 6 t ha^{-1}, indicating opportunities for future increases in maize yield through improved crop and nutrient management practices. Attainable annual yields were markedly higher for R-M (17.3 t ha^{-1}) than R-R cropping (14.1 t ha^{-1}) systems, suggesting much higher nutrient extraction and fertilizer needs for R-M than R-R as these cropping systems approach their Yt. The estimated yield can subsequently be used to assess evolving fertilizer needs as cropping system diversify, intensify and increase in yield.

Likewise, Pasuquin et al. (2007) demonstrated how diversification from R-R or R-W systems to R-M systems can impact on fertilizer use. They also used ORYZA 2000 and Hybrid-Maize and long-term satellite-derived NASA climate data to study the impact on fertilizer demand by changing from either R-R or R-W systems to R-M system in NW Bangladesh. The Yp of the *Aman* rice transplanted during the rainy season in June/July, is about 7–9 t ha^{-1}. When grown as a *Boro* crop towards the cooler months of the year, Yp increases but with associated risks of cold injury during the seedling stage. The Yp of maize is highest when planted during September to November (up to 20 t ha^{-1}), while wheat is ideally planted in November achieving a Yp of about 6.5 t ha^{-1}. Figure 1 shows the production potential of R-W, R-R, and R-M systems. There is no alternative to growing rice in the rainy season so that the production potential changes depending on the second crop grown after T *aman* rice. The production potential is highest for R-M system with about 25 t grain ha^{-1} yr^{-1}, followed by R-R (20 t ha^{-1} yr^{-1}) and R-W systems (14 t ha^{-1} yr^{-1}).

Site-specific nutrient management approaches developed for rice (Fairhurst et al. 2007) and maize (Witt and Pasuquin 2007; Witt et al. 2006, 2009) have

Table 11 Simulated Yp (t ha^{-1}) and growth duration (d) for rice and maize planted during farmers' preferred planting times in Sadar Upazilla, Kustia District, Bangladesh (Source: Buresh and Timsina 2008)

Season	Crop	Planting date	Yp (t ha^{-1})		80% of Yp (t ha^{-1})	Mean growth duration (d)
			Mean	Standard error		
Aman	Rice	1 August	7.7	0.2	6.2	110
Boro	Rice	1 February	9.9	0.1	7.9	121
Rabi	Maize	1 December	13.9	0.3	11.1	130

the potential to optimize nutrient management as farmers replace crops in their crop rotations. Fertilizer consumption is expected to increase when farmers shift from either a R-R or a R-W system to a R-M system due to a greater demand for nutrients at higher production levels. Shifting from one crop to another is likely to have moderate impact on fertilizer demand, while shifting from a single to a double or from a double to a triple-cropping system would result in increased fertilizer consumption and demand, as well as increased farmers' productivity (Pasuquin et al. 2007).

Future priorities for research in nutrient management for R-M systems

As maize cropping becomes more widespread and intensive in South Asia an emerging issue of great importance is how to sustain the productivity of R-M cropping systems through integrated soil fertility management strategies. Recent anecdotal evidences of stagnation and declines in maize yield in R-M systems in Bangladesh appear to be related to soil fertility problems, including deficiencies of N, P, and K arising from improper N management and imbalanced/inadequate fertilizer use (Ali et al. 2009). There is a need to understand more about the extent and rate of nutrient depletion and soil physical degradation in the intensifying R-M systems in South Asia before formulating appropriate amelioration strategies. To push the achieved grain yields even higher up the Yp curve will require larger amounts of nutrients, their better management and overall soil stewardship. On-farm nutrient management experiments with very high input and high-yielding maize crops is required to understand how to manage such systems to meet the requirement of maize in South Asia from a fixed soil resource base.

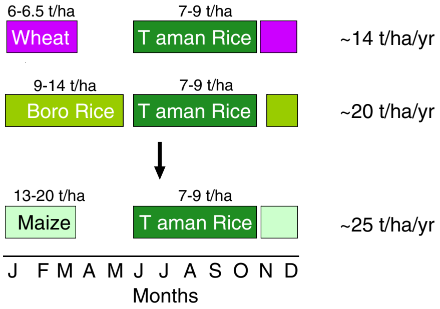

Fig. 1 Potential grain production (t ha^{-1}) of rice-based cropping systems in Dinajpur, Bangladesh. (Source: Pasquin et al. 2007)

Nutrient management for the R-R and R-W systems has been widely researched and blanket fertilizer recommendations for these systems are somewhat available in South Asia. However, not much is known about soil and fertilizer management practices for the emerging R-M systems, particularly involving high-yielding maize hybrids. This system is complicated because the component crops are grown in sharply contrasting physical, chemical and biological environments as that for R-W systems (Timsina and Connor 2001). Here the role of SOM becomes crucial, as a supplier of secondary and micronutrients, and also, especially for maize, as a natural "soil amendment" that creates a congenial soil physical environment for these crops. Organic matter becomes more important given that most soils of South Asia currently have low organic matter contents. In this context, integrated plant nutrition system (IPNS), envisaging conjunctive use of inorganic and organic sources of nutrients, including crop residues, could be considered for sustaining soil health and crop productivity (Rao and Srivastava 2001). IPNS packages and management guidelines for intensive R-M cropping systems can be developed for use in follow-up technology dissemination initiatives for farmers in South Asia. Ali et al (2009) have suggested the following IPNS research for R-M systems for Bangladesh which can also be applied for other similar agro-ecological areas in South Asia:

1. Understanding soil fertility constraints in representative R-M growing areas across the country.
2. Assessing crop nutrient requirements for optimum yield targets for both maize and rice in the intensifying systems in the prevailing biophysical environments.
3. Multi-location research on mineral fertilizer use, possibilities of adding quick growing legumes such as mungbean into the system, making use of BNF in rice, use of appropriate bio-fertilizers for legumes, and crop residue retention and recycling techniques, etc.
4. Maximum use of residual fertility in the cropping system to reduce the cost of fertilizers.
5. Field testing the IPNS packages in comparison with farmers' existing practices.
6. Financial analysis of the IPNS packages to evaluate farmers' profit margins.
7. Farmers' feedback on the acceptance of IPNS packages
8. Combination of IPNS packages with water management and soil physical management, and with water-efficient maize that may be developed.

Large amounts of cow dung and poultry manure are produced in South Asia but during the dry season most is used as household fuel for cooking. Sharma and Biswas (2004) have presented the recommended IPNS packages for various cropping systems for different agro-climatic regions of India, but unfortunately little is mentioned about such packages for R-M systems. We suggest that future research address and generate the appropriate IPNS packages for R-M systems across different soil types and fertility levels in South Asia.

Research on SSNM for rice and maize separately has now been well developed and the SSNM technologies disseminated (Fairhurst et al. 2007; Witt et al. 1999, 2007). Future research and dissemination should now focus on SSNM for R-M systems considering the yield goals, crop demand for nutrients, indigenous soil nutrient levels, and residual soil fertility. Dissemination of nutrient management technologies for R-M systems will be faster if simple computer-based decision support systems (DSS) tools can be developed for use by farmers and extension workers from governmental and non-governmental organizations and from the private sector. One of such DSS is Nutrient Manager for Rice (IRRI 2009) that has already been developed, evaluated, and promoted in the Philippines and Indonesia and is under development and evaluation for India and Bangladesh. The partial maintenance and partial maintenance plus yield gain approaches presented by Buresh et al. (2010) for P and K can be used in Nutrient Manager for Rice, which is designed to quickly provide extension workers, crop advisors, or farmers with fertilizer best management practices for specific rice fields. This tool integrates the existing knowledge on SSNM in rice and is capable of providing field-specific N, P, and K recommendations based on farmer responses to about 10 questions (Buresh et al. 2010). Nutrient Manager for Maize (Witt et al. 2009) and for R-M systems for South Asia is in development and evaluation stage. Future approach should give priority to the development and refinements of such simple DSS tools for integration and widespread delivery of improved nutrient management strategies to diverse R-M agro-ecologies of South Asia.

Conclusions

R-M cropping systems are emerging in South Asia. Area under this system is much less compared to R-R, R-W or M-W systems but is increasing rapidly in recent years. The increase is very rapid in Bangladesh and South India. Yield potential of rice and maize is quite high in South Asia. However, large yield gaps between potential and attainable yields, between attainable and actual yields, and between potential and actual yields exist in farmers' fields. There is potential to reduce yield gaps through better crop and nutrient management despite the challenges and constraints in farmers' fields. This review has highlighted some of such constraints and challenges and also opportunities for better nutrient management for reducing yield gaps for R-M systems.

Nutrient demand of the R-M system is very high since high-yielding rice varieties and maize hybrids are used. High nutrient demand is associated with high extraction or uptake of nutrients from soils leading to declining fertility unless the extracted nutrients are replenished from external sources. This is particularly true for R-M systems where residues of both crops are generally removed from fields aggravating soil fertility depletion, especially K. However, nutrient balance studies in R-M systems are very few in South Asia. Recently some efforts are being made in India and Bangladesh to develop nutrient balances for these systems but conclusive results are not yet available. SSNM provides scientific principles for optimally supplying crops with nutrients as and when needed for specific fields in a particular cropping season. Application of SSNM principles, aided by nutrient balance studies, can help improve nutrient management in R-M systems towards improving yield and profitability. This will, however, require better understanding and development of SSNM principles for maize to the extent of rice.

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