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The relative importance of drought and other water-related constraints for major food crops in South Asian farming systems

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Abstract Variation in water availability is a major source of risk for agricultural productivity and food security in South Asia. Three hundred and thirty expert informants were surveyed during 2008-09 to determine the relative importance of drought and water-related constraints compared with other constraints limiting the production of four major food crops (wheat, rice, sorghum, chickpea) in five broad-based South Asian farming systems. Respondents considered drought an important constraint to crop yield in those farming systems that are predominantly rainfed, but associated it with low yield losses (well below 10% of all reported losses) for crops in farming systems with well-developed irrigation. In these systems, other water-related constraints (including difficult access to sufficient irrigation water, the high cost of irrigation, poor water management, waterlogging and flooding of low-lying fields) were more important. While confirming the importance of drought and water constraints for major food crops and farming systems in South Asia, this study also indicated they may contribute to no more than 20–30% of current yield gaps. Other types of constraint, particularly soil infertility and the poor management of fertilizer and weeds for the cereals, and pests and diseases for chickpea, contributed most yield losses in the systems. Respondents proposed a wide range of interventions to address these constraints. Continued investments in crop-based genetic solutions to alleviate drought may be justified for food crops grown in those South Asian farming systems that are predominantly rainfed. However, to provide the substantial production, sustainability and food security benefits that the region will need in coming decades, the study proposed that these be complemented by other water interventions, and by improvements to soil fertility for the cereals and plant protection with chickpea.

Keywords Crop production constraints · Drought · Water use and management · Production solutions · Food crops · Farming systems · South Asia

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Introduction

Demographic growth and economic development are putting unprecedented pressure on water resources throughout the world (FAO 2009). Water scarcity and drought (crop water deficit) present increasing risks for agricultural sustainability and food security in many developing regions (Kijne et al. 2003; CAWMA 2007). Drought is a severe constraint to crop production in rainfed semiarid and sub-humid regions throughout Asia (Wade et al. 1999; Ali and Talukder 2008), and is also considered important in some intensively-cropped, irrigated farming systems such as the Rice-Wheat system on the Indo-Gangetic plain (Kataki et al. 2001; Prasad 2005). Major international agricultural research programs, including the CGIAR Generation Challenge Programme (GCP), have identified the alleviation of drought as their highest priority (see http://www.generationcp.org/).

With its heavy reliance on monsoon rainfall and snow-melt in rivers, water availability for agriculture in South Asia is highly sensitive to climate change (Battisti and Naylor 2009; Aggarwal et al. 2004). The region is vulnerable to droughts and floods. Prospects for expanding irrigated land and for further increasing cropping intensities in areas with adequate irrigation are limited. Yield growth for principal cereal crops in South Asian farming systems has slowed down in the last two decades, including in the strategically important Rice-Wheat system (Pingali et al. 1997; Duxbury 2001; Kataki et al. 2001; Ladha et al. 2003; Prasad 2005). Limited crop yield potentials, stagnant input use efficiencies, soil and water resource degradation, inadequate investments in agricultural research and rural infrastructure (including irrigation systems), poverty, input support policy, and the effects of climate change are all implicated. Drought and water issues will likely become more intractable in South Asia according to Battisti and Naylor (2009), who predict the region will be warmer and drier in coming years. To adapt, a range of integrated changes are expected to be needed to the farming systems in the region (e.g. Aggarwal et al. 2004).

There is substantial interest in addressing drought and water deficits in South Asia through crop genetics. Breeding for drought tolerance is underway in major projects for several food crops in the region (see the GCP, http://www.generationcp.org/; Drought-Tolerant Rice Project, http://beta.irri.org/projects15/stresses/drought-tolerant-rice). To help justify and plan such initiatives, information on the relative importance of drought and other crop constraints for major food crops in several key farming systems is essential (Hyman et al. 2008). However, previous assessments of crop production constraints in South Asia have concentrated on one crop or type of constraint, or one farming system. For example, Widawsky and O'Toole (1996) identified production constraints for rice in eastern India, while Kataki et al. (2001); Joshi et al. (2007) and Kumar et al. (2007) addressed limitations to wheat production in the Rice-Wheat system. Pande et al. (2005) and Van Rheenen and Singh (1997) described constraints with chickpea production in Nepal and India. Several studies have looked at water and drought constraints in the context of farming systems in the region. The Rice-Wheat system in India and Pakistan has received considerable attention (Timsina and Connor 2001; Kataki et al. 2001; Erenstein 2009, 2010), but other examples exist (e.g. Ali et al. (2009) for rice-maize systems in Bangladesh).

In this paper we present results from a survey of expert opinion on the importance of drought and water constraints for four principal food crops grown in five major farming systems covering much of South Asia. The experts also proposed solutions to the most severe constraints that they identified. As far as we are aware this is the first study that uses a set of systematically-collected data to examine the relative importance of water constraints and opportunities across several food crops and farming systems in the region. We discuss findings about the water constraints and their implications for investments in agricultural technologies (including drought tolerant germplasm) in the region to raise food production, system sustainability and food security.

Methods

Survey design and conduct

This study analyzed a subset of data from a larger GCP project (reported in Waddington et al. 2009, 2010) that assessed a broad range of crop yield constraints and solutions in Africa and Asia. The current study focused specifically on drought and other water-related constraints in South Asia. The project design and methodology used in the overall study were described by Waddington et al. (2009, 2010), and are summarized below.

The GCP identified five key farming systems in South Asia (Fig. 1; Hyman et al. 2008) from the FAO/World Bank classification of 72 farming systems across six regions of the world (www.fao.org/farmingsystems/). These South Asian farming systems are characterized by extensive poverty and high drought risk, and food crops important for the GCP are widely grown in the systems (Table 1). Hyman et al. (2008) characterized the *Rice-wheat* and *Dry rainfed* farming systems to be of high drought intensity with large expected losses to crop production from drought (i.e. high Potential Drought Impact Index, PDII). The *Rainfed mixed* and *Rice* systems experience moderate drought intensity and high PDII, while the *Highland mixed* system has moderate drought intensity and moderate PDII. Rainfall amounts and patterns vary greatly across the five farming systems, influencing the choice of crops, cropping patterns and their intensity, and the availability of surface water and groundwater for irrigation. Rainfall varies from around

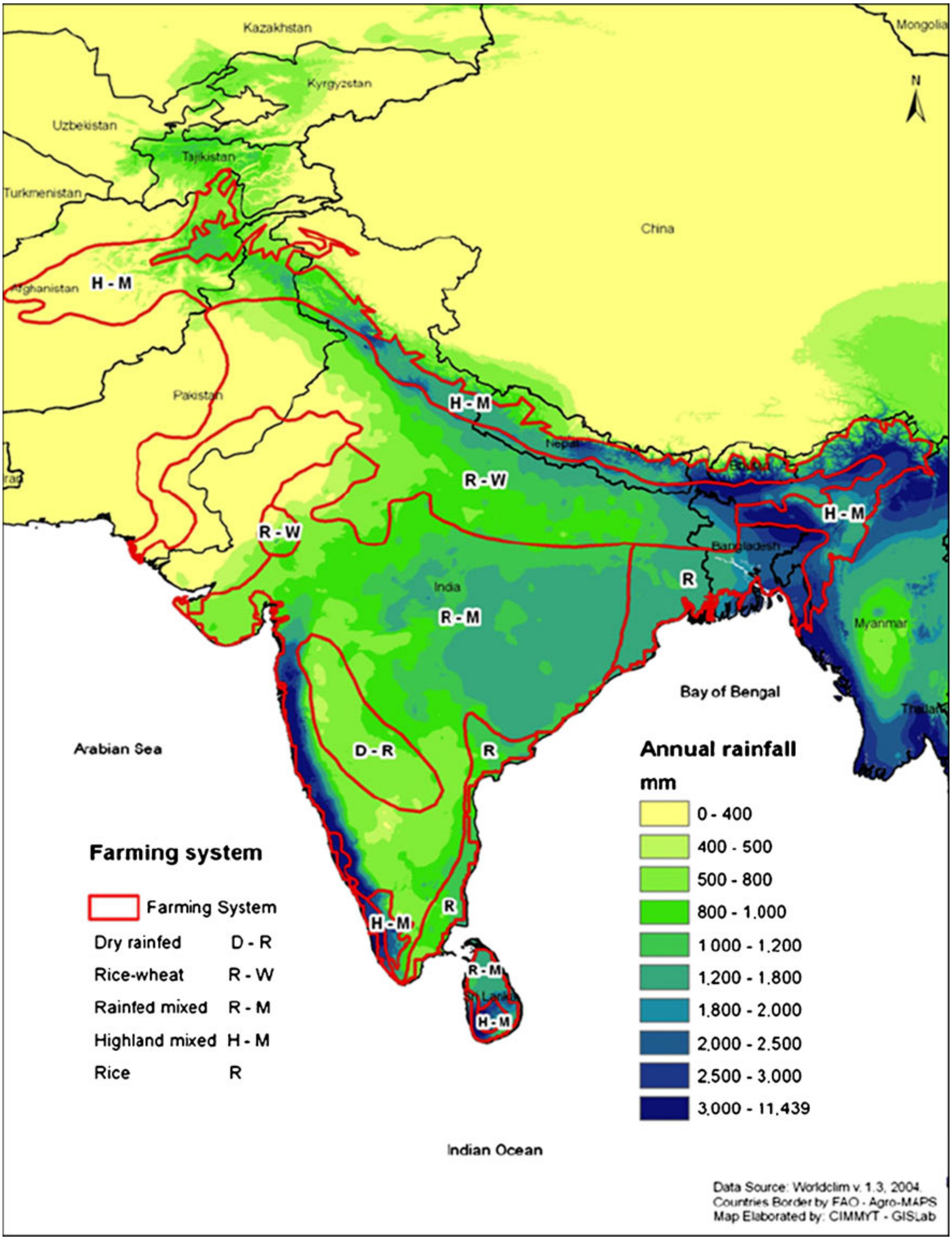

Fig. 1 Distribution of annual rainfall across five farming systems in South Asia

400 mm per annum in the *Dry rainfed* system to over 2,500 mm per annum in parts of the *Rice* and *Highland mixed* systems (Fig. 1). Wheat, rice, sorghum and chickpea were the crops chosen for the survey. They are principal staple food crops in South Asia and among those of highest priority for the GCP. Based on largest proportions of crop areas in the farming systems, 16 system x crop combinations were surveyed: rice and chickpea for the *Rice* system; rice, wheat, and chickpea in the *Rice-wheat* and *Highland mixed* systems; rice, wheat, sorghum, and chickpea for the *Rainfed mixed* and *Dry rainfed* systems (Table 1).

Table 1 Farming system characteristics and focus crops for five farming systems in South Asia

Farming system	Prevalence of poverty	Annual rainfall range (mm)	Irrigation availability	Severity of drought (PDII[a])	Prevalence of the focus crops (% of total crop area)			
					Wheat	Rice	Sorghum	Chickpea
Highland mixed	Moderate-extensive	1,200–3,000	Low	Low	28.1	29.9	NP	4.5
Rice	Extensive	1,000–2,500	High	Medium	NP	69.5	NP	2.5
Rice-wheat	Moderate-extensive	500–2,000	High	Medium	34.9	28.6	NP	3.0
Rainfed mixed	Extensive	800–1,800	Low	High	7.3	19.6	8.7	4.8
Dry rainfed	Moderate	400–800	Medium	High	4.1	8.6	19.4	4.2

Based on Dixon et al. (2001), with additional information

[a] PDII, Potential Drought Impact Index (Hyman et al. 2008)

NP Not present on a substantial area

We defined a smallholder farm yield gap as the difference between the highest achieved yield on smallholder farms and average yield on smallholder farms (Shumba et al. 1990; Evenson et al. 1996). Yield losses that make up the yield gap result from four broad categories of constraint—biotic, abiotic, management and socioeconomic, and each category can be divided into specific constraints (and their causes). A rapid interactive "Delphi" survey methodology (Dalkey 1969) was used to collect and focus the information. Three rounds of interaction took place with panels of expert informants between April 2008 and February 2009. The first round addressed crop yields, important constraints and associated yield losses, and trends in severity with those constraints; the second adjusted results from round one and identified interactions between constraints; the last round requested possible solutions for the dominant constraints. Expert panelists with knowledge of the crops and farming systems in South Asia were identified by the researchers and through key focal persons in the region (see Waddington et al. 2010). Most panelists were located in the region and were interviewed by focal persons. Panelists included agricultural researchers such as plant breeders, agronomists, agricultural economists and plant protection professionals; extension and training staff, representatives of farmer organizations, suppliers of seed and other inputs, and knowledgeable farmers. Wide-ranging lists of possible important constraints for each crop were given to panelists, including various potential drought and water-related constraints. Overall, 330 panelists provided their personal responses to the survey for South Asia. Panelists proposed the highest achieved yield on smallholder farms and average yield on smallholder farms for each crop in each system, and these were averaged across respondents to calculate a smallholder farm yield gap (Waddington et al. 2010). They suggested the 24 most-severe constraints for each crop in each system and estimated the grain yield losses associated with each constraint. These were again averaged across respondents for each crop and farming system. The most frequently reported constraints associated with the largest yield losses were considered the most severe (see Waddington et al. 2010). Panelists proposed possible solutions for the ten constraints with the largest estimated yield losses.

Definition and analysis of constraints

In our study, drought constraints (involving water deficits experienced by the crop) were categorized as abiotic constraints, although there could be cause and effect relationships with constraints in other categories. Respondents described drought constraints in different ways depending on the crop. For example, with wheat these included 'mid-season drought', 'terminal (grain filling) drought', and 'temporary drought (dry spells) in supplementary irrigation systems'. 'Drying of the soil surface during crop establishment' and 'progressive drought as the crop develops and through grain filling' were given for chickpea. Besides drought, other broader water-related constraints were classified as abiotic, socioeconomic or management constraints. These included 'excessive soil moisture (waterlogging)', 'flooding of low-lying fields', 'poor crop establishment on residual moisture', 'cyclone damage', 'difficult access to sufficient irrigation water', 'high cost of irrigation', and 'inadequate water management'. Many of the other types of constraint identified by panelists during the study are described in Waddington et al. (2009, 2010).

From the 24 most-severe constraints identified for each crop in each farming system, we summed the estimated yield losses for i) All drought-related constraints, ii) All water-related constraints (including drought), and iii) All the other severe constraints identified. The yield loss sums were used to compare the relative importance of the three sets of constraints for the crops and farming systems. Standard deviations (SD) of the yields and yield gaps were calculated.

Results

Crop yield gaps

The highest achieved on-farm grain yield and the average on-farm grain yield, as estimated by panelists for the four crops in the five farming systems are in Table 2. Relatively large yield gaps, compared to current average on-farm yields, were estimated for all the four crops in South Asia. They were smallest for rice and largest for sorghum and chickpea. They were smaller in the more intensively-cropped (*Rice* and *Rice-wheat*) farming systems and larger in the other (more marginal, rainfed) farming systems (Table 2).

The *Rice* and *Rice-wheat* systems of South Asia feature widespread irrigation, substantial crop inputs (seed, fertilizer, pesticides), and well-developed field management, with on-farm yields generally higher than in the other systems (Table 2). Yield gaps for rice and wheat were often smaller than current average farm yields. Chickpea (which is usually grown on residual soil moisture in the cool dry *rabi* season) had a yield gap larger than its current modest average farm yield (Table 2). In contrast, cropping in the *Rainfed mixed* system relies predominantly on rainfall, although small areas irrigated from tanks and deep wells reduce vulnerability to drought. Probably because of limited water, the achieved highest yields for rice were here reported lower than those in the intensive *Rice* and *Rice-wheat* systems. Chickpea, being drought tolerant, grows well in the *Rainfed mixed* system in the cool season, and here was estimated to have its highest grain yield (2.4 t ha^{-1}) overall in the region (Table 2).

The *Dry rainfed* system has a higher proportion of localized irrigation than the moister surrounding *Rainfed mixed* areas, allowing it to support a similar range of irrigated and rainfed crops despite the drier climate (Dixon et al. 2001). Relatively more-fertile soil and a narrow range of temperature also add to crop performance. The reported highest crop yields were higher than equivalent yields in other systems with 5.3 t ha^{-1} for wheat, 6.6 t ha^{-1} for rice, and 4.5 t ha^{-1} for sorghum (Table 2), although the cropped areas in the system are modest. The *Highland mixed* system (being relatively marginal, and characterized by small fields, shallow soils and variable soil moisture), had low reported highest farm yields, average yields and yield gaps (Table 2).

Severity of drought and water-related constraints

The important drought constraints and water-related constraints identified for the crops in each farming system are in Table 3. Table 4 gives the estimated grain yield losses associated with these constraints. The severity of drought constraints and water-related constraints varied among farming systems and crops (Fig. 2). Drought was reported to be severe only in the predominantly rainfed systems

Table 2 Estimated on-farm grain yield and yield gap (t ha^{-1}) for four food crops in South Asia, 2008-09

Crop	Farm yield[a]	Farming system					Average
		Highland Mixed	Rice	Rice-Wheat	Rainfed Mixed	Dry Rainfed	
Wheat	Y_H	3.8 (1.6)	–	4.8 (1.2)	5.0 (1.1)	5.3 (1.0)	4.7
	Y_A	2.1 (1.0)	–	2.5 (0.7)	2.4 (0.6)	2.2 (0.4)	2.3
	Y_G	1.8 (0.9)	–	2.4 (0.9)	2.5 (0.8)	3.1 (0.7)	2.5
Rice	Y_H	4.7 (1.6)	7.0 (1.7)	6.2 (1.3)	5.0 (1.1)	6.6 (1.8)	5.9
	Y_A	2.5 (0.6)	3.7 (1.2)	3.1 (1.4)	2.9 (0.7)	3.9 (1.5)	3.2
	Y_G	2.2 (0.6)	2.8 (1.2)	2.8 (0.8)	2.1 (1.0)	2.6 (0.8)	2.5
Sorghum	Y_H	–	–	–	3.1 (1.5)	4.5 (1.3)	3.8
	Y_A	–	–	–	1.6 (0.3)	1.8 (0.7)	1.7
	Y_G	–	–	–	1.7 (1.4)	2.9 (1.3)	2.3
Chickpea	Y_H	1.6 (0.3)	2.0 (0.4)	2.0 (0.8)	2.4 (0.5)	2.0 (0.4)	2.0
	Y_A	0.9 (0.2)	1.0 (0.4)	0.9 (0.7)	1.3 (0.7)	0.9 (0.2)	1.0
	Y_G	0.7 (0.3)	1.2 (0.4)	1.1 (0.6)	1.1 (0.5)	1.1 (0.3)	1.1

[a] Y_H = Highest farm yield; Y_A= Average farm yield; Y_G = Yield gap

These were estimated independently. Thus in some cases $Y_A + Y_G$ does not sum to Y_H

Standard deviation (SD) given in brackets

Table 3 The most-severe drought and water-related constraints for focus crops and farming systems, 2008-09

Farming system	Crop	Drought constraints	Other water-related constraints
Highland Mixed	Wheat	Mid season drought (W)[a]	Irrigation problems (poor water management, deteriorating irrigation system) (W)
		Terminal (grain filling) drought (W)	
	Rice	Drought or intermittent water stress on light or heavy soils (W)	Difficult access to sufficient irrigation water (rights, supply constraints) (W)
			High cost of irrigation (W)
	Chickpea	Drought (water deficit) or soil surface drying during crop establishment (W)	Excessive soil moisture at any stage of crop growth (R)
		Progressive drought with developing crop and through grain filling (W)	
Rice	Rice	Drought or intermittent water stress on light or heavy soils (W)	Flooding of low-lying fields (W)
			Cyclone/typhoon damage (W)
			High cost of irrigation (water pumps, pipes, electricity, diesel) (W)
			Difficult access to sufficient irrigation water (R)
			Inadequate water management (flooding, too many or few irrigations, groundwater too deep, field losses, poor water pumps, canals, pipes) (W)
	Chickpea	Drought (water deficit) or soil surface drying during crop establishment (LC)	Excessive soil moisture (water logging) at any stage of crop growth (R)
			Presence of irrigation, favoring irrigated crops as competitors and raising humidity (W)
Rice-Wheat	Wheat	Terminal (grain filling) drought (W)	
	Rice	Drought or intermittent water stress on light or heavy soils (W)	Flooding of low-lying fields (W)
			Difficult access to sufficient irrigation water
			High cost of irrigation (W)
			Inadequate water management (W)
	Chickpea	Drought (water deficit) or soil surface drying during crop establishment (W)	Excessive soil moisture at any stage of crop growth (R)
			Presence of irrigation, favoring irrigated crops as competitors and raising humidity (W)
Rainfed Mixed	Wheat	Temporary drought in supplementary irrigation systems (W)	Crop establishment on residual moisture
			Irrigation problems (W)
		Terminal (grain filling) drought (W)	
	Rice	Drought or intermittent water stress on light or heavy soils (W)	High cost of irrigation (W)
			Inadequate water management (W)
			Difficult access to sufficient irrigation water (W)
	Sorghum	Drought, dry spells, with developing crop or in grain filling (W)	Wet spells during grain filling and maturity leading to spoiling of grain (LC)
		Drought (water deficit) during crop establishment (W)	
	Chickpea	Progressive drought with developing crop and through grain filling (W)	
		Drought (water deficit) or soil surface drying, during crop establishment (W)	
Dry Rainfed	Wheat	Terminal (grain filling) drought (LC)	Irrigation problems (R)
		Mid season drought (crop water deficit) (LC)	
	Rice	Drought or intermittent water stress on light or heavy soils (W)	Flooding of low-lying fields (R)
			High cost of irrigation (W)
			Difficult access to sufficient irrigation water (R)

Table 3 (continued)

Farming system	Crop	Drought constraints	Other water-related constraints
			Inadequate water management (R)
	Sorghum	Drought, dry spells, with developing crop or in grain filling (W)	Wet spells during grain filling and maturity leading to spoiling of grain (R)
		Drought (water deficit) during crop establishment (W)	
	Chickpea	Progressive drought with developing crop and through grain filling (W)	
		Drought (water deficit) or soil surface drying during crop establishment (W)	

[a] (W) = constraint is getting worse; (R) = constraint is reducing; (LC) = severity of constraint little changed over last 5 years

while issues related to water management and irrigation infrastructure were widespread in both the irrigated and the rainfed systems.

Drought and water-related constraints of wheat, rice and chickpea were surveyed in the *Rice-wheat* system, which has a relatively well developed irrigation infrastructure. Rice is the previous crop to wheat in this system and is often the following crop as well (Timsina and Connor 2001). Rice is grown mainly during the rainy monsoon season whereas wheat is cropped only in the post-monsoon cool dry (*rabi*) season. 'Drought or intermittent water stress' counted for 5.5% of the rice yield gap in this system. All water-related constraints were estimated to contribute 18% of the yield gap. In the *Rice-wheat* system, wheat is fully or partially irrigated. It requires far less water than rice and can grow well with a few irrigations (e.g. Timsina and Connor 2001). 'Terminal drought during grain filling' was the only reported drought issue for wheat, responsible for only 1.3% of the yield gap. But the related wheat constraint, 'terminal heat during grain filling', was reported to be severe, contributing an average 7.0% of the yield gap. Chickpea, which is usually planted on residual soil moisture after the harvest of rice, commonly faces water deficit during crop establishment and sometimes excessive water (caused by early rains) during later stages of crop development. Drought and water constraints of chickpea in the *Rice-wheat* system contributed to 7.7% of the yield gap (Table 4).

In contrast, in the *Rainfed mixed* system, where dependence on direct rainfall is much greater, drought was felt responsible for 5.8% of yield losses for wheat, 11.1% for rice, 8.9% for sorghum, and 9.5% with chickpea. Yield losses due to all water-related constraints were reported large for wheat (18.5%) and very large for rice (31.0%). The 'high cost of irrigation', 'difficult access to sufficient irrigation water' and 'inadequate water management' were all considered important for rice. For wheat, 'crop establishment on residual moisture', 'poor water management', and 'deteriorating irrigation system' were important. With the other crops, drought accounted for most of the losses due to water-related constraints (10.7% for sorghum and 9.5% for chickpea) (Tables 3 and 4).

Sorghum is widely-grown in the *Dry rainfed* system on almost 20% of total crop area (Table 1). Drought constraints were reported to affect sorghum throughout crop development, contributing 13.3% of the total yield gap (Table 4). Adding 'wet spells during grain filling and maturity leading to spoiling of grain', all the water-related constraints contributed 15.0%. Drought was a comparatively less severe constraint for rice in the *Dry rainfed* system but 'monsoon floods', 'limited access to irrigation', 'high cost of irrigation', and 'poor water management' were more important, and accounted for 10.2% of the total yield gap. With chickpea in this system, 'drought (water deficit) or soil-surface-drying during crop establishment' and 'progressive drought with developing crop and through grain filling' lead to significant (15.6%) yield loss.

The *Highland mixed* system has 58% wheat and rice area combined. 'Drought' was not considered important; judged to be responsible for only 4.1% and 3.5% of yield gaps with these crops. Adding 'irrigation management', 'high cost, and access to irrigation water', the water-related constraints counted for 7.0% of wheat losses and 10% of those for rice. 'Drought' or 'soil surface drying during crop establishment' and 'progressive drought with developing crop and through grain filling' contributed 6.9% of the chickpea yield gap. This rose to 8.3% when 'excessive soil moisture at any stage of crop growth' was added.

Almost all the drought constraints were felt to be getting worse for the four crops in the five farming systems (see Table 3). Similar deteriorating trends were reported for other water-related constraints like 'high cost of irrigation' and 'difficult access to sufficient irrigation water'. There was a perception by most panelists that overall this region is getting dryer, rainfall more erratic and water use more intensive. Many panelists felt that constraints related to 'excess water/waterlogging' for chickpea, 'wet spells during grain filling and maturity leading to spoiling of grain' for sorghum, and 'irrigation problems' for rice in the *Dry rainfed* system, were declining.

Table 4 Estimated grain yield losses (kg ha^{-1}) associated with drought, water-related and all other identified constraints for focus crops and farming systems, 2008-09

Farming system	Crop	Drought constraints (a)		All water-related constraints (b)		Percentage of a to b	All other constraints	
		Grain loss (kg ha^{-1})	% of all losses	Grain loss (kg ha^{-1})	% of all losses	(%)	Grain loss (kg ha^{-1})	% of all losses
Highland Mixed	Wheat	72	4.1	123	7.0	58.5	1,634	93.0
	Rice	76	3.5	218	10.0	34.9	1,962	90.0
	Chickpea	50	6.9	61	8.3	82.0	674	91.7
Rice	Rice	117	4.1	661	23.2	17.7	2,188	76.8
	Chickpea	53	4.5	123	10.5	43.1	1,048	89.5
Rice-Wheat	Wheat	31	1.3	31	1.3	100.0	2,354	98.7
	Rice	152	5.5	497	18.0	30.6	2,264	82.0
	Chickpea	23	2.2	82	7.7	28.0	983	92.3
Rainfed Mixed	Wheat	147	5.8	470	18.5	31.3	2,071	81.5
	Rice	232	11.1	648	31.0	35.8	1,564	74.8
	Sorghum	150	8.9	181	10.7	82.9	1,511	89.3
	Chickpea	119	9.5	119	9.5	100.0	1,134	90.5
Dry Rainfed	Wheat	174	5.6	347	11.2	50.1	2,751	88.8
	Rice	95	3.7	357	13.9	26.6	2,211	86.1
	Sorghum	380	13.3	429	15.0	88.6	2,431	85.0
	Chickpea	168	15.6	168	15.6	100.0	909	84.4

Solutions to constraints

Informants frequently proposed complex interventions to adequately cope with the drought and water-related constraints identified in South Asia (Table 5). These involved integrated provision of appropriate germplasm and knowledge about its use, better crop field management and socio-economic support. Better germplasm, i.e. principally the breeding and use of crop varieties with tolerance to water deficits, was a popular solution to drought. Depending on the crop, different traits were identified, including drought tolerance during several stages of crop development, dual plant habit able to grow in variable depth water, and water-saving ability in general. Improving irrigation infrastructure, developing advanced and efficient irrigation approaches such as drip irrigation, raising overall water-use efficiency, reducing water loss, customizing efficient irrigation schedules based on local trials, and the rescheduling of planting dates to fit changes in climatic patterns were among the management solutions proposed for both drought and other water constraints with specific crops (Table 5). Policy and socio-economic solutions were also considered important by many respondents. Those included creating awareness among farmers and extension staff on crop water requirements, on new irrigation and water conservation technology, and on crop traits and the cultivation of new varieties; training farmers on irrigation technologies and field practices, subsidies to farmers to maintain and develop irrigation systems and water conservation practices, and help to access finance for irrigation.

Discussion

Relative importance of drought and water constraints

The expert opinion surveyed indicated that drought was among the important constraints to crop production in South Asia, especially in those farming systems that rely predominantly on rainfed dryland cropping. The largest proportion of yield loss from drought was reported in the *Dry rainfed* system, particularly for chickpea and sorghum. Drought was also considered severe in the *Rainfed mixed* system, where all four surveyed crops experience large losses to drought. Comparing drought to all water-related constraints for the predominantly rainfed dryland crops (chickpea and sorghum), drought accounted for most of the water-related yield losses in the rainfed systems (with 83% and 89% for sorghum, and 100% for chickpea, see *Dry rainfed* and *Rainfed mixed* in Table 4 'Percentage of a to b' and Fig. 2). With rice, drought contributed a small proportion (18% to 36%) of all the water-related yield losses (Table 4). It is clear that water-related constraints other than drought are very important for rice, including

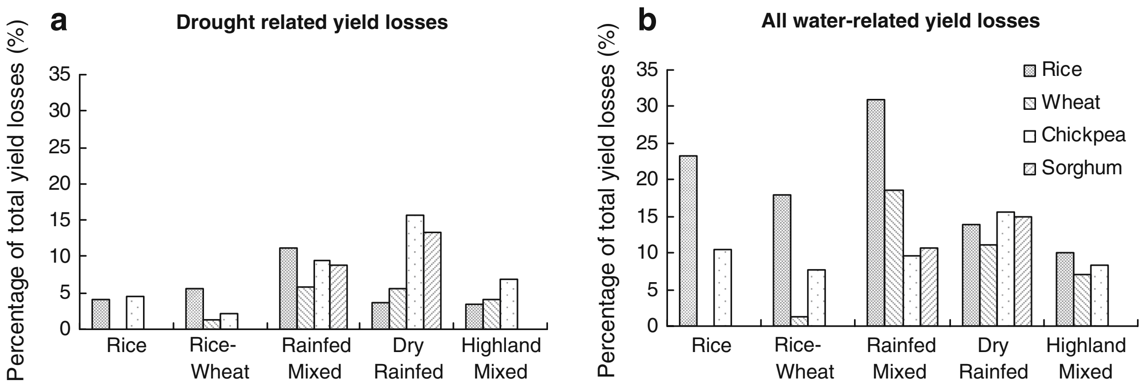

Fig. 2 Variation in estimated yield losses associated with important drought and water-related constraints for four food crops in South Asia, 2008-09. **a** Drought related yield losses. **b** All water related yield losses

difficulties with water management and its high cost, flooding and cyclone damage. In the *Rice* system in Bangladesh for example, the devastating cyclone and flood of 2007 damaged around 2.3 million t of rice, which is 8-9% of annual rice production (Selim et al. 2007). For wheat, among all water constraints, the contribution from drought was variable but large (31% in the *Rainfed mixed* system, 50% in the *Dry rainfed*, 59% for the *Highland mixed*, and 100% in the *Rice-wheat* system) (Table 4). There is clear need for major investments to address all water issues, drought and beyond, in the major South Asian farming systems, especially for rice and wheat.

Importance of other constraints

The water crisis and drought have been viewed as a critical challenge for global agricultural production and have recently received considerable attention (e.g. Kijne et al. 2003; CAWMA 2007; de Fraiture et al. 2010). While confirming the importance of drought and water constraints for major food crops and farming systems in South Asia (Table 3), our study also indicated they may contribute to no more than 20–30% of current yield gaps. Other very important constraints were indentified that merit attention.

Two biotic constraints, *Helicoverpa* pod borers and botrytis grey mould, were considered the top constraints to chickpea production (combined accounting for 16–24% of the yield gap) for both irrigated and rainfed systems. Soil fertility depletion, N deficiency, poor use and management of fertilizer, and competition from weeds were severe for rice and wheat (the two most important food crops in South Asia) in most farming systems, with each constraint contributing losses around 6–10% of yield gaps. Many of these constraints were especially severe in the marginal *Dry rainfed* and *Highland mixed* systems. Recent concern about the non-sustainability of intensive cereal-based farming systems in South Asia (e.g. Timsina and Connor 2001; Ali et al. 2009; Erenstein 2010) has focused to an increasing extent on the depletion of soil fertility and non-sustainable fertilizer use and management. Unsuitable variety and seed were further severe constraints for wheat in the *Rainfed mixed* and *Dry rainfed* systems. In areas where water availability is variable and scarce, farmers opt for low-input strategies—the low use of N, minimal management of water and fertilizer, choice of varieties with greater tolerance to drought but lower potential yield. Such activities reduce financial risk when drought and water problems are encountered but offer little potential to respond to more favorable conditions. By contrast, farmers in water-secure areas tend to opt for high input, high potential productivity strategies which reduce pressure on soil fertility depletion and accelerate the updating of varieties. For example, based on broad farmer surveys on the Indo-Gangetic plain in India, the rice variety MTU7029 (Swarna) used to dominate in canal-irrigated areas, where it was planted on around 90% of the rice land area. Due to declining availability of water, this has fallen to less than 40% in the last 5 years.

Research priorities with drought and water-related solutions

Multiple solutions to drought and water constraints were provided by respondents (see Table 5). When we classified them into three categories—a) variety, germplasm, and genetic solutions (VG); b) solutions related to policy and socio-economics (finance, markets), knowledge and training (PSE); and c) solutions involving crop management (CM)—a profile of the potential range of research and development opportunities appeared (Fig. 3). VG solutions (42% of the solution pool) were the most frequently proposed type of intervention for both drought and all the water issues with the focus crops, compared with 29% each for CM and PSE solutions (Fig. 3). Sorghum solutions were dominated by VG-type responses, which comprised 80% of suggested solutions. Many diverse CM and VG solutions were given for chickpea, while with rice, a broad set of CM solutions

Table 5 Suggested solutions to the drought constraints and other water-related constraints for focus crops and farming systems, 2008-09

Farming system	Crop	Suggested solutions to	
		Drought constraints	Other water-related constraints
Highland Mixed	Wheat	NS[a]	Policy makers should plan new irrigation schemes
			Sow wheat earlier to escape from post-anthesis heat stress
			Sow crops when soil moisture is adequate
			Predict rainfall using suitable crop models and then provide life saving irrigation to wheat at critical growth stages
	Rice	Introduce drought resistant cultivars	Breed drought resistant rice varieties for use in upland paddy
		Employ intercropping systems and use more organic matter in soils	
			Assess alternative water saving cropping patterns and appropriate water management options to increase water productivity
	Chickpea	Introduce drought resistant chickpea lines and breed drought-tolerant chickpea varieties	NS
		Conserve residual soil moisture through intercropping and conservation tillage	
		Mulch chickpea	
		Restore soil fertility	
		Sow chickpea in time to harvest residual soil moisture	
Rice	Rice	Use drought-tolerant varieties, and practice aerobic rice cultivation	Raise farmer awareness on importance of saving water and using it efficiently
		Customize irrigation amounts through timing and management trials	Follow water-saving irrigation systems and use modern devices for irrigation
		Intermittent irrigation on rotational basis	Increase access to finance for irrigation
		Minimize conveyance losses of water by using water harvesting approaches	Make water guards and proper irrigation and drainage structures
	Chickpea	Breed drought-tolerant chickpea	NS
		Plant on fields that have more soil moisture	
Rice-Wheat	Wheat	NS	NS
	Rice	NS	Breed dual-habit rice able to grow in variable depths of water
			Make bunds and raised soil beds
			Adopt resource conservation technologies
			Transplant early
	Chickpea	Improve terminal drought tolerance of chickpea	Plant on soil bed systems when fields are prone to waterlogging
		Brief farmers about irrigating the crop at critical growth stages (branching and pod filling)	Protect from surplus moisture at seedling and flowering stages
			Use proper irrigation and drainage channels
Rainfed Mixed	Wheat	Breed and plant drought-tolerant wheat varieties	Improve irrigation techniques
		Organize and train farmers on best irrigation scheduling to spread scarce water over dry periods	Provide subsidies or other incentives to farmers to maintain and develop their irrigation systems and water conservation practices
		Improve capacity for crop saving irrigation	Use wheat varieties with greater tolerance to water stress
	Rice	Invest in improved irrigation infrastructure	Raise awareness, training and knowledge on good water management practices
		Breed drought-tolerant varieties	Breed rice varieties with better water use
			Provide better irrigation infrastructure and training on improved water management

Table 5 (continued)

Farming system	Crop	Suggested solutions to	
		Drought constraints	Other water-related constraints
	Sorghum	Manage drought using crop life-saving irrigation	NS
		Breed drought-tolerant high-yielding sorghum varieties	
		Strengthen supplementary irrigation systems	
		Develop and provide the farmer with technology for efficient water conservation and use	
		Organize a watershed management program	
		Promote mulching to improve water use efficiency	
	Chickpea	Breed drought-tolerant, broadly-adapted chickpea varieties that can be late-planted to take advantage of rain showers	NS
		Mulch the crop	
		Develop and use advanced irrigation systems such as drips	
		Subsidize irrigation equipment and strengthen water conservation	
Dry Rainfed	Wheat	Breed wheat with drought tolerance	Strengthen irrigation infrastructure and promote new irrigation techniques, including drip irrigation
		Strengthen irrigation infrastructure and promote new water-efficient irrigation techniques such as drip irrigation	
			Breed wheat with greater water stress tolerance
		Promote knowledge of efficient irrigation scheduling	Promote knowledge about efficient use of water
		Upgrade efficient and cheaper irrigation facilities	Develop better water management techniques and improve irrigation infrastructure
	Rice	Breed varieties with drought tolerance	NS
		Follow appropriate crop management techniques and strengthen irrigation infrastructure	
	Sorghum	Breed drought-tolerant sorghum	NS
		Develop and promote water conservation and efficient water use package	
		Develop and use conservation agriculture	
		Strengthen irrigation networks	
	Chickpea	Use an early maturing rice variety so that farmers can sow their chickpea crop early	NS
		Breed drought-tolerant varieties	
		Develop advanced and water-efficient irrigation such as drip irrigation	
		Employ good seedbed preparation techniques	
		Promote water conservation and associated agronomic packages	

[a] NS = No Solutions suggested by the panelists

were proposed for drought and other water constraints. With wheat, PSE solutions were frequently suggested for all water constraints. Therefore a wider range of agricultural research and development was proposed besides genetic biotechnology and the breeding of improved varieties; including crop and water management, knowledge distribution and training, and appropriate agricultural policy support.

The PSE solutions were especially broad, and included input and output price support policies, market development, as well as improved training and access to agricultural information. There has been a long history of input subsidy and produce price support for major staple foods in the farming systems of South Asia (Acharya 1997; Gulati and Narayanan 2003; Erenstein 2010). Water rights and water management policy have also been highlighted for researchers and policy makers to address in this region (Shah 2007; Erenstein 2009). For example, subsidies on electricity and diesel for irrigation contributed greatly to the expansion of small–scale (well and tube well) irrigation in India and Pakistan (Erenstein

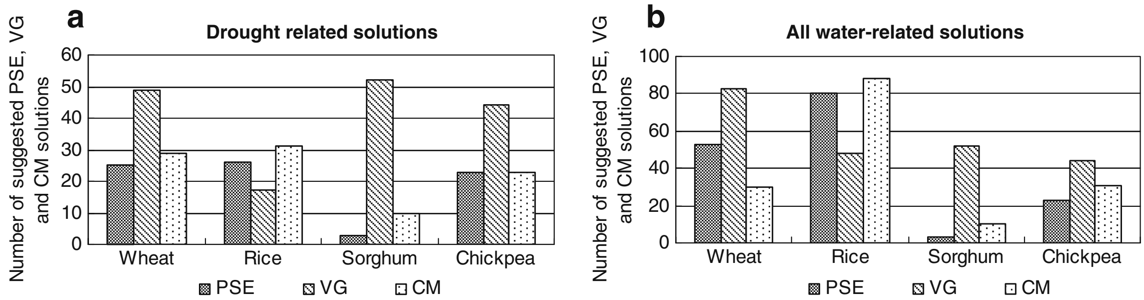

Fig. 3 The importance of policy/socioeconomic (PSE), variety/germplasm (VG) and crop management (CM) solutions for four food crops in South Asia, 2008-09. **a** Drought related solutions. **b** All water related solutions

2009). Such policies stimulated the adoption of agricultural technology, growth in agricultural production, and poverty reduction in the region, but are now increasingly viewed as inefficient and unsustainable (Pingali and Shah 2001; Gulati and Narayanan 2003; Erenstein 2009, 2010).

Investments in water-related research

This study indicated that there is great interest in South Asia to breed and plant varieties of rice, wheat, sorghum and chickpea with added drought tolerance or lower water requirements. The early 21st Century requires a “Blue Revolution—more crop for every drop” to complement the so-called "Green Revolution" of the 20th Century (Borlaug and Dowswell 2000). To improve the effectiveness of breeding for drought tolerance, screening should take place under limited irrigation. Trials evaluating candidate germplasm in India used to be conducted in only two types of water environment—full irrigation or rainfed, but limited-irrigation trials have very recently become part of the All India Coordinated Wheat Improvement Project (Directorate of Wheat Research 2007). Likewise, the CIMMYT wheat breeding program is giving priority to developing broadly-adapted varieties that require less water (Trethowan et al. 2002).

Cropping-system based solutions were also thought to be good investments. For the South Asian *Rice-wheat* and *Rice* systems, cropping system interventions refined through crop system simulation modeling are valuable (e.g. Manjunath and Korikanthimath 2009; Aggarwal et al. 2004). In our study, strengthening irrigation infrastructure and introducing new water-efficient irrigation techniques were commonly proposed for rice. With wheat, policy and social-economic interventions including maintaining good market function, improving roads, developing storage facilities, financial help on mechanization, quality seed and fertilizer, knowledge sharing and farmer training about efficient use of water can help substantially. For example, Gujarat state (*Rainfed mixed* system) in India has improved wheat production by more than 40% per year during 2001–2007 by enhancing the availability of water through investments in infrastructure, irrigation networks and other public goods (Gulati et al. 2009). For sorghum (which is grown primarily in semi-arid rainfed environments), it is likely that genetic-varietal solutions to drought will remain the most promising and practical for farmers. With chickpea, exploring the conservation of residual soil moisture through intercropping and conservation tillage, and promoting mulching to improve water use efficiency may be worthwhile.

Conclusions

A large sample of expert opinion suggests that drought and other types of water constraint are important but do not dominate constraint sets for major food crops in South Asian farming systems. Drought was usually considered responsible for less than 10–15% of yield losses reported even in those systems that are mainly rainfed, and all water-related constraints combined were usually responsible for below 30% of estimated losses. Other types of constraint were often thought responsible for most yield losses. In particular, constraints related to soil infertility, poor use of fertilizer and competition from weeds were extremely severe for wheat and rice, which are the dominant staple food crops in most of South Asia. Pests and diseases were more important for chickpea, while weeds, pests and diseases and insufficient access to information were considered more severe for sorghum. We conclude that some continued investment in crop-based genetic solutions to alleviate drought should be helpful for major food crops in South Asia, especially those that are widely planted in predominantly rainfed farming systems. However, to contribute to the substantial production, sustainability and food security benefits that the region will need in coming decades, these need to be complemented by other water interventions and improvements in soil fertility and weed management for the cereals and by programs to reduce pests and diseases with chickpea.

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