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Getting the focus right: production constraints for six major food crops in Asian and African farming systems

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Abstract To determine the most important production constraints and associated yield losses for six major food crops in 13 farming systems with high poverty in Sub-Saharan Africa, South Asia and East Asia, surveys were conducted with 672 experts representing a diversity of backgrounds and experience. Respondents reported large gaps between highest achieved crop yield on smallholder farms and average yield on farm. Yield gaps were smallest for rice (about 60% of current average smallholder farm grain yields), mid size for wheat and cassava, and larger (sometimes double current farm yields) for sorghum, cowpea and chickpea. Gaps were also smaller in the high input and yield farming systems of East Asia and largest in the marginal, drier systems, particularly in Sub-Saharan Africa. Four categories of production constraint (abiotic, biotic, management and socio-economic) were considered important contributors to yield gaps. A diversity of specific constraints was reported for the crops in the different systems. The most severe and widespread specific constraints for wheat involved the deficiency, high cost and poor management of N fertilizer, and problems associated with drought stress at grain filling, mid season drought and irrigation management. Those for rice included N fertilizer problems, soil fertility depletion, various leaf, stem and head pests and diseases, weed competition and inadequate water management. *Striga* and weed competition, soil resource degradation, poor soil fertility management, and drought were the most severe specific constraints for sorghum. Insect pests of pod, leaf, stem and flower and the high cost of their control dominated the constraint set for cowpea. *Helicoverpa* pod borer, *Botrytis* grey mould and control costs were the most severe for chickpea. Unsuitable varieties/poor seed, soil infertility and fertilizer constraints were also widespread with the legumes. Marketing problems and lack of finance were concerns for cassava along with weed competition, African cassava mosaic virus and poor varieties/planting materials. The findings can help to inform priority setting for international agricultural research and development activities on important food crops in major farming systems occupying areas of high poverty.

Keywords Crop production constraints · Food crops · Poverty · Smallholder farming systems · Yield gap

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Introduction

With persistent poverty, high food prices, uneven growth of yield of food crops and inadequate research budgets in many parts of Africa and Asia, the need for improved information for prioritizing and targeting agricultural research has never been greater. A complexity of abiotic, biotic, and socioeconomic constraints and those related to crop management (Dixon et al. 2001) reduce yields and productivity of food crops for smallholders in farming systems throughout the developing world. If research can identify and address the most severe constraints, there is substantial potential to further increase crop yields of smallholders, food security and farm incomes in developing countries.

The importance of individual constraints and their associated yield losses will vary by crop, management and the environmental and socio-economic characteristics of the farming system. From an appreciation of constraints and losses (complemented by other factors such as potential opportunities, the probability that a loss/opportunity can be effectively addressed, and the benefits it may then have), technology experimentation, training, socio-economic and policy support investments can be prioritized (Alston et al. 1995; Mills 1998). Concepts and techniques from agricultural economics, such as economic surplus and cost-benefit analysis, have been widely used in priority setting. Simple, multi-disciplinary decision support tools have a role in informing the allocation of agricultural research resources (Dixon and la Rovere 2009) and, increasingly, participatory approaches are advocated for prioritizing agricultural research projects in developing countries (Byerlee 2000; Smith 2001).

Various types of constraint assessments of crop production have been undertaken over the last 20-30 years. Farming systems research, involving the participatory identification and assessment of crop and animal production problems, formulation of technology and management solutions to the problems identified, and the implementation of research programs on farm to test and modify the solutions was widely applied during the 1980s and 1990s in developing country agriculture (Collinson 2000). Such work often investigated important crop enterprises together and attempted to cover many constraints, but implementation was generally limited to a local level—covering a few villages, or at most a province or watershed—and studies were rarely merged to build a broader picture.

Most of the geographically expansive studies have concentrated on specific types of constraints for specific crops. For example, Duveiller et al. (2007) assessed wheat pest and disease losses across many developing countries, while the CABI pest distribution maps and database (www.cabi.org/dmpp/) contain comprehensive general information on losses due to pests and their distribution. There are few recent examples of large-scale studies of production constraints for major food crops in different farming systems.

Perhaps the most comprehensive broad study remains that of Evenson et al. (1996a), which brought together a series of constraint-assessment and priority-setting exercises at the country and regional level for rice, undertaken by national research programs and international organizations in South and East Asia. In those studies, researchers identified and quantified several important rice production systems and a wide range of biotic and abiotic constraints. Identified constraints often varied considerably across local cropping environments and broader farming systems (e.g. Widawsky and O'Toole (1996) for rice in eastern India). In a recent comprehensive study of wheat, constraints were given by wheat scientists from nearly twenty major producing countries (Kosina et al. 2007; Reynolds et al. 2008). They underlined the importance of several types of constraint for wheat in developing countries, including many socio-economic, abiotic and biotic problems. Among the few other broad studies, Johansen et al. (1994) examined production constraints for cool season legumes—including chickpea—in Asia and Africa.

An important concern with constraint studies that attempt to average out problems and their losses over farms, villages, watersheds or farming systems is the spatial and temporal variation encountered in crop yields, and types and severity of constraints. Spatial variation is often substantial, even at a farm and plot scale (parts of the same small field, across field types on a farm). Many smallholder farming systems frequently exhibit historically variable and targeted inputs (e.g. of manures and fertilizers) and large management differences. These inconsistencies are superimposed on variability in biophysical factors such as soil types, field water availability, weed and pest distribution (Carter and Murwira 1995; Giller et al. 2006). Accounting for all this variation is a challenge for the collection of information on constraints and their interpretation at a larger scale.

Despite the earlier work, many gaps remain in assessments of production constraints for research program planning, particularly for legumes and root crops, and for most crops in the more marginal farming systems. Thus, to generate information in order to identify areas for future investment, the Generation Challenge Program (GCP) of the Consultative Group for International Agricultural Research (CGIAR) commissioned a study of smallholder production constraints for important food crops in major farming systems with high levels of poverty. The study covered wheat, rice, sorghum and cassava (which together provide much of the dietary energy derived from plants in the developing world), along with cowpea and chickpea (important diet diversity crops) grown in 13 broad farming systems with high poverty, significant drought susceptibility and large production areas of food crops in South Asia, East Asia and Sub-Saharan Africa (Hyman et al. 2008). It adopted the approach of an earlier pilot study on production constraints for another major food crop, maize, in the same farming systems (Gibbon et al. 2007). Given the scarcity of systematically-collected data, the identification of yield constraints for these major food crops will help to focus and set priorities for agricultural research which aims to reduce poverty and food insecurity in the major farming systems in the developing world where more than 80% of the agricultural poor live.

Methodology

This study used the FAO/World Bank classification of 72 farming systems across six regions of the world (Dixon et al. 2001, www.fao.org/farmingsystems/). From this broad classification, the GCP identified a subset of 13 key farming systems (Fig. 1) covering three major developing regions—South Asia, East Asia and Sub-Saharan Africa—which are characterized by extensive poverty (as indicated by large numbers of stunted children) and high drought risk, and in which key GCP crops are widely grown (see Hyman et al. 2008). Short descriptions and regional maps of the farming systems were modified from Dixon et al. (2001), customized for each crop and distributed to participants during the survey. Locations and livelihoods of the 13 farming systems are given below.

Sub-Saharan African farming systems

The *Highland Temperate Mixed* system is mainly located at altitudes between 1,800 and 3,000 metres above sea level (masl) in the highlands and mountains of Ethiopia. Smaller areas are found in Eritrea, Lesotho, South Africa, Angola, Cameroon and Nigeria, generally in subhumid or humid agro-ecological zones. Livelihoods are wheat, barley, tef,

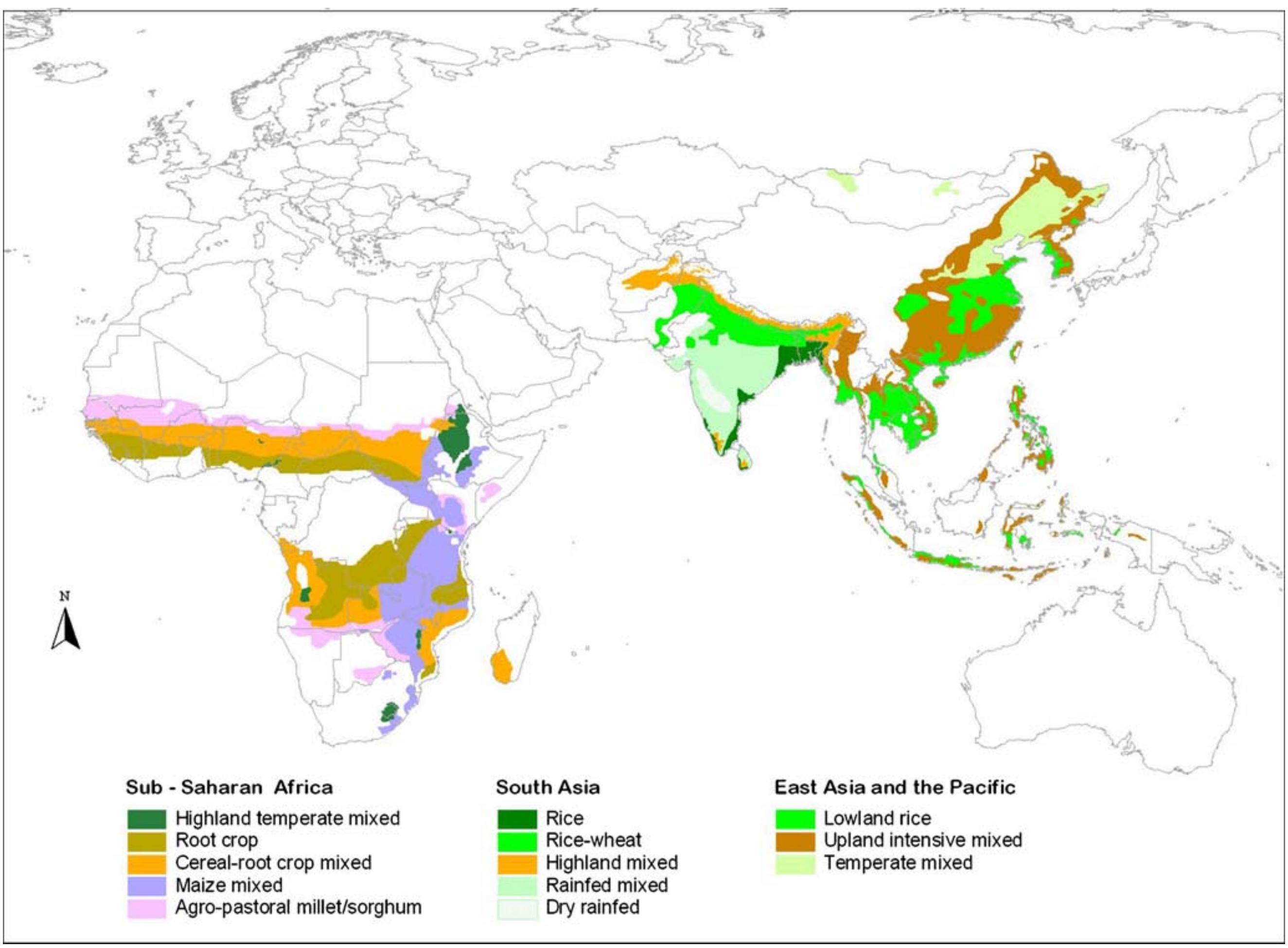

Fig. 1 Map of the African and Asian farming systems surveyed in the constraints study, 2008–09. These farming systems feature high levels of poverty (child stunting), high incidence of drought, large areas of food crops, and are high priority for the CGIAR Generation Challenge Program

peas, lentils, broadbeans, rape, potatoes, sheep, goats, livestock, poultry and off-farm work. The *Root Crop* system is situated in, and extends from, Sierra Leone to Côte d'Ivoire, Ghana, Togo, Benin, Nigeria and Cameroon, in the moist subhumid and humid agro-ecological zones. There is a similar strip in Central and Southern Africa, in Angola, Zambia, Southern Tanzania and Northern Mozambique—and a small area in Southern Madagascar. Livelihoods include cultivation of yams, cassava and legumes and off-farm work. The *Cereal-Root Crop Mixed* system extends from Guinea through Northern Côte d'Ivoire to Ghana, Togo, Benin and the mid-belt states of Nigeria to Northern Cameroon; and there is a similar zone in Central and Southern Africa. Maize, sorghum, millet, cassava, yams, legumes and cattle are the main livelihoods. *Maize Mixed* system is the most important food production system in East and Southern Africa, extending across plateau and highland areas at altitudes of 800 to 1,500 masl, from Kenya and Tanzania to Zambia, Malawi, Zimbabwe, South Africa, Swaziland and Lesotho. Climate varies from dry subhumid to moist subhumid. Principal livelihoods are maize, tobacco, cotton, cattle, goats, poultry and off-farm work. The *Agro-Pastoral Millet/Sorghum* system is found in the semiarid zone of West Africa from Senegal to Niger, and in substantial areas of East and Southern Africa from Somalia and Ethiopia to South Africa. Livelihoods include sorghum, pearl millet, pulses, sesame, cattle, sheep, goats, poultry and off-farm work.

South Asian farming systems

The *Highland Mixed* system extends across the entire length of the Himalayan range, from Afghanistan to the extreme northeast of India, as well as in isolated areas of Kerala and Central Sri Lanka. Livelihoods include cereals, livestock, horticulture and seasonal migration. The *Rice* system is concentrated in Bangladesh and West Bengal, but smaller areas are found in Tamil Nadu and Kerala States of India, and Southern Sri Lanka. Wetland rice (both seasons), vegetables, legumes, off-farm activities are the main livelihoods. The *Rice-Wheat* system produces the bulk of the marketed foodgrains that feed the cities and urban areas of South Asia. It forms a broad swathe across Northern Pakistan and India, from the Indus irrigation area in Sindh and Punjab, across the Indo-Gangetic plain to the northeast of Bangladesh. Major livelihoods are irrigated rice, wheat, vegetables, livestock including dairy and off-farm activities. The *Rainfed Mixed* system occupies the largest area within the sub-continent and, with the exception of a small area in Northern Sri Lanka, is confined entirely to India. Cereals, legumes, fodder crops, livestock and off-farm activities are the important livelihoods. The *Dry Rainfed* system is located in the 'rain shadow' area of the Western Deccan in India. Major livelihoods include coarse cereals, irrigated cereals, legumes and off-farm activities.

East Asian farming systems

The *Lowland Rice* system is found in both humid and moist subhumid agro-ecological zones in well-watered mainly flat landscapes. Large areas are located in Thailand, Vietnam, Myanmar, South and Central East China, Philippines and Indonesia. Smaller areas are in Cambodia, Korea DPR, Republic of Korea, Laos DPR and Malaysia. Livelihoods are rice, maize, pulses, sugarcane, oil seeds, vegetables, livestock, aquaculture and off-farm work. The *Upland Intensive Mixed* system is found in upland and hill landscapes of moderate altitude and slope, in humid and subhumid agro-ecological zones, with major areas located in all countries of East and Southeast Asia. Rice, pulses, maize, sugarcane, oil seeds, fruits, vegetables, livestock and off-farm work are the major livelihoods. *Temperate Mixed* system is found in moist and dry subhumid agro-ecological zones in Central-Northern China and restricted areas of Mongolia. Major livelihoods are wheat, maize, pulses, oil crops, livestock and off-farm work.

Six food crops—wheat, rice, sorghum, cowpea, chickpea and cassava—were chosen for the constraints survey because they are important food crops for the world, and are highest priority for the GCP. An earlier study of maize constraints had been conducted by Gibbon et al. (2007) using a similar approach. Additional important food crops could not be included in the study because of resource limitations. Based on area and production data of each crop in each farming system in each country (CIMMYT-CIAT databases), farming systems were selected in which the particular crop is planted on more than 100,000 ha or more than 3% of the arable area in the farming system. This procedure, which builds on the targeting rationale of Hyman et al. (2008) resulted in the initial 40 crop x farming system combinations listed in Table 1, which represented the sample for the survey. They include 86% of the harvested rice area in the developing world, around 75% of the chickpea and cowpea, and over 60% of the sorghum. They also cover about 45% of the wheat and cassava area in developing regions.

The concept of a yield gap is a useful framework for on-farm constraints analysis and priority setting (de Datta et al. 1978; Shumba et al. 1990; Evenson et al. 1996b; Widawsky and O'Toole 1996). Yield can be defined in various ways: theoretical maximum yield potential of the crop; the highest attainable yield (usually on a good research station); the highest (best) actual achieved yield on (smallholder) farms; the economic (recommended) optimum yield on farms; and the average actual achieved yield on (smallholder) farms. Whilst many interpretations of yield gap are possible, in

Table 1 Combinations of food crops by farming system surveyed in the constraints study, 2008–09[a]

Region	Farming System	Wheat	Rice	Sorghum	Cowpea	Chickpea	Cassava
Sub Saharan Africa	Highland Temperate Mixed	✓		✓		✓	
	Root Crop		✓	✓	✓		✓
	Cereal-Root Crop Mixed		✓	✓	✓		✓
	Maize Mixed			✓	✓		✓
	Agro-Pastoral Millet/Sorghum			✓	✓		
South Asia	Highland Mixed	✓	✓			✓	
	Rice-Wheat	✓	✓			✓	
	Rice		✓			✓	
	Rainfed Mixed	✓	✓	✓		✓	
	Dry Rainfed	✓	✓	✓		✓	
East Asia Pacific	Lowland Rice	✓	✓				✓
	Upland Intensive Mixed	✓	✓				✓
	Temperate Mixed	✓	✓				
No. of systems		8	10	7	4	6	5

[a] The six important food crops surveyed (where planted on >3% cropped area or > 100,000 ha in system) in the 13 focus farming systems featuring high levels of poverty

this study we pragmatically defined the *Smallholder farm yield gap* as the *difference between the highest (best) achieved yield on smallholder farms and the average yield on smallholder farms* (Shumba et al. 1990; Evenson et al. 1996b). Any given smallholder yield gap can be decomposed into losses due to four categories of constraint—biotic, abiotic, management and socio-economic. Each category can be further divided into specific constraints. Biotic constraints include pests, diseases, weeds, bird damage and inappropriate varieties. Nutrient deficiency, drought, waterlogging, cold stress and heat are examples of abiotic constraints. Management constraints include unsuitable planting time or late planting, incorrect seeding rate, inadequate irrigation and poor choice of variety. Examples of socio-economic constraints are high price of seed or fertilizer, inadequate farmer knowledge, labour shortage and inaccessibility to markets. Studies often assume constraints are additive, although in practice many constraints interact and may be multiplicative. Some socio-economic constraints (such as shortage of credit) may not directly lead to yield losses and can be viewed as causes of other types of constraints. Some researchers and many extension staff and farmers are aware of the average yields of the crop on smallholder fields in a particular area. In addition, researchers and development agents are often familiar with the highest or best yields that have been obtained on smallholder farms under good inputs and crop management. In many cases the best farm yield is more relevant than the research station yield which is produced under management and input levels which may not be attainable and is sometimes irrelevant to the typical conditions found on small farms.

For each crop, a list of 10–20 potential production constraints per category was developed and tested. Sources of information for likely constraints included suggestions from expert scientists, the authors' experience, published research and extension materials and internet websites. Additional important constraints were added by panelists during the survey.

The study used a modified "Delphi" survey methodology (Dalkey 1969; Gibbon et al. 2007)—a rapid, interactive procedure, originally developed by the Rand Corporation to support decision making on subjects characterized by a high degree of uncertainty. Questionnaires were developed, customized and tested for each crop and farming system, and translated as appropriate into Chinese, Hindi or French (for West Africa). Example questionnaires are available on the website of the Food Security journal. Two rounds of interaction took place with panels of experts between April 2008 and February 2009. In the first round, information was sought from panelists on their crop and system knowledge, on yield gaps, the important constraints in the four categories and their associated yield losses. To promote convergence, summary results from the first round were provided to panelists in the second round to allow them to adjust gaps, constraints and losses. Additional information was obtained on the severity and changing nature of the constraints, their spatial and temporal distribution, effects on income and health, major interactions among the most severe constraints and important effects of the key constraints on the broader farming system or farm enterprise.

The expert knowledge of at least 15 panelists familiar with the particular crop in each farming system was sought in order to ensure sufficient diversity of opinion from research to extension and farming. In addition, twelve persons in government research, universities and CGIAR centers acted as focal persons for the survey in China, the Philippines, India, Bangladesh, Nepal, Ethiopia, Zimbabwe, Nigeria, Benin and Mexico. More than 1,400 prospective panelists with a range of backgrounds and personal experience of the given farming system and crop were contacted in the first round by a regional focal person or from CIMMYT HQ. Prospective panelists included agricultural researchers such as plant breeders, agronomists, agricultural economists and plant protection experts; extension and training staff, representatives of farmer organizations, seed and other input suppliers, as well as some knowledgeable farmers. Individuals from many national agricultural research and extension institutions throughout Sub-Saharan Africa, South and East Asia participated, as did staff from CGIAR centers including IRRI, CIMMYT, ICRISAT, CIAT, IITA and WARDA. NGOs and the private sector were also represented.

Six hundred and seventy two panelist returns were received in the first round, averaging 16.4 returns per crop x system combination. Overall, 22.7% of the respondents were plant breeders or geneticists/biotechnologists, 4.6% plant protection scientists, 24.7% agronomists/soil or water scientists, 8.8% were social scientists or economists. 25.4% of respondents were involved in agricultural extension or training, 7.3% were input (seed, fertilizer) suppliers or crop marketers and 6.5% were farmers. There was variation in panel size for the different crop x system combinations and fewer than 15 panelists (minimum 10) were accepted in 15 of the 40 crop x farming system combinations. Two crop x system combinations were dropped during the survey because of insufficient responses; sorghum in the *Root Crop* system of Sub-Saharan Africa and cassava in the *Lowland Rice* system of East Asia. Full results were obtained from 10 or more panelists for 38 crop x system combinations; eight involving wheat, ten for rice, six for sorghum, four for cowpea, six for chickpea and four for cassava.

A mean yield loss was calculated for each constraint, adjusted for frequency of occurrence. Constraints were ranked according to the size of their mean yield losses, separately for each of the four categories of constraint. The estimated yield losses for the top six constraints in each category were given in the second round questionnaires. Panelists were invited to make revisions, and adjustments were made to calculate the final mean losses. Summary tables of the 10 most severe constraints (i.e. those with the estimated largest yield losses) for each crop x system combination are reported here. Standard deviations (SD) are given for the yield estimates. SDs are not reported for the estimates of yield losses due to the constraints because the loss assessments were not from one sample; they came from all panelists in the first round and then the means were adjusted by a subset of panelists that replied on this topic in the second round.

Results

Panelists identified large smallholder farm yield gaps (as a percentage of current average smallholder farm yields) for most crops in most farming systems (Table 2). Gaps were smallest for rice (averaging about 60% of current average smallholder farm grain yields), mid size for wheat and cassava, and usually larger for sorghum and the two legumes (averaging slightly more than, but sometimes double current farm yields) (Table 2). Gaps also tended to be larger in the more marginal rainfed, drier farming systems.

Initial estimates of the losses associated with categories of constraint revealed that all four categories (abiotic, biotic, management and socio-economic) were important but their magnitude differed between the crops (Table 2). Abiotic and management constraints tended to be more important for wheat, socio-economic and management issues for rice and cassava, and abiotic constraints for sorghum. Biotic constraints dominated the two legumes, cowpea and chickpea.

Panelists identified many important individual abiotic, biotic, socio-economic and management constraints for the 38 specific combinations of crop x farming system. Those constraints with the largest yield losses and widely present over fields and years were considered to be the most severe. Together, the yield losses associated with the 24 most severe constraints identified by panelists for each crop x farming system (not reported) represented between 60% and 95% of the estimated on-farm yield gaps. For the ten most severe constraints identified, the combined yield losses contributed between 45% of the average yield gap for cassava in four systems and 56% for chickpea in six systems (Table 3). For all the crops in most systems, panelists felt the most severe constraints were getting worse and to be present on more than half of fields most years.

The ten most severe constraints and associated grain or root yield losses identified for each crop x farming system combination are in Tables 4, 5, 6, 7, 8 and 9. The size of the estimated yield loss, adjusted for spatial and temporal variation, was used to rank the constraints. Overall, the most commonly found very severe production constraints for these food crops and farming systems relate to soil fertility depletion and poor management and shortages of fertilizer; various specific pests, diseases and weeds; water shortages and water management problems. Shortcomings with germplasm and socio-economic constraints were sometimes very severe. Groups of related constraints often

Table 2 Estimated smallholder farm yield gaps and an initial breakdown of yield losses associated with four categories of constraint for six food crops in Asian and African farming systems

Crop	Region	Farming system	Highest smallholder farm yield[a] (t/ha) (SD)	Average smallholder farm yield (t/ha) (SD)	Smallholder yield gap (t/ha) (SD)	Yield losses by constraint category (Percent of total yield gap)[b]			
						Socio-Economic	Abiotic	Biotic	Management-related
Wheat									
	Sub Saharan Africa	Highland Temperate Mixed	4.14 (1.51)	2.02 (1.11)	2.12 (0.69)	28	20	19	32
	South Asia	Highland Mixed	3.80 (1.62)	2.05 (0.99)	1.76 (0.89)	23	30	21	27
		Rice-Wheat	4.81 (1.16)	2.46 (0.74)	2.38 (0.89)	20	28	20	31
		Rainfed Mixed	4.96 (1.11)	2.39 (0.57)	2.54 (0.80)	20	28	22	28
		Dry Rainfed	5.32 (0.99)	2.16 (0.42)	3.10 (0.72)	23	30	18	30
	East Asia Pacific	Lowland Rice	8.18 (2.32)	5.12 (1.76)	3.06 (1.00)	20	29	20	30
		Upland Intensive Mixed	7.81 (3.43)	3.99 (1.51)	3.82 (3.02)	24	30	17	29
		Temperate Mixed	8.74 (1.71)	5.84 (2.67)	3.13 (0.98)	20	34	20	27
	Crop Mean		5.97	3.25	2.74	22	29	20	29
Rice									
	Sub Saharan Africa	Root Crop	4.54 (1.85)	2.88 (1.36)	1.72 (1.01)	38	18	25	18
		Cereal-Root Crop Mixed	4.83 (2.31)	2.74 (1.31)	2.09 (1.34)	51	14	16	19
	South Asia	Highland Mixed	4.70 (1.60)	2.52 (0.57)	2.18 (0.59)	27	29	21	23
		Rice	6.98 (1.69)	3.74 (1.17)	2.85 (1.16)	27	25	22	26
		Rice-Wheat	6.23 (1.29)	3.12 (1.44)	2.76 (0.82)	26	26	20	27
		Rainfed Mixed	5.04 (1.12)	2.95 (0.65)	2.09 (0.99)	27	22	19	31
		Dry Rainfed	6.58 (1.77)	3.88 (1.53)	2.57 (0.76)	27	24	23	26
	East Asia Pacific	Lowland Rice	8.95 (2.72)	5.93 (2.02)	2.94 (1.20)	28	21	17	35
		Upland Intensive Mixed	9.94 (1.20)	6.88 (1.27)	3.05 (1.23)	25	29	19	27
		Temperate Mixed	10.35 (1.11)	6.85 (0.74)	3.54 (0.99)	29	24	23	24
	Crop Mean		6.81	4.15	2.58	31	23	21	26
Sorghum									
	Sub Saharan Africa	Highland Temperate Mixed	3.44 (1.28)	1.80 (0.58)	1.64 (1.44)	15	25	28	29
		Cereal-Root Crop Mixed	2.93 (1.44)	1.13 (0.55)	1.80 (1.18)	23	23	26	24
		Maize Mixed	2.30 (1.67)	1.09 (0.78)	1.23 (1.34)	30	29	19	22
		Agro-pastoral Millet/ Sorghum	2.15 (1.33)	0.66 (0.37)	1.50 (1.12)	24	32	18	27
	South Asia	Rainfed Mixed	3.11 (1.50)	1.62 (0.31)	1.69 (1.36)	23	25	22	30
		Dry Rainfed	4.47 (1.27)	1.85 (0.65)	2.86 (1.27)	27	30	20	23
	Crop Mean		3.07	1.36	1.78	24	27	22	26

Table 2 (continued)

Crop	Region	Farming system	Highest smallholder farm yield[a] (t/ha) (SD)	Average smallholder farm yield (t/ha) (SD)	Smallholder yield gap (t/ha) (SD)	Yield losses by constraint category (Percent of total yield gap)[b]			
						Socio-Economic	Abiotic	Biotic	Management-related
Cowpea									
	Sub Saharan Africa	Root Crop	0.80 (0.45)	0.38 (0.19)	0.41 (0.48)	31	16	31	21
		Cereal-Root Crop Mixed	0.97 (0.62)	0.54 (0.43)	0.50 (0.42)	22	21	37	21
		Maize Mixed	1.36 (0.90)	0.42 (0.41)	0.92 (0.77)	27	25	28	20
		Agro-pastoral Millet/ Sorghum	1.63 (1.14)	0.62 (0.52)	1.01 (0.81)	21	21	30	29
	Crop Mean		1.19	0.49	0.71	25	21	32	23
Chickpea									
	Sub Saharan Africa	Highland Temperate Mixed	2.60 (0.90)	1.18 (0.45)	1.43 (0.83)	19	18	33	30
	South Asia	Highland Mixed	1.60 (0.30)	0.87 (0.23)	0.73 (0.28)	19	28	33	19
		Rice	2.04 (0.35)	0.96 (0.44)	1.17 (0.38)	19	24	33	19
		Rice-Wheat	1.99 (0.75)	0.89 (0.66)	1.06 (0.57)	20	23	32	25
		Rainfed Mixed	2.43 (0.49)	1.26 (0.66)	1.25 (0.48)	19	24	31	27
		Dry Rainfed	1.99 (0.36)	0.91 (0.22)	1.08 (0.26)	16	28	33	25
	Crop Mean		2.11	1.01	1.12	19	24	33	24
Cassava									
	Sub Saharan Africa	Root Crop	22.67 (11.21)	13.77 (6.26)	8.24 (5.81)	32	23	22	24
		Cereal-Root Crop Mixed	21.35 (12.66)	12.88 (2.27)	9.00 (5.91)	31	20	23	26
		Maize Mixed	19.87 (7.32)	8.74 (3.78)	12.22 (5.14)	25	20	25	29
	East Asia Pacific	Lowland Rice	40.00 (7.07)	21.00 (1.41)	19.00 (5.66)	15	25	25	35
		Upland Intensive Mixed	27.13 (17.26)	15.80 (3.89)	19.20 (5.98)	28	27	17	28
	Crop Mean		26.20	14.44	13.53	26	23	22	28

[a] The highest farm yield, average farm yield and yield gap estimated by panelists in the round 1 questionnaire were adjusted independently by respondents during round 2. Thus, in some cases the reported average yield plus the yield gap does not sum to the highest farm yield

SD = standard deviation

[b] Initial (round 1) percent estimate for four categories of constraint

occurred together. For example, poor management, high cost and deficiency of N fertilizer, and soil fertility depletion were often reported together for the cereals, as were drought stress and poor water management. Specific biotic constraints and the high cost of their control often dominated the legumes.

Interactions between the most severe constraints were noted with the crops in many systems, especially causal effects of socio-economic and management constraints on abiotic and biotic constraints. For example, the high cost and poor management of fertilizers were commonly reported to be reasons for nutrient deficiencies in wheat in Asia. Effects of constraints on the broader farming system were given, including concern about declines in system sustainability with reductions in soil fertility and increasing water scarcity and concerns about the consequences of constraints for other crops in the system. An example was the excessively long duration of rice cultivars restricting the incorporation of other crops such as wheat or chickpea into intensifying cropping systems in Asia. Systems concerns were particularly prominent with those crops often grown as intercrops (cowpea) and that have several different functions or uses within the system (principally sorghum, cowpea and cassava).

A wide range of effects of constraints on income (not directly related to grain or root yield) was given for the crops. Panelists were particularly concerned about poor quality grain and roots for human consumption; excessive costs associated with inputs such as fertilizer, labor and irrigation; animal fodder effects and occasional negative effects on human health.

Wheat

Wheat was surveyed in East Asia, South Asia and in eastern and southern Africa. The smallest yield gaps for wheat (around two thirds of current farm yields) were found in the highest yielding (about 5 t/ha) East Asian systems (Table 2). Gaps were similar to current average farm yields in most of the South Asian and Sub-Saharan Africa systems. The wheat yield gap was largest (about 1.5 times current yields) in the more marginal *Dry Rainfed* system of South Asia. Among types of constraint, panelists reported that biotic constraints were usually of least importance overall. Abiotic and management constraints were more important for wheat than the other categories in most of the South Asia and East Asia Pacific systems (Table 2). Overall average grain yield losses from the ten most severe constraints for wheat were 1.2 t/ha, representing 46% of the average yield gap (Table 3).

In the East Asian systems, the most severe (i.e. associated with the largest yield losses) and widespread wheat constraints were either abiotic or related to management (Table 4). Those concerning N deficiency, N fertilizer management and its high cost were important in these systems. Drought stress during grain filling, mid season drought, irrigation water management constraints and heat stress during grain filling were also severe in East Asia (Table 4).

There was some similarity with the South Asia highlands, where soil fertility depletion, N deficiency and the high cost of N fertilizer dominated wheat production constraints. These problems were less important in lowland South Asia systems where late planting of the crop and associated heat stress during grain filling were widespread and severe (Table 4). Weed competition was reported severe for wheat throughout South Asia, as were poor quality seed and unsuitable varieties. Irrigation problems, along with drought during grain filling or mid season were also of major concern.

In eastern and southern Africa, the unavailability of quality wheat seed was extremely severe (with the largest yield loss), along with soil fertility and N fertilizer problems. Two biotic constraints—rusts and weed competition—were also severe.

Table 3 Average yield loss (t/ha) and proportion of yield gap associated with the ten most severe constraints identified for six food crops in Asian and African farming systems with high poverty

Crop	Number of farming systems	Average yield loss (t/ha)[a]	Yield loss as a percent of average yield gap	Percent range over systems
Wheat	8	1.19	46	35–58
Rice	10	1.25	49	38–60
Sorghum	6	0.92	51	39–65
Cowpea	4	0.37	52	47–60
Chickpea	6	0.62	56	46–63
Cassava	4	5.31	45	37–53

[a] Grain yield; wet root yield for cassava

Rice

Rice was also surveyed in East Asia, South Asia and Africa. Yield gaps of only half of current average yields were reported in the high-input, high-yielding (over 6 t/ha grain) and intensive management systems of East Asia (Table 2). Respondents reported yield gaps equivalent to three quarters of current yields in the intensifying systems of South Asia. Yield gaps were also small for rice in Sub-Saharan Africa. Overall, socio-economic and management constraints were the most important for the rice systems. Socio-economic issues were especially prominent for rice in Sub-Saharan Africa and biotic constraints were relatively unimportant in South Asia and East Asia (Table 2). Average yield losses with the ten most severe constraints across the ten systems were about 1.25 t/ha (49% of the yield gap) (Table 3).

There were no clear dominant severe constraints across all the East Asian systems, and the most severe constraints were very different in the *Temperate Mixed* system (Table 5). Overall, pests and diseases were most severe and widespread, with leaf, stem, head pests and head diseases being widely reported, along with diseases of the leaf or stem. Inadequate control or management of these pests and diseases was a major concern. As with wheat, several constraints related to N deficiency, costs and management of N fertilizer were severe, especially in the more tropical systems (Table 5).

In South Asia, the most widespread severe (with largest yield loss) constraints for rice in all five systems were soil

Table 4 The ten most severe production constraints identified for wheat in eight farming systems in South Asia, East Asia and Sub-Saharan Africa. Constraints ranked by size of grain yield loss

Wheat constraint	Yield loss (kg/ha)	% of yield gap	Wheat constraint	Yield loss (kg/ha)	% of yield gap
SS Africa—Highland Temperate Mixed			***South Asia—Highland Mixed***		
Unavailability of quality seed	167	8	Soil fertility depletion	182	10
N fertilizer expensive/in short supply	159	8	N deficiency	96	5
N deficiency	146	7	Unavailability of quality seed	89	5
Rusts (stem, leaf, yellow)	142	7	Weed competition	88	5
Weed competition	120	6	N fertilizer expensive/in short supply	79	4
Soil fertility depletion	106	5	Use of unsuitable variety	78	4
Insufficient access to agricultural information	102	5	Rusts (stem, leaf, yellow)	73	4
Farmers do not have timely access to right machinery	98	5	Irrigation problems	68	4
Difficult access to finance	98	5	High price of seed	55	3
Inadequate farmer production and utilization knowledge/training	96	5	Late planting of crop	55	3
Total	**1235**	**58**	**Total**	**863**	**49**
South Asia—Rice-Wheat			***South Asia—Rainfed Mixed***		
Late planting of crop	187	8	Irrigation problems	269	11
Heat during grain fill	163	7	Weed competition	190	7
Weed competition	149	6	Heat during grain fill	133	5
Leaf and stem fungal diseases (other than rusts)	132	6	Rodents and wild animals	124	5
Use of unsuitable variety	117	5	Use of unsuitable variety	122	5
Unavailability of quality seed	90	4	Temporary drought in supplementary irrigation systems	95	4
Inadequate farmer production and utilization knowledge/training	76	3	Unavailability of quality seed	92	4
Soil fertility depletion	75	3	Inadequate farmer production and utilization knowledge/training	85	3
Inappropriate use of fertilizers other than N	70	3	Leaf and stem fungal diseases (other than rusts)	74	3
Poor management of N fertilizer	61	3	Soil physical degradation	71	3
Total	**1120**	**47**	**Total**	**1255**	**49**
South Asia—Dry Rainfed			***East Asia P—Lowland Rice***		
Late planting of crop	284	9	Poor management of N fertilizer	183	6
Heat during grain fill	241	8	Poor seedbed preparation	170	6
Irrigation problems	174	6	N fertilizer expensive/in short supply	128	4
Weed competition	152	5	N deficiency	116	4
Unavailability of quality seed	98	3	Unsuitable plant population density	105	3
Insufficient access to agricultural information	98	3	Use of unsuitable variety	86	3
Terminal (grain filling) drought	88	3	Head diseases	86	3
Mid season drought	87	3	Terminal (grain filling) drought	79	3
Difficult access to finance	86	3	Leaf, stem, head pests	77	3
Poor crop rotations	84	3	Mid season drought	76	2
Total	**1393**	**45**	**Total**	**1106**	**36**
East Asia P—Upland Intensive Mixed			***East Asia P—Temperate Mixed***		
Terminal (grain filling) drought	168	4	Lodging	160	6
N fertilizer expensive/in short supply	160	4	Irrigation problems	154	6
N deficiency	154	4	Leaf, stem, head pests	144	5
Poor management of N fertilizer	143	4	Heat during grain fill	138	5
Mid season drought	142	4	Mid season drought	123	5
Irrigation problems	142	4	Poor management of N fertilizer	119	4

Table 4 (continued)

Wheat constraint	Yield loss (kg/ha)	% of yield gap	Wheat constraint	Yield loss (kg/ha)	% of yield gap
Rusts (stem, leaf, yellow)	126	3	Low price of grain and other products	108	4
Use of unsuitable variety	97	3	Terminal (grain filling) drought	100	4
No incentive to produce higher quality wheat, markets do not pay	95	2	Unsuitable plant population density	94	4
Low price of grain and other products	93	2	Use of unsuitable variety	86	4
Total	**1319**	**35**	**Total**	**1226**	**46**

fertility depletion, N deficiency, problems with the cost and supply of N fertilizer and poor fertilizer use and management. By far the most severe biotic constraint was weed competition, which was extremely important in all the wetter systems. Water unavailability or access, its high cost and poor management, and drought or intermittent water stress were further severe constraints to rice production in all the South Asian systems. Problems with poor quality seed and low yielding or old rice varieties were reported in the more marginal *Dry Rainfed* and *Highland* systems (Table 5).

The most important rice constraints in Africa also involved N fertilizer inputs and management, and the depletion of soil fertility (Table 5). Problems with irrigation water management, access to water and the high cost of irrigation were major concerns. Among biotic constraints, competition from weeds and shortcomings in weed management were severe, while poor access to agricultural information and inadequate farmer knowledge and training were also important for rice in Africa.

Sorghum

In both Sub-Saharan Africa and South Asia, sorghum yield gaps were similar to current farm yields in the wetter and higher elevation systems, and again larger (1.5 times to double current yields) in marginal, drier systems such as the *Agro-pastoral Millet/Sorghum* system in Africa (Table 2). With sorghum, there was considerable variability in responses across the different farming systems, with more emphasis on abiotic constraints and less on biotic constraints for many systems, particularly those in South Asia. The ten most severe sorghum constraints reduced grain yield, on average, by about 0.9 t/ha (51% of the gap).

Overall, *Striga* and weed competition were very severe specific constraints in Sub-Saharan Africa, except in the driest sorghum system (Table 6). Soil infertility, including N deficiency, soil physical degradation and poor fertilizer management were severe and widespread. Drought during crop establishment and with the developing crop or in grain filling, was severe in all four African systems (Table 6).

In South Asia, sorghum is severely affected by abiotic stresses, particularly drought with the developing crop, in grain filling, and sometimes during crop establishment (Table 6). Several biotic constraints, particularly pests and diseases of the leaf, stem and panicle, and competition from weeds, were also very severe. Poor access to agricultural information and inadequate farmer knowledge and training, were additional concerns with sorghum in these relatively marginal systems.

Cowpea

Cowpea yield gaps were large; similar to current average farm yields, and ranging up to 2.2 times current yields for the *Maize Mixed* system in Sub-Saharan Africa (Table 2). With the four cowpea systems, all found in Africa, non grain products such as leaf relish and pods were as important as grain. Biotic constraints were considered far more important than the other three categories for cowpea (Table 2). Overall average grain yield losses with the top ten cowpea constraints were about 0.37 t/ha (52% of the yield gap) (Table 3).

Insect pest problems on pod, leaf, stem and flower and the high cost of their control dominated these systems (Table 7). Constraints related to fertilizer cost and supply shortages, and soil fertility depletion, were severe in several of the systems, as were shortages of quality seed, the use of unsuitable varieties and competition from weeds.

Chickpea

For most chickpea systems, yield gaps were estimated to be slightly larger than or about the size of current farm yields (Table 2). Biotic constraints were also the most important type of constraint (Table 2). Socio-economic constraints were relatively unimportant in the South Asian systems and in the *Highland Temperate Mixed* system of East Africa. Overall average yield losses with the ten most severe

Table 5 The ten most severe production constraints identified for rice in ten farming systems in South Asia, East Asia and Sub-Saharan Africa

Rice constraint	Yield loss (kg/ha)	% of yield gap	Rice constraint	Yield loss (kg/ha)	% of yield gap
SS Africa—Root Crop			***SS Africa—Cereal-Root Crop Mixed***		
N fertilizer expensive/in short supply	120	7	N fertilizer expensive/in short supply	215	10
High cost of irrigation	119	7	Insufficient access to agricultural information	110	5
Inappropriate/poor nutrient/fertilizer use and management	95	6	Use of low yielding or old variety	97	5
Soil fertility depletion	88	5	Difficult access to finance	90	4
Weed competition	79	5	Inadequate farmer knowledge/training	86	4
Use of low yielding or old variety	76	4	Inadequate water management	79	4
Difficult access to finance	74	4	Hired labor shortage	77	4
Bird damage	68	4	Bird damage	76	4
No access to timely mechanization	68	4	Weed competition	67	3
Inappropriate/poor weed management	51	3	Difficult access to sufficient irrigation water	63	3
Total	**837**	**49**	**Total**	**958**	**46**
South Asia—Highland Mixed			***South Asia—Rice***		
Soil fertility depletion	252	12	Weed competition	183	6
Weed competition	191	9	N deficiency	179	6
N deficiency	161	7	Soil fertility depletion	172	6
N fertilizer expensive/in short supply	125	6	N fertilizer expensive/in short supply	150	5
Unavailability of quality seed	124	6	Inappropriate/poor nutrient/fertilizer use and management	148	5
Leaf, stem, panicle diseases	109	5	Inadequate water management	144	5
Inadequate water management	107	5	Leaf, stem, panicle diseases	140	5
Use of low yielding or old variety	80	4	Leaf and stem pests	139	5
Drought or intermittent water stress on light or heavy soils	77	4	Use of low yielding or old variety	128	4
Difficult access to sufficient irrigation water	75	3	Drought or intermittent water stress on light or heavy soils	116	4
Total	**1301**	**60**	**Total**	**1500**	**53**
South Asia—Rice-wheat			***South Asia—Rainfed Mixed***		
Weed competition	175	6	Drought or intermittent water stress on light or heavy soils	233	11
Soil fertility depletion	160	6	Inadequate water management	189	9
Drought or intermittent water stress on light or heavy soils	151	5	Weed competition	138	7
Leaf, stem, panicle diseases	151	5	Difficult access to sufficient irrigation water	127	6
N fertilizer expensive/in short supply	128	5	High cost of irrigation	107	5
Leaf and stem pests	127	5	Soil fertility depletion	87	4
Inappropriate/poor nutrient/fertilizer use and management	127	5	Rodent damage	85	4
Inadequate water management	113	4	Leaf and stem pests	84	4
Inappropriate/poor insect/disease management	109	4	High price of inputs other than N	78	4
Unavailability of quality seed	108	4	Inadequate farmer knowledge/training	76	4
Total	**1348**	**49**	**Total**	**1203**	**58**
South Asia—Dry Rainfed			***East Asia P—Lowland Rice***		
Leaf and stem pests	155	6	Inappropriate/poor nutrient/ fertilizer use and management	200	7
Unavailability of quality seed	127	5	Low price of output/products	196	7
Use of low yielding or old variety	126	5	Leaf and stem pests	175	6
Inappropriate/poor nutrient/fertilizer use and management	116	5	Inappropriate/poor insect/disease management	131	4
Leaf, stem, panicle diseases	101	4	Inadequate water management	126	4

Table 5 (continued)

Rice constraint	Yield loss (kg/ha)	% of yield gap	Rice constraint	Yield loss (kg/ha)	% of yield gap
Drought or intermittent water stress on light or heavy soils	96	4	Use of low yielding or old variety	118	4
Insufficient access to agricultural information	91	4	Inadequate plant population	114	4
Soil fertility depletion	89	3	Leaf and stem fungal diseases	96	3
Difficult access to finance	84	3	Soil fertility depletion	95	3
Inadequate farmer knowledge/training	84	3	Inadequate farmer knowledge/training	92	3
Total	**1070**	**42**	**Total**	**1341**	**46**
East Asia P—Upland Intensive Mixed			***East Asia P—Temperate Mixed***		
Leaf and stem pests	228	7	Use of low yielding or old variety	200	6
Drought or intermittent water stress on light or heavy soils	215	7	Low temperature (cold) stress	177	5
Inadequate farmer knowledge/training	192	6	Leaf, stem, panicle diseases	156	4
Inadequate water management	172	6	Low price of output/products	152	4
Leaf, stem, panicle diseases	153	5	Difficult access to sufficient irrigation water	127	4
Inappropriate/poor insect/disease management	134	4	Drought or intermittent water stress on light or heavy soils	119	3
N fertilizer expensive/in short supply	133	4	Leaf and stem pests	113	3
Cyclone/typhoon damage	131	4	Inadequate water management	113	3
Soil fertility depletion	130	4	Soil fertility depletion	103	3
Inappropriate/poor nutrient/fertilizer use and management	120	4	Flooding of low lying fields	96	3
Total	**1607**	**53**	**Total**	**1356**	**38**

constraints were about 0.62 t/ha (56% of the average gap) (Table 3).

Helicoverpa pod borer was the dominant constraint throughout the five South Asia farming systems surveyed while *Botrytis* grey mould was also very important except for the driest system (Table 8). These specific biotic constraints were associated with concerns about the high cost of their control. Soil fertility and fertilizer use constraints were very severe in several systems, as was the sparse planting of chickpea. Also important and widespread in the drier systems were constraints involving drought and water management throughout crop development (Table 8).

In East Africa, root or soil diseases and the perception of production risk were the most severe, followed by the use of unsuitable varieties and poor quality of saved seed for planting.

Cassava

Cassava was surveyed in three Sub-Saharan Africa systems and one system in East Asia. Small yield gaps of little more than half of current farm yields were reported for the main cassava farming systems in Africa, but the gap appeared larger in East Asia (Table 2). Although variable across the systems in East Asia and Africa, socio-economic constraints and management constraints were usually thought more important for cassava than biotic and abiotic constraints. The combined ten most severe constraints for cassava reduced root yield by an average of 5.3 t/ha fresh weight, 45% of the estimated yield gap (Table 3).

In Africa, the most severe constraints identified involved shortages of finance, lack of policy support for the crop and inadequate markets for roots (Table 9). Two biotic constraints—weed competition and African cassava mosaic virus—were considered very severe throughout the African systems, as were constraints related to the use of unimproved or unsuitable varieties and poor quality stakes or cuttings for planting.

In East Asia, weed and variety constraints were again important for cassava, but there was more concern about soil physical degradation and fertility depletion, along with high fertilizer costs and shortcomings with fertilizer management (Table 9).

Discussion

Yields and yield gaps

The average yields of smallholder farms reported by panelists in our study fitted well with authors' expectations for the crops in the farming systems and corresponded

Table 6 The ten most severe production constraints identified for sorghum in six farming systems in Sub-Saharan Africa and South Asia

Sorghum constraint	Yield loss (kg/ha)	% of yield gap	Sorghum constraint	Yield loss (kg/ha)	% of yield gap
SS Africa—Highland Temperate Mixed			***SS Africa—Cereal-Root Crop Mixed***		
Leaf, stem, panicle pests	113	7	*Striga*	150	8
Weed competition	111	7	N deficiency	125	7
N deficiency	102	6	Drought (water deficit) during crop establishment	124	7
Crop establishment difficulties	93	6	Inadequate fertilizer use and management	123	7
Striga	88	5	Soil fertility depletion	119	7
Drought (water deficit) during crop establishment	81	5	Fertilizer expensive/in short supply	110	6
Soil physical degradation	64	4	Weed competition	103	6
Soil fertility depletion	59	4	Drought, dry spells, with developing crop or in grain filling	97	5
Cold stress/frost damage	55	3	Unavailability of quality seed	91	5
Inadequate farmer production and utilization knowledge/training	51	3	Leaf, stem, panicle pests	81	4
Total	**816**	**50**	**Total**	**1122**	**62**
SS Africa—Maize Mixed			***SS Africa—Agro-Pastoral Millet/Sorghum***		
Weed competition	81	7	Difficult formal market access for grain	195	13
Soil physical degradation	63	5	Drought, dry spells, with developing crop or in grain filling	108	7
Drought, dry spells, with developing crop or in grain filling	49	4	Fertilizer expensive/in short supply	105	7
Drought (water deficit) during crop establishment	48	4	Inadequate fertilizer use and management	99	7
Inadequate farmer production and utilization knowledge/training	47	4	N deficiency	96	6
Fertilizer expensive/in short supply	46	4	Use of unimproved or unsuitable varieties	84	6
N deficiency	44	4	Highly variable and risky planting times	75	5
Crop establishment difficulties	38	3	*Striga*	74	5
Bird damage	34	3	Unsuitable plant population density	69	5
Insufficient access to agricultural information	34	3	Bird damage	65	4
Total	**482**	**39**	**Total**	**969**	**65**
South Asia—Rainfed Mixed			***South Asia—Dry Rainfed***		
Insufficient access to agricultural information	87	5	Drought, dry spells, with developing crop or in grain filling	251	9
Drought, dry spells, with developing crop or in grain filling	83	5	Weed competition	170	6
Leaf, stem, panicle pests	78	5	Leaf, stem, panicle pests	158	6
Drought (water deficit) during crop establishment	67	4	Leaf, stem, panicle diseases	140	5
Soil fertility depletion	63	4	Use of poor quality saved seed	128	4
Weed competition	62	4	Drought (water deficit) during crop establishment	128	4
Unavailability of quality seed	61	4	Insufficient access to agricultural information	120	4
Difficult access to finance	60	4	Fertilizer expensive/in short supply	119	4
Use of poor quality saved seed	57	3	Lack of policy support for crop	113	4
Inadequate farmer production and utilization knowledge/training	54	3	Highly variable and risky planting times	108	4
Total	**670**	**40**	**Total**	**1435**	**50**

Table 7 The ten most severe production constraints identified for cowpea in four farming systems in Sub-Saharan Africa

Cowpea constraint	Yield loss (kg/ha)	% of yield gap	Cowpea constraint	Yield loss (kg/ha)	% of yield gap
SS Africa—Root Crop			***SS Africa—Cereal-Root Crop Mixed***		
Inadequate farmer production and utilization knowledge or training	34	8	Pod insect pests	51	10
Insufficient access to agricultural information	28	7	Fertilizer expensive or in short supply	28	6
Pod insect pests	24	6	Use of unimproved or unsuitable varieties	26	5
Plant too little cowpea to help to soil fertility or crop system sustainability	22	5	Leaf, stem, flower insect pests	24	5
High cost of pest or disease control	22	5	Insufficient access to agricultural information	22	4
Use of unimproved or unsuitable varieties	19	5	Soil fertility depletion	20	4
Weed competition	18	4	Leaf, stem, pod diseases	19	4
Unavailability of quality seed from supplier	17	4	Seed storage pests	16	3
Excessive soil moisture (waterlogging) at any stage of crop growth	13	3	Drought, dry spells, with developing crop or in grain filling	15	3
Difficult access to finance	12	3	Unavailability of quality seed from supplier	15	3
Total	**207**	**51**	**Total**	**235**	**47**
SS Africa—Maize Mixed			***SS Africa—Agro-Pastoral Millet/Sorghum***		
High cost of pest or disease control	58	6	Drought, dry spells, with developing crop or in grain filling	75	7
Leaf, stem, flower insect pests	54	6	Fertilizer expensive or in short supply	73	7
Unavailability of quality seed from supplier	50	5	Weed competition	67	7
Soil fertility depletion	45	5	Drought (water deficit) during crop establishment	64	6
Use of unimproved or unsuitable varieties	44	5	Use of unimproved or unsuitable varieties	61	6
Pod insect pests	44	5	Soil fertility depletion	61	6
Fertilizer expensive or in short supply	39	4	Pod insect pests	54	5
Unsuitable sole crop or intercrop plant populations	37	4	Parasitic weeds	53	5
Difficult access to finance	35	4	High cost of pest or disease control	49	5
Weed competition	35	4	Inadequate farmer production and utilization knowledge or training	49	5
Total	**440**	**48**	**Total**	**605**	**60**

approximately to FAOSTAT yield data where direct comparisons were meaningful. It should be borne in mind that FAOSTAT estimates are averaged across all types of farm for each country or region while our estimates are for smallholder farms in a farming system that often incorporates similar zones of several countries—especially the case with Sub-Saharan Africa. In cases where comparison is more valid such as China or India (large countries with predominantly small farms, representing most of one or more farming systems), the yield estimates in our study were close to those in FAOSTAT. For example, study panelists reported an average wheat yield in the South Asia *Rice-Wheat* system of 2.5 t/ha and in the *Rainfed Mixed* system of 2.4 t/ha, while FAOSTAT reports the average wheat yield in India is about 2.6 t/ha. The FAOSTAT rice yield in China is around 6.3 t/ha compared with study panelists' estimates of 6.8 t/ha in the *Temperate Mixed* system and 5.9 t/ha in the *Lowland Rice* system.

The closing of yield gaps signals effective research, knowledge sharing, policies and infrastructure successfully fostering adoption and productivity increase. The large yield gaps for smallholder farms identified for most crops in most farming systems imply significant scope for improvement of farm yields. Our findings on the size of the total yield gaps for smallholder farms with rice and wheat are broadly in line with previous reported studies for these crops (Evenson et al. 1996a; Widawsky and O'Toole 1996; Cassman 1999; Peng et al. 1999; Hobbs et al. 1998; Evans and Fischer 1999). The relatively small yield gaps with rice reflect the very high rice yields currently achieved in many of the East and South Asian systems where the use of high yielding varieties (HYVs) and N fertilizer technologies have been combined with good irrigated production

Table 8 The ten most severe production constraints identified for chickpea in six farming systems in South Asia and Sub-Saharan Africa

Chickpea constraint	Yield loss (kg/ha)	% of yield gap	Chickpea constraint	Yield loss (kg/ha)	% of yield gap
SS Africa—Highland Temperate Mixed			***South Asia—Highland Mixed***		
Root/soil diseases	128	9	Helicoverpa pod borer	85	12
Farmers perceive a significant risk with producing the crop	110	8	Soil fertility depletion	76	10
Use of unimproved or unsuitable varieties	106	7	High cost /non availability of quality seed from suppliers for planting	43	6
Inadequate farmer production and utilization knowledge or training	93	7	Botrytis grey mould	39	5
Short or risky planting period/window	81	6	Use of unimproved or unsuitable varieties	38	5
Ascochyta blight	76	5	Inadequate fertilizer use and management	36	5
Progressive drought with developing crop and through grain filling	75	5	Deficiency of minor nutrients	32	4
Unsuitable seeding rates/plant population	73	5	Drought (water deficit) or soil surface drying, during crop establishment	31	4
Helicoverpa pod borer	73	5	Leaf, stem, flower, seed insect pests	31	4
Use of poor quality saved seed for planting	65	5	Insufficient access to agricultural information	28	4
Total	**880**	**62**	**Total**	**438**	**60**
South Asia—Rice			***South Asia—Rice-Wheat***		
Helicoverpa pod borer	142	12	Helicoverpa pod borer	109	10
Botrytis grey mould	139	12	Botrytis grey mould	68	6
Progressive drought with developing crop and through grain filling	65	6	Soil fertility depletion	60	6
Plant too little chickpea to help soil fertility or crop system sustainability	64	5	High cost of pest or disease control	48	5
Inadequate farmer production and utilization knowledge or training	60	5	High cost /non availability of quality seed from suppliers for planting	44	4
Root/soil diseases	60	5	Use of unimproved or unsuitable varieties	42	4
Drought (water deficit) or soil surface drying, during crop establishment	52	4	Farmers perceive a significant risk with producing the crop	36	3
Seed storage pests	50	4	Root/soil diseases	36	3
Short or risky planting period/window	50	4	Excessive soil moisture (waterlogging) at any stage of crop growth	35	3
Inadequate fertilizer use and management	50	4	Progressive drought with developing crop and through grain filling	35	3
Total	**733**	**63**	**Total**	**512**	**48**
South Asia—Rainfed Mixed			***South Asia—Dry Rainfed***		
Helicoverpa pod borer	115	9	Helicoverpa pod borer	116	11
Root/soil diseases	74	6	Progressive drought with developing crop and through grain filling	99	9
Botrytis grey mould	74	6	Drought (water deficit) or soil surface drying, during crop establishment	69	6
Progressive drought with developing crop and through grain filling	61	5	Root/soil diseases	60	6
Drought (water deficit) or soil surface drying, during crop establishment	57	5	Excessively high temperature (heat) stress, especially around pod fill	51	5
High cost of pest or disease control	45	4	Soil fertility depletion	49	5
Excessively high temperature (heat) stress, especially around pod fill	42	3	Use of unimproved or unsuitable varieties	35	3
Seed germination and crop establishment difficulties	41	3	Poor choice of weeding practice	34	3
Farmers perceive a significant risk with producing the crop	38	3	Cold stress/frost damage	33	3
Insufficient access to agricultural information	33	3	Weed competition	33	3
Total	**580**	**46**	**Total**	**581**	**54**

Table 9 The ten most severe production constraints identified for cassava in four farming systems in Sub-Saharan Africa and East Asia. Constraints ranked by size of root yield loss

Cassava constraint	Yield loss[a] (kg/ha)	% of yield gap	Cassava constraint	Yield loss (kg/ha)	% of yield gap
SS Africa—Root Crop			***SS Africa—Cereal-Root Crop Mixed***		
Difficult access to finance	722	9	Difficult access to finance	653	7
Lack of policy support for crop	691	8	Use of unimproved or unsuitable varieties	491	5
Unavailability of stable formal market for roots	542	7	Weed competition	471	5
Excessively long occupation of field by crop	445	5	Lack of policy support for crop	471	5
Weed competition	436	5	Inadequate fertilizer management	421	5
African cassava mosaic virus	362	4	Unavailability of stable formal market for roots	384	4
Soil fertility depletion	336	4	Soil fertility depletion	377	4
Use of unimproved or unsuitable varieties	326	4	African cassava mosaic virus	351	4
Inadequate fertilizer management	288	3	Excessively long occupation of field by crop	329	4
Poor choice of planting time; late planting	215	3	Early harvest of roots	273	3
Total	**4364**	**53**	**Total**	**4221**	**47**
SS Africa—Maize Mixed			***East Asia P—Upland Intensive***		
Use of unimproved or unsuitable varieties	603	5	Soil physical degradation	1058	6
Poor quality stakes/cuttings (or seed) for planting	528	4	Soil fertility depletion	984	5
Weed competition	491	4	Weed competition	936	5
Soil fertility depletion	482	4	Inadequate fertilizer management	895	5
N deficiency	449	4	Fertilizer expensive and in short supply	890	5
Inadequate fertilizer management	445	4	Use of unimproved or unsuitable varieties	804	4
Inadequate farmer production and utilization knowledge or training	424	3	Drought, dry periods, with the growing crop	744	4
African cassava mosaic virus	383	3	Poor quality stakes/cuttings (or seed) for planting	631	3
Continuous cropping, reduced bush fallow period	349	3	Lack of policy support for crop	604	3
Soil physical degradation	346	3	Difficult access to finance	590	3
Total	**4499**	**37**	**Total**	**8134**	**42**

[a] Root wet weight

environments and good farming. Rice scientists have suggested the need to raise the yield potential of the rice crop since actual farm yields are already around 80% of those achieved in research fields (Cassman 1999; Peng et al. 1999). Nevertheless, the yield gap of at least half of the current high yields we report here represents 3–4 t/ha of extra grain that could be achieved once remaining constraints are removed. This is important because it offers the chance for substantially higher rice production on existing land to feed growing human populations in Asia and Africa. Similarly, the somewhat larger yield gaps for wheat offer substantial opportunities to raise farm yields of wheat in farming systems where poverty levels are high if the most severe constraints can be addressed. However, given the persistence of serious adaptation problems for wheat in hot wet environments despite significant investment (Chatrath et al. 2007), yield improvements may be difficult to achieve in practice in sub-tropical systems that are marginal for wheat.

The larger yield gaps with sorghum, cowpea and chickpea were expected because these crops are often grown in more marginal farming systems, with low and variable precipitation, small amounts of fertilizer and difficult socio-economic conditions. For comparison, there is less information in the scientific literature about the size and nature of yield gaps for smallholder farms available for these crops. Within a crop, the larger remaining yield gaps for the more marginal drier farming systems indicates the continuing challenge to raise yield in such systems. These may feature severe constraints that are difficult to overcome such as shallow, nutrient-depleted soils and drought, and risks or remoteness may reduce input supply and use.

Production constraints

The study confirmed the importance of all four categories of production constraint (socio-economic, abiotic, biotic and management), provided a set of systematic data on losses due to the constraints, and identified contrasts in relative importance by crop and farming system. Abiotic, management and socio-economic constraints were all previously reported to be important for wheat in South and East Asia (Kosina et al. 2007; Chatrath et al. 2007), while biotic constraints have dominated earlier studies for both chickpea (Van Rheenen and Singh 1997; Pande et al. 2005) and cowpea (Adipala et al. 2000). The large proportions of the yield gap accounted for by the 10 most severe constraints (ranging from 45% for cassava to 56% for chickpea) implies that a few constraints are responsible for much of the yield gap. Many additional constraints were identified by panelists which, although of relatively minor significance overall, can lead to substantial losses in specific situations. If solutions could be found to the few most severe constraints identified for each crop in this study then it should be possible to raise farm yields appreciably. It will be easier and more efficient for research to alleviate few constraints with large losses than many with only small effects.

In most cases the major specific constraints identified for each crop x farming system in each region correspond in general terms with previous published studies. Unlike our broad comprehensive assessment, most of the earlier studies covered one crop or region, or are restricted in the types of constraint they assess.

With wheat, a majority of the important constraints identified were the same as in the country assessments from South and East Asia and Sub-Saharan Africa listed by Kosina et al. (2007) and Reynolds et al. (2008). They identified heat (especially terminal heat stress during grain filling) and weed competition as the most important and most widespread 'environmental' constraints, followed by diseases, pests, drought stress and declining water for irrigation. Major socio-economic constraints included lack of access to mechanization, unavailability of credit, (quality) seed and fertilizer, and grain price and marketing issues (Kosina et al. 2007). The mix of wheat constraints found in South Asia was close to that reported by several authors for northern Indian systems, including Chatrath et al. (2007), Joshi et al. (2007) and Kumar et al. (2007). However, in our study some diseases (rusts, spot blotch) appeared less important or less widespread than noted previously. For northern China, Cui et al. (2008) identified fertilizer and water input issues to be the most serious for wheat.

Constraints identified for rice in East Asia, particularly in the *Temperate Mixed* system, fit those previously reported in the few earlier studies we could find for China by Lin and Shen (1996) and Sui (2007). Their severe constraints included nutrient deficiencies, soil infertility and fertilizer shortages; cold stress, low irradiance and drought; poor varieties and severe damage caused by insect pests, plant diseases and mice. Evenson et al. (1996a) reported biotic constraints such as pests, diseases and rodents to be most important in the more tropical East Asian systems. The most widespread and severe constraints we identified for rice in South Asia involved soil fertility and fertilizer inputs and management. Previous studies for northern India (Widawsky and O'Toole 1996) and Bangladesh (Dey et al. 1996) found such constraints were less important. This change may reflect the recent increased concern about the sustainability of intensive rice-based farming systems in South Asia. By far the most important biotic constraint of rice in South Asia was weed competition, previously reported by Widawsky and O'Toole (1996) to be widespread across eastern India. The other widespread and important set of constraints there related to water availability and management. Dey et al. (1996), Widawsky and O'Toole (1996) and Pandey et al. (2007) also found drought at various stages of crop development—including seedling and vegetative growth and around anthesis—to be very important. They also gave pests, especially stemborer and brown plant hopper, as very severe constraints in these systems. These were recognized in our study but estimated to give smaller losses and be more restricted than the abiotic constraints.

During the survey there was concern that it was difficult to assess generalized production constraints for the sorghum crop because of the diverse marginal environments, production systems and communities in which it is grown, especially in Sub-Saharan Africa. Several smaller studies highlighted the importance of *Striga*, poor soil fertility (including low nitrogen and phosphorus) and drought (especially water deficits during grain filling) among the most severe and widespread biophysical constraints to sorghum production in west, east and southern Africa (Chiduza et al. 1995; Kudadjie et al. 2004; Wubeneh and Sanders 2006). In South Asia the most severe constraints we identified agreed with those of Reddy et al. (2007), who reported terminal drought, soil problems, and a range of insect pests and diseases to be important in India.

The biotic pest problems identified for cowpea in Africa are well known and have been reported to be severe in West Africa (Kossou et al. 2001; Ryoichi et al. 2006) and in East Africa (Adipala et al. 2000). Seed constraints and weed competition are also documented in West Africa (Kossou et al. 2001) and southern Africa (Asiwe 2007). In contrast, the constraints related to soil nutrition, reported severe for cowpea in several systems, are little mentioned in previous studies.

Specific biotic and abiotic constraints identified for chickpea in South Asia were recognized previously. Van

Rheenen and Singh (1997) identified pod borers to be devastating pests of chickpea in South Asia, while Pande et al. (2005) described Botrytis grey mould as by far the most important chickpea production constraint in Nepal. Van Rheenen and Singh (1997) and Berger (2007) considered terminal drought the most important and widespread abiotic stress of dryland chickpea in South Asia. Very little previous information appears to be available on constraints to chickpea production in Sub-Saharan Africa.

The reported importance of finance and marketing constraints in some of the key farming systems for cassava in Africa is an ongoing and major concern with the crop (IITA 2007; EARRNET 2006) and is likely to contribute to the other severe constraints identified such as unsuitable germplasm and soil infertility. African cassava mosaic virus is widely recognized as being among the most severe and widespread biotic constraints to affect cassava on the continent (Wydra and Verdier 2002; IITA 2007), while weed competition is an issue in West Africa (Chikoye et al. 1999) and East Africa (East Africa Root Crops Research Network—EARRNET 2006). Problems with cassava germplasm and planting materials are again common in Africa (EARRNET 2006; IITA 2007). Many of the severe constraints identified for cassava in East Asia reflected well the few previous studies, e.g. Ratanawaraha et al. (2001) in Thailand.

Conclusions and future work

This study surveyed six major food crops in 13 important farming systems, which form a sub-set of the 13 crops and 15 farming systems identified by Hyman et al. (2008) to address the poor in marginal and drought-prone lands. There is no comparable systematic quantitative analysis of constraints and yield losses of major food crops across the developing regions in the literature.

The survey found significant yield gaps for smallholder farms, which were largest for sorghum, cowpea and chickpea, and large in the marginal, drier systems, particularly in Sub-Saharan Africa. All categories of production constraint—abiotic, biotic, management and socio-economic—were important contributors to yield gaps. A great diversity of specific constraints was reported for the crops in the different systems. The specific production constraints that were most severe and widespread for wheat and rice involved the deficiency, high cost and poor management of N fertilizer, soil fertility depletion, inadequate water management and drought stress. Weeds, soil degradation and drought were the most severe constraints for sorghum. Various insect pests and diseases and the high cost of their control were the major constraints for the legumes. Marketing and finance problems, and some specific biotic constraints, were the main concerns for cassava. The diversity of these important production constraints offer the agricultural research and development community an array of opportunities for solutions.

Although the study identified many interactions and some cause and effect relationships among important constraints it was not able to fully describe or quantify these. Further debate between some key panelists, perhaps in the form of a workshop, on how to rationalize and prioritize these many constraints and interactions, and examine solutions could be useful. The findings on constraints can be employed in a wide range of follow-up analyses including the assessment of the relative importance of particular groups of constraints. For example, given the interest in water scarcity and climate change, we are developing a further paper comparing the importance of drought, water constraints and all other constraints for South Asia.

At a local level, more-detailed follow-up surveys may be helpful in complex crop x farming systems (e.g. for rice in some Asian systems with two or more rice seasons), where disaggregation of severe constraints is needed (e.g. pod, leaf, stem and flower insect pests with cowpea), or where broad socio-economic constraints that contribute to other constraints were considered to be particularly severe (e.g. with cassava in Africa). Although interactions between constraints and effects of constraints on the farming system were reported with all the crops, a stronger sense of synergy and systems thinking emerged for sorghum, the legumes and cassava. These are crops usually grown as a component (often intercropped) in a mixed farming system, with several different functions in the system, and often in marginal environments and farming communities. These observations imply a need to move beyond a focus on yield losses per unit land area for single crops in future assessments. The methods may be usefully expanded to survey losses in system productivity and opportunities in a few priority systems in Africa, where several of these crops are all important.

In conclusion, building from the pilot survey on maize (Gibbon et al. 2007), this study represents, perhaps, the most systematic and comprehensive assessment to date of a broad range of types of production constraint for several very important food crops across many key farming systems in which they are grown in the developing world and where poverty and food insecurity are severe.[1] The findings should be a valuable input for priority setting and

[1] The complete report of this study, including detailed annexes on additional constraints, constraint interactions, systems effects and effects on income and health is available at: http://www.generationcp.org/sp5_impact/targeting-and-focus#dixon along with information on proposed solutions to priority constraints.

resource allocation by international agricultural research and development organizations to help them justify current and future investments in the crops, farming systems and regions surveyed. Given the magnitude of the food crisis, the international community will need to focus on a broader set of the main farming systems in developing countries (Dixon et al. 2001) for important widely-grown food crops such as wheat and cassava. Also a survey of other important food crops in the priority farming systems, including groundnut, beans, millets and sweet potatoes (Hyman et al. 2008), will be useful.

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