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Strategic approaches to targeting technology generation: Assessing the coincidence of poverty and drought-prone crop production

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ABSTRACT

The world's poorest and most vulnerable farmers on the whole have not benefited from international agricultural research and development. Past efforts have tried to increase the production of countries in more favourable environments; farmers with relatively higher potential for improvement benefited most from these advances. Current and future crop improvement efforts will focus more on marginal environments, especially those prone to drought. The objective of this research is to guide crop improvement efforts by prioritizing areas of high poverty, the key problem of high drought risk and the crops grown and consumed in these areas. Global spatial data on crop production, climate and poverty (as proxied by child stunting) were used to identify geographic areas of high priority for crop improvement. The analysis employed spatial overlay, drought modelling and descriptive statistics to identify where best to target technology generation to achieve its intended human welfare goals. Analysis showed that drought coincides with high levels of poverty in 15 major farming systems, especially in South Asia, the Sahel and eastern and southern Africa, where high diversity in drought frequency characterizes the environments. Thirteen crops make up the bulk of food production in these areas. A database was developed for use in agricultural research and development targeting and priority setting to raise the productivity of crops on which the poor in marginal environments depend.

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1. Introduction

Over the last 50 years, progress in reducing poverty and malnutrition has been mixed (World Bank, 2004; FAO, 2005). A reduction in the proportion of the poor and undernourished has been achieved in most regions of the world. But the absolute numbers of poor people continues to grow across sub-Saharan Africa and between 1991 and 2002 the number of hungry has grown by over 40 million people in central and eastern Africa and in South Asia. These negative trends exacerbate a situation in which many regions are already projected to fall short of international poverty and hunger goals (UNDP, 2006). Given the importance of agriculture in the food security and livelihoods of the poor, any strategy to address poverty in such regions must pay particular attention to raising the productivity, profitability and sustainability of agricultural enterprises (Gryseels et al., 1992; Dixon et al., 2001).

Unfortunately, most farmers in marginal environments have benefited little from agricultural research and development (Freeb-

airn, 1995; CGIAR, 2000; Evenson and Gollin, 2003). The dominant humanitarian goal of early international research and development efforts, including that of the Consultative Group on International Agricultural Research (CGIAR), was to "increase the pile of rice" in poor and famine-prone countries (Shah and Strong 1999). But, while the new Green Revolution technologies succeeded in raising overall levels of food security, they were primarily adopted by relatively well-off farmers with access to resources and capital. There is now a growing commitment to the notion that accelerating progress in reducing poverty and hunger requires an urgent refocusing of development efforts on resource-poor farmers in marginal environments. Such commitment is reinforced by mounting empirical evidence – from China and India at least – that the rates of return to investment in more marginal areas can often be higher than those in high-potential areas (Fan and Hazell, 2000a,b; Fan et al., 2000). Drought-prone areas are one of the most important types of marginal environments, because drought is a principal direct cause of crop failure and economic losses to farmers (Fuglie, 2007; Kosina et al., 2007; Pandey et al., 2007). Few if any studies have identified the magnitude of drought at detailed spatial resolution and in the context of the geographic distribution of crop production and poverty across the developing world.

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The objective of this study is to provide information for identifying regions, selecting crops and setting priorities for crop improvement initiatives for drought-prone marginal environments. Specifically, this study identifies the coincidence of poor populations, the production of key food staple crops on which the poor depend and drought-prone production environments. Farming systems, represented as 63 mapped regions in developing countries, are the units of analysis (Dixon et al., 2001). The study used malnutrition, identified by childhood stunting, as a proxy for poverty (FAO, 2003). The relative importance of different crops in the farming systems was assessed using a global database of harvested area and production for the main food staples (You and Wood, 2006). A model to appraise the susceptibility of regions more and less prone to drought was developed.

The study ranks the farming systems according to relative and absolute indicators of poverty, the average drought probability and expected losses to drought based on the cultivated area of food staple crops. The derived information base is intended to support priority setting for research and development on raising the productivity of food staple cropping systems targeted to addressing the needs of poor people in marginal environments. This study brings together a unique combination of new spatial data and analyses that allows research investors and scientists to take a broad, strategic perspective of the most important geographical regions, farming systems and crops for which development of drought-tolerant traits would likely bring major benefits to the poorest people.

The next section of the paper discusses the data sets used in the analysis, followed by a description of the types of indicators and how they were calculated for the farming systems. Section 3 describes poverty and drought by farming system, the spatial variability of drought within farming systems and spatial coincidence of these factors. The paper concludes with discussion of these results and suggestions for future work.

2. Materials and methods

2.1. Farming systems

The geographical unit of this analysis is the farming system region (hereafter referred to as “farming system”), homogenous areas delineated according to the dominant pattern of the natural resources base, farm activities and household livelihoods. Dixon et al. (2001) mapped eight broad system types and 63 detailed farming systems (Fig. S1) in the developing countries. Urban-based farming systems are excluded from the global map because of their relatively small size. The category of coastal artisanal fishing is also excluded as being non-agricultural. Thus six broad farming system types are shown in Fig. 1. They are smallholder irrigated, wetland rice based, high resource potential rainfed, rainfed in steep and highland areas, low potential rainfed in dry or cold areas and dualistic (mixed large commercial and smallholder). Cartographers and agricultural experts used on-screen digitizing in geographic information systems (GIS) to draw the boundaries of the farming systems (Dixon et al., 2001). In a workshop setting, expert panels used digital map overlays, including information on agro-ecological zones, rainfall, irrigation, slope, human population, cultivated areas, livestock systems and livestock distributions where available. They also used statistical data on climate, water availability, land cover, tenure and organization, farm size, dominant crop types, off-farm activities, technologies that determine production intensity and integration of crops, livestock and other activities. Although the exact placement of the farming system boundaries was subjectively determined, the map development process draws on far-reaching expert knowledge and statistical data.

2.2. Population and poverty

Digital population and poverty maps were acquired to assess the location of the poor and rural populations. The database includes population information from the Gridded Population of the World (GPW) Version 3 project at 1-km spatial resolution (CIESIN, 2004). Infant mortality rates and the prevalence and absolute number of underweight and stunted children were used as measures of poverty (FAO, 2003; CIESIN, 2005, 2006). The data sets of underweight and stunted children are based on health surveys such as the Demographic and Health Survey (FAO, 2003; Balk et al., 2005). The anthropometric data report the percentage and absolute number of children under 5 years of age that are two standard deviations below the international growth reference standard. The tabular data for administrative units were linked to maps in a GIS.

Stunting was chosen as the principle poverty indicator because this condition is found in children of households that cannot provide sufficient food or income for healthy nutrition. Poor families first try to improve their food and nutrition with greater income or crop production. Income or wealth as indicators are difficult to elicit or standardize in a way that allows comparison and are highly variable as a contributing factor to well-being. Only 20–30 countries in the world have detailed mapping of income or consumption that is sufficiently reliable and assessed for sub-national administrative units. The stunting indicator overcomes these problems of lack of data or inconsistent data because its measurement is straightforward, globally comparable and almost all countries have been assessed.

2.3. Crop production

The spatial distribution and productivity of crops were derived from 10-km grids using a novel allocation approach (You and Wood, 2006). These crop maps are based on sub-national crop production data from agricultural censuses and surveys, adjusted so as to obtain national production estimates that were compatible with the annual average FAO national crop statistics for 1999–2001. The 19 crops included in the analysis were barley, common bean, cassava, groundnut, maize, pearl millet, finger millet, banana, plantain, cowpea, chickpea, pigeon pea, lentils, potato, rice, sorghum, soybean, sweet potato and wheat. Some crops were combined for statistical and mapping purposes because of difficulties encountered in reporting them separately at the global scale.

You and Wood's (2006) approach was to combine crop production statistics with secondary data on farming systems characteristics, satellite-derived land cover, biophysical crop suitability and population density. Their method draws on quantitative analysis and entropy modelling to optimally allocate crop production from the large administrative areas (districts, provinces, etc.) from which data are reported to 10-km pixels according to maximum likelihood of occurrence and estimated density of production.

The prototype crop distribution database used in this study is available from the authors upon request but is currently being regenerated using newer and additional data sources (including revisions based on expert validation) and an enhanced allocation algorithm. A large share of the sub-national crop production can be downloaded directly from the FAO (2006) Agromaps site at <http://www.fao.org/landandwater/agll/agromaps/interactive/index.jsp>.

Irrigated areas are obviously less susceptible to weather variability and drought (albeit lower than normal rainfall may reduce ground and surface water needed for irrigation). A focus on poor farmers in marginal environments largely excludes the targeting of irrigated areas. The analysis excluded irrigated areas based on estimates from the global digital crop maps (You and Wood, 2006).

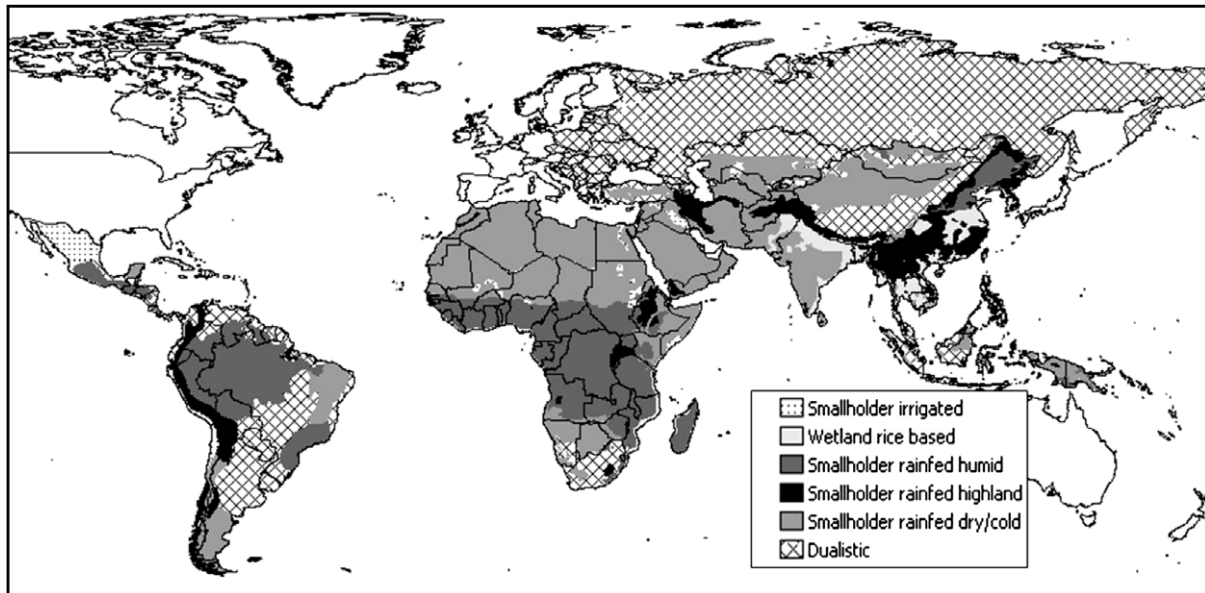


Fig. 1. The six broad categories of farming system types used for the analysis (from Dixon et al., 2001).

2.4. Failed season drought model

A method was developed to assess and map drought risk by estimating the probability of a failed growing season. A failed season is conceptualized as one in which the costs of producing the crop exceeded the value of the harvest because of the effects of water stress. The method develops a simple surrogate measurement for this concept that might apply across a number of crops. A failed season was conservatively defined as one that has rainfall at the start sufficient for germination and establishment, less than 50 growing days and a clearly defined end. This definition is clearly generic and does not apply to any specific crop. Thus the failed season approach depends upon the use of a reliable means to assess the water- and temperature-constrained length of growing period in each locale.

Rainfed crops rely on water available at the root zone to support growth and yield. The amount of water available depends upon rainfall, the water-holding capacity of the soil profile, the rooting depth of the crop and the potential and actual rates at which a crop can take up soil water during its growth cycle. Although reasonably accurate soil maps are available for most of the world, it is difficult to determine the actual soil water-holding capacity of any given square metre of soil. Our analysis assumed that all soils were capable of storing 100 mm of available soil water – a value that holds true for most of the agricultural areas in the drought-prone regions of the tropics. Where the storage capacity is larger, this assumption will lead to the under prediction of growing season lengths. For example, Fluvisols (flood plain soils) by definition are likely to have extra soil water resources within rooting depth for which this analysis cannot account.

The actual rate at which a crop consumes water (actual evapotranspiration, E_a) can often be less than the potential rate at which the crop could consume water if it was in abundant supply (potential evapotranspiration, E_t). This happens, for example, when soil water content is low and it becomes more difficult for the roots to extract water. Thus the ratio E_a/E_t is a well-established index of the water stresses a plant experiences during its growth. E_a/E_t ratios of between 0.8 and 1.0 imply little or no yield-reducing water stress. An E_a/E_t ratio of less than 0.4 is, for most crops, an indication that severe drought stress is occurring and that the ability of the crop to deliver an economic level of yield is severely com-

promised. The soil water accounting model (WATBAL, see below) uses the ratio internally to determine the dynamics of the water balance and the extent of drought stress on a daily basis.

The method establishes rules for defining a growing season. To have a reasonable chance of seed germination, certain minimum levels of soil water and temperature must prevail. Thus the method stipulates that a growing season cannot start until at least 5 days have occurred with an E_a/E_t greater than 0.8 and that the mean temperature during those days is above 8 °C. Conversely, the end of a growing season for annual crops such as maize or beans is defined as following 12 consecutive days with E_a/E_t less than 0.4 (stress days) or any sequence of 12 consecutive days with temperatures less than 4 °C. Crop physiologists will differ on the definition of water stress for relevant crops. These rules enable us to define a generic growing season. Some crops, such as cassava, would easily tolerate this stress, whereas beans would be deeply stressed. The temperature criteria are aimed at tropical and subtropical crops and do not properly represent cold-adapted, temperate cereals.

The model WATBAL (Keig and McAlpine, 1974) was used to implement the growing season analysis, which directly assesses available soil moisture in each time period based on the factors highlighted above. WATBAL assumes that the E_a/E_t ratio is proportional to the ground cover; thus a wet soil surface and/or a complete cover of an unstressed growing crop have a value of 1.0 and a completely dry soil open surface will have a ratio close to 0. This is termed the CROP FACTOR, assumed to have a value of 0.8 during a crop cycle.

Using MarkSim® (Jones and Thornton, 2000; Jones et al., 2002), 100 years of daily rainfall, temperature and radiation data were simulated for 30 arc-second pixels within the study area. Linacre's (1977) method was used to calculate potential evapotranspiration. WATBAL (originally Keig and McAlpine, 1974, here applied as a FORTRAN subroutine as in Jones, 1987) was used to calculate daily water balance.

The failed seasons model can be used as a standardized index of cropping reliability. The model is not calibrated to specific crops; for example a failed season may apply more to long- rather than short-season maize. It would be more accurate to implement the model with detailed soil data for local areas. However, the lack of such data in internationally consistent soil maps precluded this possibility.

Secondary growing seasons occur sporadically in wide geographic areas. They often do not occur with a frequency that can be reasonably planned for and exploited. Since they can be either the first or the second season in any one place or year it is not correct to label them first and second. Analysis excluded the secondary or shortest growing season because global crop production and area data are not linked to a particular growing season. Thus, drought assessment is based on the longest growing season of the year.

Fig. 2 shows the modelled percentage of failed seasons due to drought in the study areas.

2.5. Drought Indicators

Three drought indicators were developed using data on the harvested crop area and the failed seasons model. Our principle drought indicator, labelled “Potential Drought Impact Index” (PDII) in Tables 1 and 2, is a reflection of the expected loss of production due to drought. This indicator is derived for each farming system by multiplying the area of rainfed food staple crops by the probability of a failed season for each grid cell and then summing the grid cells by farming system:

$$\sum_{i=1}^n (A * F) \quad (1)$$

where *A* is the non-irrigated area harvested and *F* is the probability of a failed season for each grid cell.

The index accounts for the extent of staple food crop production weighted by the probability of a failed season. The analysis excludes yield assessment given the difficulty of measuring this variable at such detailed spatial scales. Some form of drought can occur in all farming systems. In systems where the probability of drought is low, the index may still be high if the cultivated area is large. For example, the intensive mixed system in Latin America covers relatively well-watered areas that are less prone to drought. But because the cultivated area of this system is extensive, the potential impacts of droughts when they do occur can be severe.

The mean probability of a failed season (intensity or frequency) is a second drought indicator. The value was derived by averaging the probability of a failed season (Fig. 2) over all the pixels in each of the 63 farming systems (Fig. S1). Within some systems, some areas are very dry or experience temperature extremes that render

them unsuitable for crop growth. Those pixels falling into this category were excluded from the calculation of the mean probability of a failed season. This indicator locates the most drought-prone and marginal environments. As might be expected, many of the systems with high values have very little cultivated area.

A third drought indicator – the distribution of drought frequencies within the farming systems – reveals the heterogeneity of drought conditions across those regions and where mean probabilities could be biased by a few large or small drought frequency values. The assessment also allowed us to identify the mix of crops under different drought frequency conditions across the farming systems. Cumulative frequency curves were developed that show the extent of areas under all probabilities of failed seasons.

2.6. Characterizing farming systems

Our analysis relies on comparing the 63 farming systems according to their levels of poverty, crop production and drought. A GIS algorithm was used to calculate population, poverty and crop production statistics for each agricultural region. The algorithm evaluates all grid cell values falling within each farming system, calculating descriptive statistics such as mean, median, maximum, minimum, standard deviation, sum and others for that farming system.

As described above, the method developed both intensive (relative) and extensive measures of crop production in poor and drought-prone environments with a view to disseminating drought-tolerant varieties. Interventions in farming systems with high intensity measures – the prevalence (or percentage) of stunted children and the mean drought probability – would focus on areas where most of the people are poor and drought-prone. These interventions would be less likely to spill over to non-poor and less drought-prone farmers. These systems with high intensity drought could exclude areas where the number of people subject to poverty and drought may be higher overall, simply due to higher levels of population and crop production.

Extensive (or absolute) measures include the total number of stunted children in the farming system and an indicator of the total area potentially affected by drought (PDII, described above). These measures depend on the numbers of poor people and crop area potentially affected by drought. While a relatively low proportion of people in these farming systems may be subject to poverty

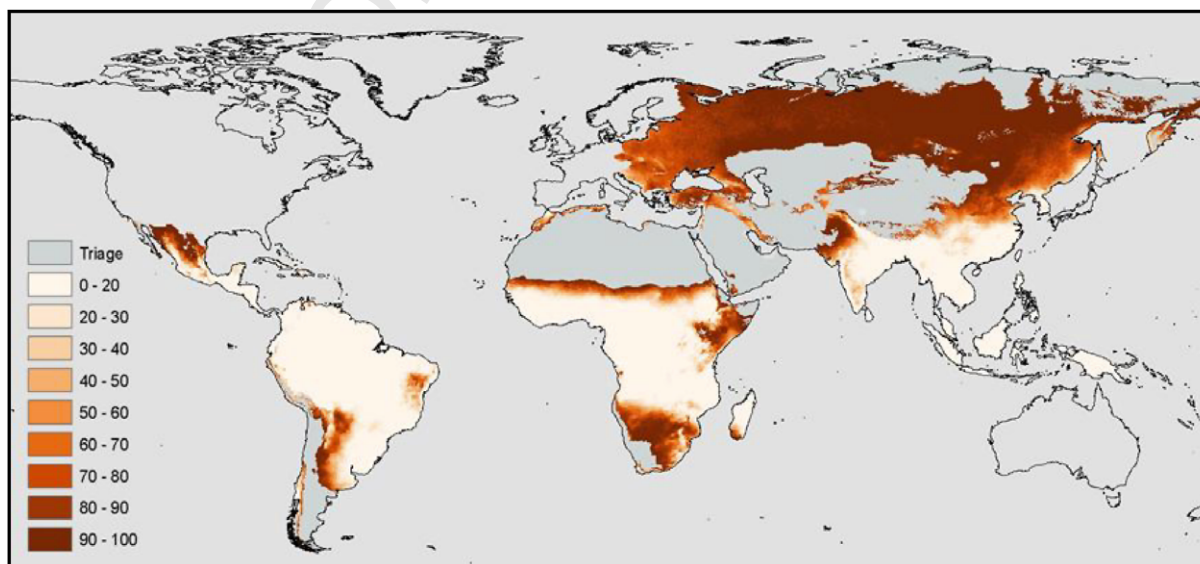


Fig. 2. Modelled percentage of failed seasons due to drought in the study areas.

Table 1
Farming systems, population, poverty and drought in 41 farming systems in developing countries

Farming systems ^a	Region ^b	Farming system category	Population (millions)			Stunted children ('000s)	Prevalence stunting (%)	Drought probability	PDII ^c
			Total	Rural	Urban				
Rainfed mixed	SA	Smallholder rainfed dry/cold	357	249	107	24,547	63	0.17	8,176,456
Lowland rice	EAP	Wetland rice based	786	496	290	13,368	34	0.08	7,963,917
Cereal-root crop mixed	SSA	Smallholder rainfed humid	84	69	15	6319	43	0.17	5,331,317
Rice-wheat	SA	Wetland rice based	491	365	126	28,310	52	0.35	4,050,261
Upland intensive mixed	EAP	Smallholder rainfed highland	502	359	144	15,435	35	0.11	3,725,591
Agro-pastoral millet/sorghum	SSA	Smallholder rainfed dry/cold	55	38	17	3136	37	0.53	2,633,259
Rice	SA	Wetland rice based	235	166	69	11,664	51	0.05	2,632,872
Maize mixed	SSA	Smallholder rainfed humid	97	73	24	6318	43	0.24	2,535,536
Coastal plantation mixed	LAC	Dualistic	123	40	82	1692	19	0.07	1,841,622
Root crop	SSA	Smallholder rainfed humid	70	47	23	4989	40	0.08	1,802,876
Intensive mixed	LAC	Smallholder rainfed humid	79	17	61	310	5	0.07	1,500,188
Temperate mixed (Pampas)	LAC	Dualistic	29	3	25	209	13	0.33	1,446,738
Dry rainfed	SA	Smallholder rainfed dry/cold	46	34	12	3610	65	0.32	1,227,981
Maize-beans (Mesoamerica)	LAC	Smallholder rainfed humid	76	29	47	2837	37	0.16	1,218,125
Cereal-livestock (Campos)	LAC	Dualistic	23	9	14	221	9	0.12	1,179,115
Mixed	EECA	Dualistic	95	41	54	93	7	0.04	1,142,759
Forest based	SSA	Smallholder rainfed humid	43	28	15	3243	37	0.03	1,029,787
Extensive mixed (Cerrados-Llanos)	LAC	Dualistic	22	8	14	225	11	0.07	1,020,812
Horticulture mixed	EECA	Dualistic	76	30	46	736	15	0.05	914,768
Highland temperate mixed	SSA	Smallholder rainfed highland	43	37	7	2761	50	0.18	909,683
Dryland mixed	LAC	Smallholder rainfed dry/cold	25	9	16	684	19	0.27	897,951
Temperate mixed	EAP	Smallholder rainfed humid	261	139	122	2596	26	0.20	849,686
Highland mixed	SA	Smallholder rainfed highland	86	66	20	5162	48	0.12	827,142
Tree crop mixed	EAP	Dualistic	51	32	19	3106	39	0.00	777,050
Highland extensive mixed	EAP	Smallholder rainfed highland	64	52	12	2537	44	0.10	682,635
Large scale cereal-vegetable	EECA	Dualistic	66	28	37	319	16	0.03	623,956
Rainfed mixed	MENA	Smallholder rainfed dry/cold	39	14	25	499	17	0.09	592,646
Large commercial-smallholder	SSA	Dualistic	34	12	22	907	23	0.67	520,323
Dryland mixed	MENA	Smallholder rainfed dry/cold	47	18	29	750	19	0.19	413,712
Coastal artisanal fishing	SSA	Coastal artisanal fishing	39	18	21	1290	43	0.09	406,598
Intensive highland mixed (N. Andes)	LAC	Smallholder rainfed highland	39	9	29	380	16	0.06	281,978
Coastal artisanal fishing	SA	Coastal artisanal fishing	40	16	24	1146	55	0.08	242,045
Small scale cereal-livestock	EECA	Smallholder rainfed dry/cold	20	9	11	382	20	0.03	205,774
High altitude mixed (Central Andes)	LAC	Smallholder rainfed highland	17	11	6	600	30	0.37	131,325
Rice-tree crop	SSA	Smallholder rainfed humid	11	9	2	962	49	0.06	126,952
Extensive dryland mixed (Gran Chaco)	LAC	Dualistic	5	1	4	66	16	0.65	106,230
Highland mixed	MENA	Smallholder rainfed highland	67	31	36	1574	21	0.35	95,782
Forest based livestock	EECA	Dualistic	30	10	20	1	16	0.01	38,016
Mediterranean mixed	LAC	Smallholder rainfed highland	13	3	10	4	10	0.01	35,361
Extensive cereal-livestock	EECA	Dualistic	93	26	67	70	12	0.01	33,873
Root-tuber	EAP	Smallholder rainfed humid	2	2	0	322	41	0.01	14,543
Total (for 63 systems)			4998	3010	1978	184,226			

^a The table shows 41 of Dixon et al.'s (2001) 63 farming systems in developing countries. Farming systems that were based on irrigation, perennial crops, trees, or pastoral and sparsely cultivated systems were excluded.

^b SA, South Asia; EAP, East Asia and the Pacific; SSA, sub-Saharan Africa; LAC, Latin America and the Caribbean; EECA, Eastern Europe and Central Asia; MENA, Middle East and North Africa.

^c PDII is the potential drought impact index, estimating the extent of cultivated area affected by drought.

Table 2
The top 10 systems in Latin America and the Caribbean, Africa and the Middle East and Asia by stunted children and rankings of the density and intensity of failed seasons

Farming system	Region ^a	Stunted children ('000s)	Drought rank ^b	
			Probability	PDII
<i>Latin America and the Caribbean</i>				
Maize-beans	LAC	2837	26	15
Plantation mixed	LAC	1692	42	9
Irrigated	LAC	809	7	38
Dryland mixed	LAC	684	19	22
High altitude mixed	LAC	600	11	42
Forest-based	LAC	464	54	31
Intensive highland mixed	LAC	380	44	37
Intensive mixed	LAC	309	41	11
Extensive mixed	LAC	225	40	19
Cereal-livestock	LAC	221	32	16
<i>Africa and the Middle East</i>				
Cereal-root crop	SSA	6319	24	3
Maize mixed	SSA	6318	20	8
Root crop	SSA	4989	39	10
Forest-based	SSA	3243	6	18
Pastoral	SSA	3230	3	27
Agro-pastoral millet-sorghum	SSA	3135	8	6
Highland temperate mixed	SSA	2761	23	21
Highland perennial	SSA	2625	31	26
Sparse arid	MENA	2417	11	56
Tree crop	SSA	2291	49	13
<i>Asia</i>				
Rice-wheat	SA	28,310	15	4
Rainfed mixed	SA	24,547	25	1
Upland intensive mixed	EAP	15,435	33	5
Lowland rice	EAP	13,368	37	2
Rice	SA	11,664	46	7
Highland mixed	SA	5162	30	24
Sparse (forest)	EAP	4360	47	36
Dry rainfed	SA	3610	18	14
Tree crop mixed	EAP	3106	60	25
Temperate mixed	EAP	2596	21	23

^a LAC, Latin America and the Caribbean; SSA, sub-Saharan Africa; MENA, Middle East and North Africa; SA, South Asia; EAP, East Asia and the Pacific.

^b Ranking out of 63 farming systems in developing countries. The probability rank refers to the mean probability of drought (intensity) in cultivated areas within the farming system. PDII is the potential drought impact index, estimating the extent of cultivated area affected by drought.

and drought, the absolute number could be high. For example, a relatively well-watered farming system may have low drought probability, while the potential area impacted by drought may be high due to large areas under production.

Selection of intensive or extensive indicators depends on research and development objectives and the nature of the intervention. Initiatives concerned with the potential for inequality of outcomes and on the most marginal environments require relative measures of intensity (e.g., stunting prevalence, drought probability). Other crop improvement programmes may seek to reach large numbers of poor and drought-prone populations to achieve broad objectives of initiatives such as the Millennium Development Goals (MDG). Efforts of this type could be guided by extensive indicators such as total number of stunted children in the farming system or total crop area affected by drought.

3. Results

3.1. Population and stunted children by farming system

The study area includes nearly 5 billion of the planet's 6 billion people (Table 1). About 60% of these 5 billion people live in rural areas and 40% in urban areas. The total number of stunted children is 184.3 million, a figure that corresponds well with the World Health Organization's estimate of 181.9 million stunted children in developing countries in the year 2000 (WHO, 2000).

Table 1 shows the total number of stunted children within the farming systems. Of the top 20 systems, in terms of the absolute

number of stunted children, only one system has a stunting prevalence below 34% (i.e., the temperate mixed system of East Asia and the Pacific, 26%).

The total number and the prevalence (or percentage) of stunted children agree reasonably well. High stunting prevalence coincides with high absolute numbers of stunted children. Of the top 10 farming systems according to absolute numbers of stunted children, four systems are in South Asia; and three each are in sub-Saharan Africa and East Asia and the Pacific. In terms of stunting prevalence, eight of the top 10 systems are in South Asia, with the remaining two in sub-Saharan Africa.

3.2. Drought probability and potential impact

The 10 systems in which the extent or potential impact of drought on the production of staple crops is the largest are found in South Asia (3 systems), sub-Saharan Africa (4), East Asia (2) and Latin America (1) (Table 1). The next group of 10 systems is dominated by five Latin American systems, two each from sub-Saharan Africa and Eastern Europe and Central Asia, and one South Asian system. The remaining 43 systems in the ranking (not all shown in Table 1) are varied in their regional composition. Farming systems in the Middle East and North Africa tend to be found in the lower half of the ranking, reflecting the smaller cultivated area in these regions. The bottom one third of the 63 systems is made up of farming systems that are marginal for cropping. Although these areas are drought-prone, they have insufficient cultivated area to rank high on the list. In other words, people usually cultivate very little where

drought is a frequent problem; because of this, target areas where many people can and do grow crops and where drought is a major problem affecting food security were emphasized.

The values for mean drought probability of a failed season show a wide distribution throughout the list of 63 systems. Some systems have relatively low mean values of the probability of a failed season. For example, the root crop system in sub-Saharan Africa has a high PDII, indicating large areas susceptible to drought but a relatively low drought probability value (mean failure) of eight. Even though droughts may be relatively infrequent compared to other systems, the large cultivated area of the root crop system in sub-Saharan Africa generates higher losses to production. The rice system in South Asia and the lowland rice system in East Asia are two other systems that have high losses to production from drought but overall low drought intensity.

Many farming systems have high probabilities of failed seasons but comparatively less cultivated area. The highest drought probabilities are associated with arid farming systems with a small aggregate of cultivated areas. For example, the sparse arid system in sub-Saharan Africa has a 93% probability of failed seasons. This system occurs in the Kalahari Desert and has very little area under cultivation.

3.3. The spatial variability of drought frequencies within farming systems

The incidence and frequency of drought varies within individual farming systems, ranging from completely absent to always present. Figs. 3 and 4 show inverted cumulative frequency curves depicting the proportion of area of the farming systems that are susceptible to different drought probabilities in four important regions of the developing world. (Inverted cumulative frequency curves for the Middle East and North Africa and for Eastern Europe and Central Asia are available as supplementary Fig. S2a and b.) With the exception of the South Asian rice system, all show a wide range of drought frequency as evidenced by the gently sloping curves. The curves closer to 45° show more varied environments. Farmers in these high-poverty systems are therefore attempting to cope with a range of drought regimes; and this is probably the reason for the diversity of cropping in these systems.

The driest systems have large areas where the probability of a failed season is high. Well-watered systems have small areas with a high probability of a failed season. At these two extremes, the farming systems rely on fewer crops. Not surprisingly, high value and perennial systems are all found in well-watered areas, while pastoral systems are found in the drier areas.

The sub-Saharan Africa systems shown in Fig. 3B illustrate the range of system types across different levels of drought. The tree crop and highland perennial systems are relatively well watered and have smaller proportions of their area susceptible to failed seasons. At the other extreme, on the right-hand side of Fig. 3B, the pastoral and sparse-arid systems have high proportions of their areas susceptible to failed seasons. Water stress is too high in these systems to support most cropping systems. The high-poverty systems (>2.5 million stunted children) shown by solid curves in the center of the graph reveal farming systems highly varied in their susceptibility to failed seasons and with a diverse mix of cropping systems. Farming systems that have values with a wide range of failed seasons rely on a greater number of crops. These high-poverty systems all show moderate to severe drought risk in between the extremes.

3.4. Coincidence of poverty, crops and drought

Table 2 shows the number of stunted children and drought rankings among the 63 farming systems in three developing-world

continents. The rankings position each farming system according to measures of intensiveness (drought probability) and extensiveness of drought (PDII).

In Latin America and the Caribbean, the maize-bean system in Mexico and Central America stands out, with 2.8 million stunted children, a drought probability ranking of 26 and a PDII ranking of 15. The second in the list is coastal plantation mixed, a system that follows much of the coast of northern South America, Central America and Mexico. This system has high numbers of urban population related to the port cities on the coast. The third system, irrigated, is found in northern Mexico and along the Peruvian coast. This system also has high urban population, including one of the region's largest cities, Lima, Peru. The fourth system, dryland mixed, is often considered to be particularly drought-prone, ranking in the top third of the 63 farming systems in terms of drought probability and the PDII. While some of the remaining systems in Latin America have high drought rankings, they all have fewer stunted children compared to other farming systems. Overall, Latin America and the Caribbean conform to the accepted view that the region is less poor than Africa and Asia and suffers less from drought.

Sub-Saharan Africa, the Middle East and North Africa suffer more from poverty and drought compared to Latin America. Each of the poorest top 10 systems has more than 2 million stunted children (Table 2). Four of these systems are in the top 10 globally in their PDII drought rankings, while three of them are in the top 10 with respect to drought probability. The cereal-root crop and maize mixed systems, each with 6.3 million stunted children, span the southern portion of the Sahel and a large part of East Africa and have high rural populations. The root crop system has a high number of stunted children (5 million), even though drought probability is relatively low. The most notable system in this region is agro-pastoral millet-sorghum, a Sahel system with more than 3 million stunted children and both high drought probability (rank = 8) and large cultivated areas subject to drought (PDII = 6).

Areas of high drought risk in Asia have even higher numbers of stunted children (Table 2). Five of the top seven drought systems as measured by PDII are in the top five systems with stunted children, with more than 10 million in each farming system. The rice-wheat system in South Asia has the highest number of stunted children and the fourth highest PDII drought ranking. The rainfed mixed system in South Asia also stands out, with the second highest stunting value and the highest PDII drought ranking. The lowland rice system in East Asia and the Pacific has the second highest PDII but less than half as many stunted children compared to the South Asian rice-wheat system. These three Asian systems are marked by large populations with large cultivated areas. The upland intensive mixed system of East Asia has somewhat lower drought probability but large cultivated areas susceptible to drought. The Asian systems rank high for poverty and high for area susceptible to drought. But the intensity of drought is generally lower than in African farming systems.

Overall, poverty and drought are more severe in the farming systems of Africa and Asia, with notably lower severity in Latin America. Farming systems in Eastern Europe and Central Asia and in the Middle East and North Africa generally have fewer poor and less cultivated areas susceptible to drought. While these regions do suffer from drought combined with poverty, they are relatively less important in the context both of population and cultivated area.

Table 3 shows the proportional area of each crop in the 15 farming systems with the highest absolute number of stunted children. Each of the crops highlighted in grey covers at least 5% of the total cultivated area in each respective farming system. Maize, millet, sorghum, groundnut and rice stand out in the table, with substantial crop area in the majority of the high-poverty systems. Wheat

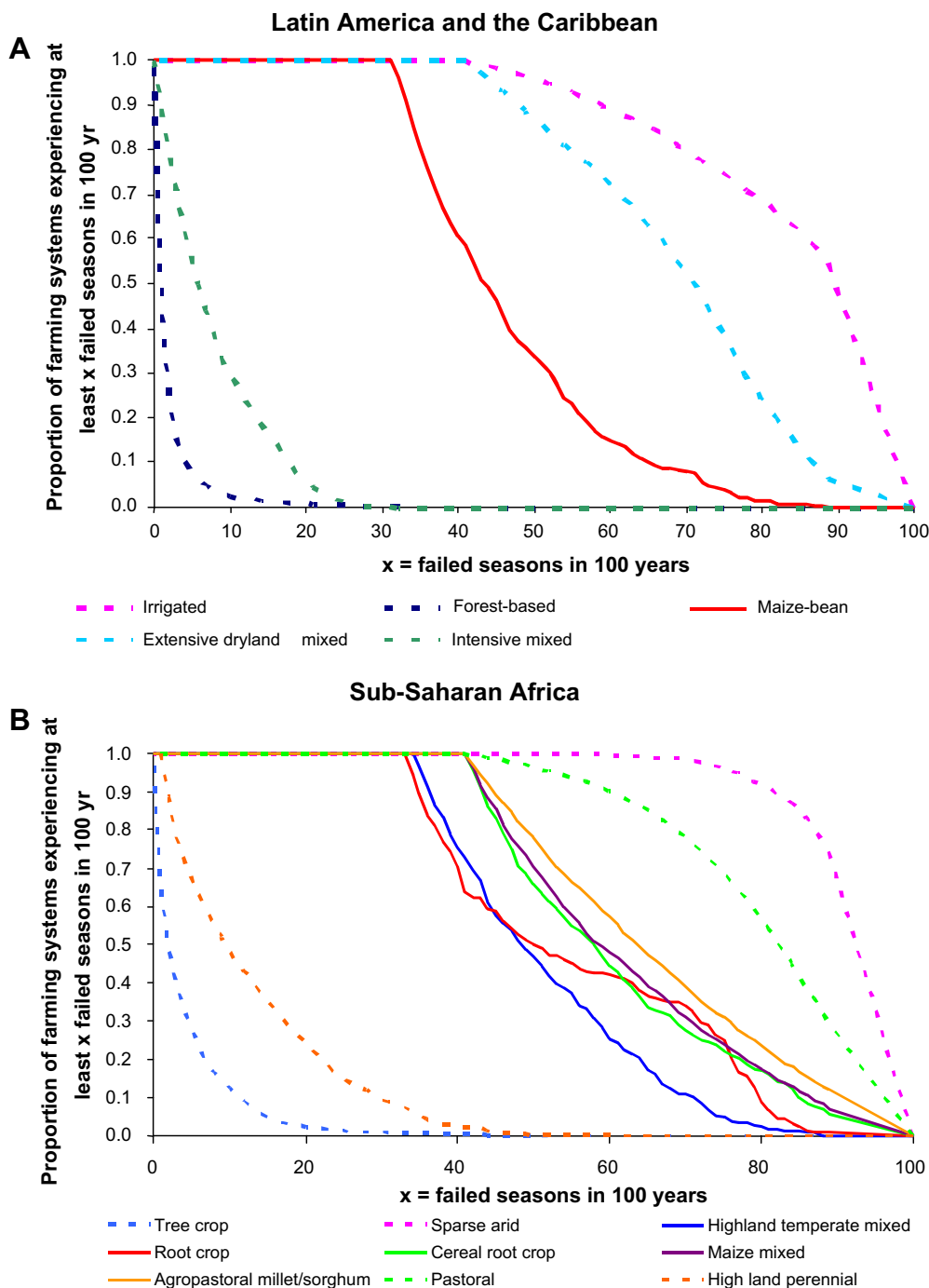


Fig. 3. The proportion of area within each farming system experiencing at least a given number of failed seasons in a 100-year period for (A) Latin America and the Caribbean and (B) sub-Saharan Africa. Systems represented by solid lines are among the 15 systems of the world with more than 2.5 million stunted children.

and common bean have substantial crop area in more than one third of these high-poverty systems. Cassava, sweet potato and potato have a few systems in this group of high-poverty farming systems. Barley only has substantial crop area in the highland temperate mixed system of sub-Saharan Africa.

The high-poverty systems are shown in Table 4 with their main principle crops. Each of these systems has more than 2.5 million stunted children, a number chosen as a threshold for inclusion here because these systems rely more heavily on staple crops. Below these systems in the list in Table 1, the number of stunted children begins to decrease substantially or the systems are pastoral, forest

or sparse. The cut-off point of 2.5 million stunted children falls at a natural break in the data, allowing us to differentiate levels of poverty.

The main crops of the farming systems with high levels of poverty and drought are also shown in Table 4. The crops for each system are listed from largest to smallest proportion of the total staple crop area. The identity of the “other pulses” was determined by inspection of FAO crop production data by country. This list suggests that poor farmers in drought-prone areas rely largely on 13 crops. Listed in approximate order of importance as determined by area in high-poverty systems (Table 3), the crops are maize,

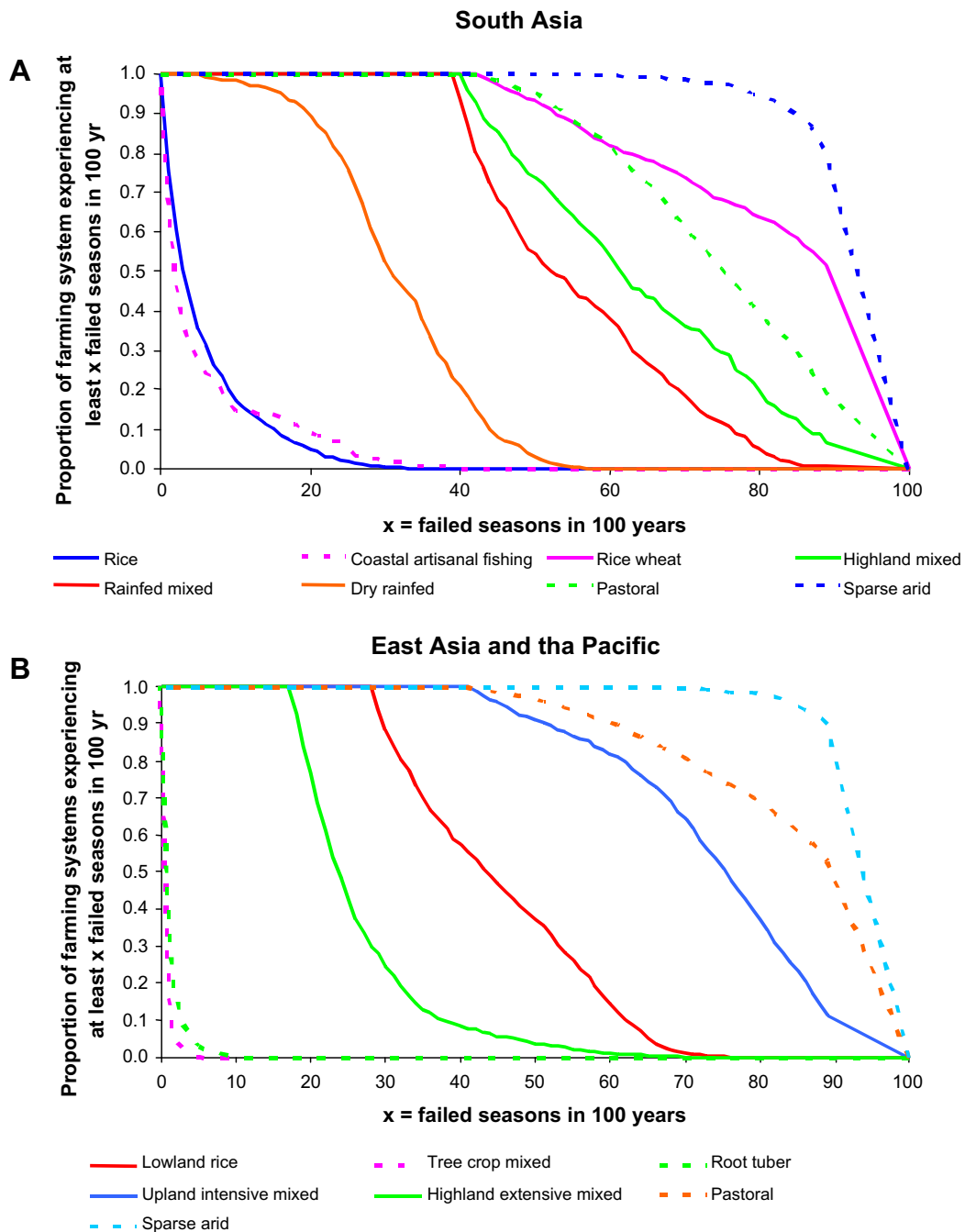


Fig. 4. The proportion of area within each farming system experiencing at least a given number of failed seasons in a 100-year period for (A) South Asia and (B) East Asia and the Pacific. Systems represented by solid lines are among the 15 systems of the world with more than 2.5 million stunted children.

millet, groundnut, sorghum, rice, wheat, common bean, cowpea, chickpea, sweet potato, potato, cassava and barley.

The drought PDII ranking of the 15 systems shown in Table 4 are all within or near the top third of the 63 farming systems globally (Table 1). Nine of these fifteen systems are in the top 10 in terms of their PDII drought ranking. Only the East Asia temperate mixed system (PDII = 23) and the East Asia highland extensive mixed system (PDII = 28) did not fall into the top third of the 63 systems.

The listing of systems and crops in Table 4 suggests three groups of farming systems in the context of targeting for drought tolerance in marginal environments of resource-poor farmers

(Fig. 5). The first group includes those systems with both high drought intensity and high expected losses to production from drought. The agro-pastoral millet-sorghum, maize mixed, rice-wheat and dry rainfed systems are all within the top one third of farming systems in both drought intensity (mean failed season probability) and expected loss of production due to drought (PDII). A second group of farming system have PDII rankings in the top 10, but drought probability rankings in the second or third terciles of the 63 systems. These include cereal-root crop mixed, rainfed mixed (South Asia), upland intensive mixed, root crop, lowland rice and rice. The third group are high-poverty systems in the top half of both intensity and PDII rankings.

Table 3
The proportional area (%) of each crop in the agricultural systems with more than 2.5 million stunted children

Farming system	Region ^a	BANP ^b	Barley	Bean	Cassava	Groundnut	Maize	Millet	OPUL ^c	Potato	Rice	Sorghum	SWP ^d	Wheat
Maize-beans (Mesoamerica)	LAC	0.017	0.008	0.161	0.002	0.007	0.668	0.000	0.009	0.005	0.009	0.098	0.000	0.016
Cereal-root crop mixed	SSA	0.007	0.001	0.032	0.052	0.093	0.125	0.224	0.126	0.004	0.045	0.255	0.033	0.002
Maize mixed	SSA	0.000	0.004	0.057	0.091	0.063	0.461	0.059	0.073	0.023	0.024	0.075	0.056	0.016
Root crop	SSA	0.004	0.000	0.060	0.222	0.074	0.275	0.030	0.027	0.002	0.117	0.074	0.117	0.000
Agro-pastoral millet/sorghum	SSA	0.003	0.002	0.010	0.018	0.125	0.065	0.377	0.146	0.001	0.009	0.238	0.006	0.001
Highland temperate mixed	SSA	0.000	0.166	0.040	0.009	0.008	0.251	0.062	0.051	0.008	0.003	0.168	0.016	0.218
Rice-wheat	SA	0.002	0.009	0.053	0.000	0.011	0.101	0.109	0.118	0.023	0.428	0.038	0.001	0.106
Rainfed mixed	SA	0.002	0.002	0.109	0.001	0.071	0.066	0.170	0.150	0.001	0.205	0.166	0.001	0.056
Rice	SA	0.015	0.001	0.011	0.011	0.020	0.009	0.038	0.100	0.021	0.722	0.023	0.003	0.026
Highland mixed	SA	0.009	0.023	0.026	0.007	0.007	0.196	0.081	0.117	0.021	0.281	0.013	0.002	0.217
Dry rainfed	SA	0.001	0.000	0.053	0.000	0.064	0.021	0.327	0.132	0.001	0.020	0.358	0.000	0.023
Upland intensive mixed	EAP	0.012	0.009	0.060	0.035	0.045	0.267	0.017	0.021	0.062	0.249	0.005	0.080	0.137
Lowland rice	EAP	0.012	0.012	0.043	0.041	0.060	0.166	0.004	0.009	0.026	0.379	0.004	0.097	0.148
Temperate mixed	EAP	0.000	0.010	0.037	0.005	0.070	0.532	0.057	0.026	0.080	0.002	0.041	0.049	0.093
Highland extensive mixed	EAP	0.004	0.008	0.041	0.012	0.056	0.144	0.022	0.055	0.094	0.427	0.002	0.015	0.119

Areas in bold have more than 5% of the area in their respective system.

^a LAC, Latin America and the Caribbean; SSA, sub-Saharan Africa; SA, South Asia; EAP, East Asia and the Pacific.

^b BANP, combined category of bananas and plantain.

^c OPUL, combined category of cowpea, chickpea, lentils and other pulses.

^d SWP, sweet potato.

Table 4
Fifteen farming systems with over 2.5 million stunted children and showing the main crops of the systems

Farming system ^a	Stunted children ('000s)	Crops ^b
SA rice-wheat	28,310	Rice, pulses (chickpea), millet, wheat, maize, bean
SA rainfed mixed	24,547	Rice, millet, sorghum, chickpea, bean, groundnut, maize, wheat
EAP upland intensive mixed	15,435	Maize, rice, wheat, sweet potato, potato, bean
EAP lowland rice	13,368	Rice, maize, wheat, sweet potato, groundnut
SA rice	11,668	Rice, pulses (chickpea)
SSA cereal-root	6319	Sorghum, millet, pulses (cowpea), maize, groundnut, cassava
SSA maize mixed	6318	Maize, cassava, sorghum, pulses, groundnut, millet, bean, sweet potato
SA highland mixed	5162	Rice, maize, wheat, potato, groundnut, pulses (chickpea)
SSA root	4989	Maize, cassava, rice, sweet potato, cowpea, sorghum, groundnut, bean
SA dry rainfed	3610	Sorghum, millet, chickpea, groundnut, bean
SSA agro-pastoral millet/sorghum	3135	Millet, sorghum, pulses, groundnut, maize
LAC maize-beans	2837	Maize, bean, sorghum
SSA highland temperate mixed	2761	Maize, wheat, sorghum, barley, millet, pulses
EAP temperate mixed	2596	Maize, wheat, potato, groundnut, millet
EAP highland extensive mixed	2537	Rice, maize, wheat, potato, groundnut, pulses

^a SA, South Asia; SSA, sub-Saharan Africa; LAC, Latin America and the Caribbean; EAP, East Asia and the Pacific.

^b Crops appearing for the first time in the list are in italics.

Drought-tolerant varieties aimed at four high-poverty farming systems – agro-pastoral millet-sorghum (Sahel), maize mixed (East Africa), rice-wheat (stretching across the northern parts of Pakistan, India and Bangladesh) and dry rainfed (southwest India) – will target regions with both high drought intensity and high expected loss to production. Six systems in Fig. 5 exhibit high expected loss to production but not necessarily the highest drought intensity. Interventions in these systems may reach crop improvement programmes with large numbers of farmers even through drought intensity is relatively lower. Breeding efforts for these systems between drought resistance and yield are being made. The word "bean" should be in italics. The word "cassava" should be in italics. This group of systems in Fig. 5 would aim for high-poverty areas even though drought intensity and expected losses to production from drought are lower than in the other two groups.

With few exceptions, the poorest, most drought-susceptible systems and farmers have developed effective strategies to cope with risk. These farmers cope through various means, including livestock. Judicious interventions may well be successful if the varieties can fit into such diverse and risky systems.

The databases used and developed in this study have substantial potential for research and priority setting for developing country agriculture. Our assessment used criteria that would help focus on a reasonable number of regions and crops that could be given priority for investment in agricultural research and development. These criteria could be easily modified to reflect other priorities than those developed in the study to date.

Although the resolution of the data sets used in this study is quite detailed, future work could include other poverty indicators and poverty analysis at even finer geographic resolutions within the farming systems. Further work should develop crop-specific drought models that distinguish the main drought types according to the crop cycle (establishment, around flowering and terminal) in order to provide more detailed information to crop improvement programmes. This analysis excluded assessment of factors such as variety adoption, the potential to use agricultural technology and the larger context of research investment (Pardey et al., 2006). Nor were economic assessments made to estimate the potential impact of focusing on the priority crops and systems identified in the study. While further research could complement the results obtained here, this study provides an initial assessment of

4. Conclusions

This assessment of poverty, crops and drought suggests that 15 farming systems should be given high priority for agricultural research and development (Table 4 and Fig. 5). These systems account for substantial populations of the poor, including over 70% of stunted children in the world. The 15 systems have large areas of cultivated lands susceptible to drought. Land use and the agricultural economy in these systems rely largely on just 13 crops.

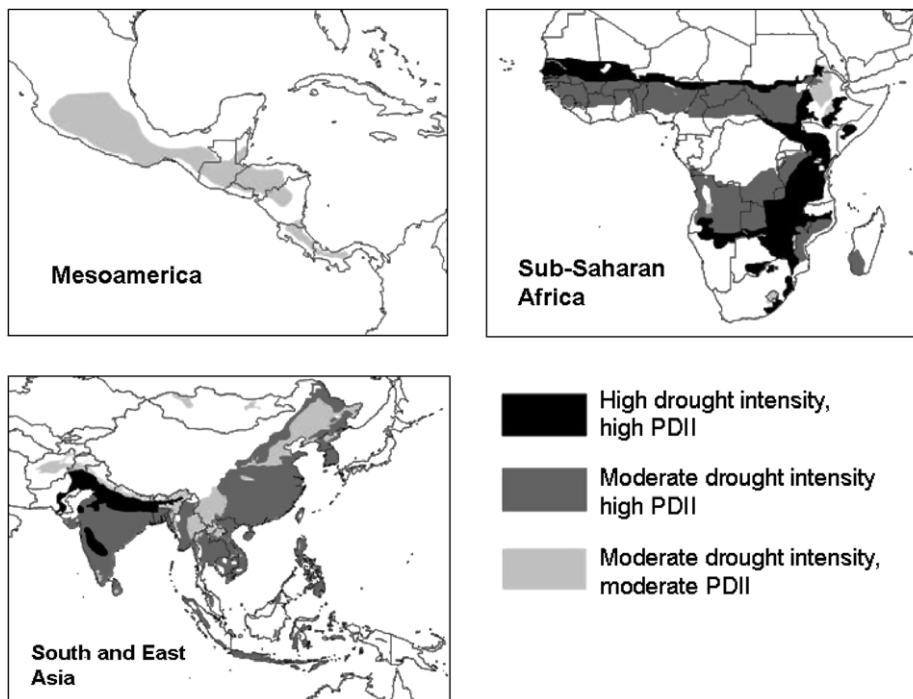


Fig. 5. Priority systems in Mesoamerica, sub-Saharan Africa and South and East Asia with over 70% of all stunted children and substantial drought, by drought intensity and expected loss to production from drought (PDII).

the previously bypassed poor that face high drought risk, and of the principal crops on which they depend.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.agsy.2008.04.001.

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