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Potentially Obtainable Yields in the Semi-Arid Tropics

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COMPREHENSIVE Assessment of water management in agriculture

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Abstract

Close to one billion people in the world are undernourished and world population is expected to increase by 30% to approximately 9 billion by 2050 while food demand is expected to double. There is increasing competition for land and water resources from other sectors and increasing competitive demand for agricultural products for biofuel production. The UN's Millenium Development Goal of reducing the number of undernourished to less than 420 million by 2015 has placed additional emphasis on the question of how we can secure food for the current and future populations and where the additional food requirement can be produced. One world region that possesses significant potential for improvements in agricultural output is the Semi-Arid Tropics (SAT), which lie primarily in developing countries where agriculture is almost entirely rainfed and largely comprises poor, smallholder farms. Due to a variety of factors including high climatic variability in time and space, poverty and poor education, poor policy and institutional support, and political instability, many areas within the SAT are far from reaching their potential agricultural production. Developing their full agricultural potential would help these areas feed their often rapidly growing populations as well as reduce poverty, boost their economies and provide more food for world markets. In this report, IIASA's Agro-Ecological Zones (AEZ) methodology is applied to assess the agricultural potential of the semi-arid tropics and compare it to currently reported yields. Yield potentials are calculated for rain-fed conditions under high inputs and advanced management to show how much yields can be improved. Furthermore, the AEZ methodology is adjusted to model the impacts on yield potentials of water management techniques such as rainwater harvesting and soil moisture management. Bio-physical constraints to agriculture and the impacts of climate change are also analyzed with AEZ. Results indicate that modeled potential yields under high inputs and advanced management are on average 3.6 times more than the current average yields in countries under the SAT. Soil moisture management and rainwater harvesting practices could add an additional 10% on average to these high input potentials while further reducing the variability in yields and number of failure years. Climate change impacts are slightly positive for the SAT as a whole, but all results in the study vary considerably depending on the crop and the region.

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Contents

Introduction

About 800 million people, or about 12% of the world's population, are chronically undernourished. The nations of the world have set a goal of reducing this number to half by 2015, and surely the long-term goal should be to eliminate hunger completely, particularly since the world currently produces enough to adequately feed the world's population, but progress remains slow. One of the primary problems is poverty, both in terms of natural resources and money. The regions that suffer the greatest from hunger are developing regions with some of the highest population growth rates, often without adequate land and water resources to feed these growing populations, and without the means to purchase either food from the world market or the institutions, infrastructure and technology with which to improve their own agricultural yields. Partially because of this, approximately 80% of the world's agriculture and 60% of the agricultural production is rain-fed. Although irrigated agriculture is arguably more productive, it is safe to assume that the majority of the world's agriculture will remain on rain-fed land over the next few decades, partly because of water availability and economic reasons already mentioned, and also for institutional and policy related reasons (SIWI, 2001)

One of the critical regions in these contexts is the semi-arid tropics (SAT), where poor small-holder farmers make their living from the land, which lie primarily within developing countries with rapid population growth and serious land degradation problems, and which also can be seen as one of the regions with the highest potential for increasing rain-fed agricultural production. For the purposes of this study, the semi-arid tropics are defined as areas where the length of growing period (LGP), the number of days in which soil water availability and prevailing temperatures permit crop growth, is between 75 and 180 days. This region is further split into two zones, the dry semi-arid tropics with LGP between 75 and 120 days and the moist semi-arid tropics with length of growing period between 120 and 180 days. These zones are depicted in Figure 1 along with the arid regions with LGP from 30 to 75 days and sub-humid regions with 180-270 days, which are also discussed in this study for the sake of comparison.

The SAT accounts for approximately 13% of the world's cultivated area and 14% of the rain-fed agricultural land. About 10% of the world's population currently lives in the SAT, a number that is expected to increase to between 11 and 12% by 2025 (FAO, 2000; FAO, 2008).

There are a variety of challenges to rain-fed agriculture in the semi-arid tropics. About 98% of the agriculture in the SAT is rain-fed, and wherever precipitation is relied upon, climate is one of the most important factors. The semi-arid tropics, as the name implies is quite dry, receiving an average of about 760 mm per year of precipitation, 520 mm per year in the dry semi-arid zone and 870 mm in the moist semi-arid zone. On average this may be enough to meet the water requirements of the crops grown in these regions. However, precipitation is highly variable in time, making it difficult to know if the precipitation will be enough in any particular year. For example, annual precipitation in Ecuador varied from 450 mm in 1979 to 3180 mm in 1983. Precipitation is also highly variable in space, ranging from a 30-year average of 390 mm in the SAT zones of Mauritania to 2200 mm in Myanmar.

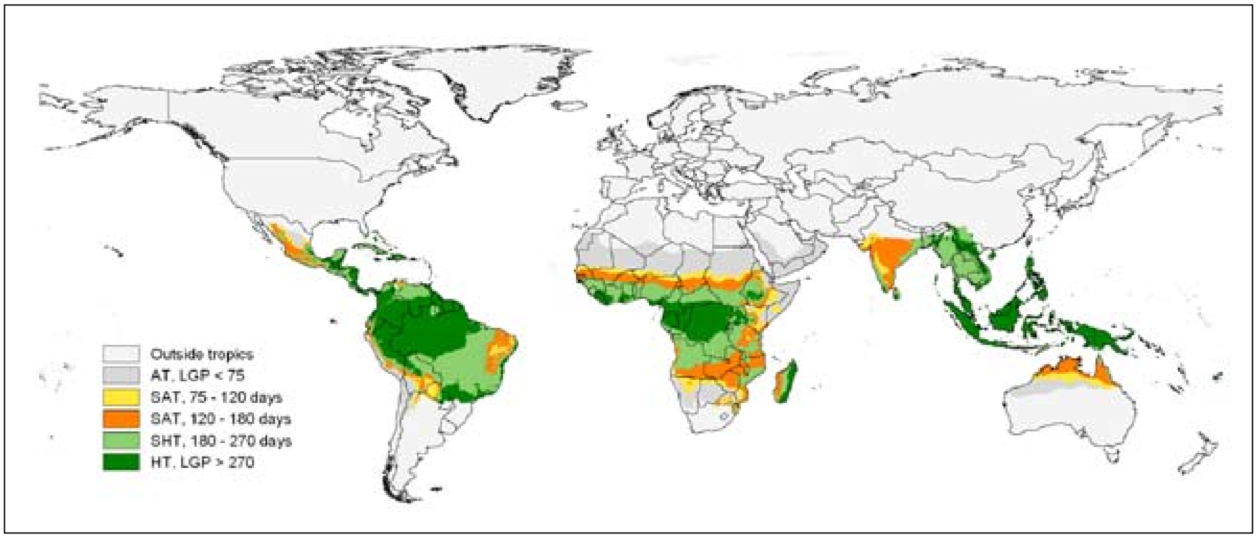

Figure 1. Tropical regions delineated by length of growing period, the arid tropics (AT) in gray, the dry semi-arid tropics (SAT) in yellow, the moist semi-arid tropics (SAT) in orange, the sub-humid tropics (SHT) in light green, and the humid tropics (HT) in dark green.

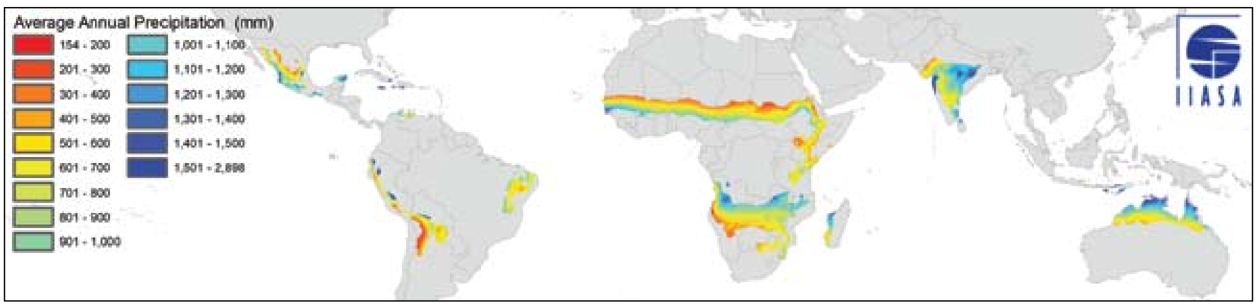

Figure 2. Average annual precipitation in the semi-arid tropics for the period 1961-1990.

The high variability throughout the SAT results in a total crop failure on average once every ten years and has drastically reduced yields 2-4 years of every 10. Analysis of the climatic constraints to agriculture in the SAT using IIASA's AEZ implementation also indicates that moisture constraints are the most important climatic constraints to agriculture in the SAT. The result is shown spatially in

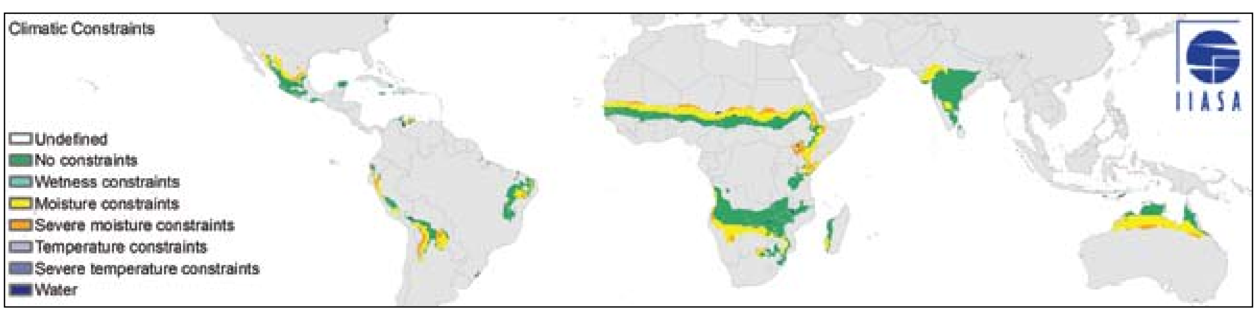

Figure 3. Climatic constraints to agriculture in the SAT.

Figure 3, clearly correlated to the precipitation shown in Figure 2. Temperature is also a factor, but is generally within the necessary ranges in the SAT.

Agriculture in the SAT is also constrained to some extent by terrain and soil properties. Maps of the different types of soil and terrain constraints can be found in Appendix II.

The other important challenge in the SAT is the human factor. The population of the SAT is currently approximately 600 million, resulting in a population density for the region of 55 people per square kilometer, not so high by global standards. This population density is projected to increase in the coming years as the population in the SAT reaches about 800 million by 2025. As previously mentioned, though poverty is widespread in the SAT and education systems, institutions and government priorities are often not in place, or lack the resources to improve agricultural output and the quality of life in these areas.

From the numbers and the discussion above, the challenge is clear. There is a need to increase agriculture productivity throughout the world and the SAT may hold significant potential. Currently, millions of farmers are struggling to support themselves and their communities in the SAT by relying on rain-fed production under conditions of highly variable precipitation, with little institutional support in some cases. The number of people to support is constantly and rapidly growing while at the same time land is being degraded. Under such circumstances, is it possible to even maintain the status quo in these areas of farmers barely, and in many cases, not being able to support themselves and their local populations, much less progress toward attaining the UN's Millennium Development Goals of reducing poverty and hunger? If it is possible for these areas to be self-sufficient and beyond that to be productive enough to export agricultural products, what agricultural improvements will be necessary?

Much can be done in the SAT with improved education and institutions that can provide access to weather information, markets, choices of crops and crop varieties, pesticides, fertilizers, and capital. Irrigation can also improve yield in the SAT, but this often requires substantial infrastructure investments that farmers themselves in these regions can't afford and governments are slow to construct. However, simpler ways of augmenting the available water supply through rain-fed agricultural land exist through improved soil and water conservation and management practices. A number of rainwater harvesting and supplemental irrigation techniques have been used throughout thousands of years to great success in some areas. These techniques have the advantages that they can be done on the farm and are inexpensive to implement, requiring primarily only labor.

The challenge of this study is to estimate the potential for rain-fed agriculture in the SAT. How much more can be produced under the best possible conditions by rain-fed agriculture? In trying to answer this question, we will model the potentially attainable rain-fed yields in the SAT and compare them to observed and estimated rain-fed yields of countries in the SAT, calculating the gap between the actual and potentially obtainable yields. Furthermore, we will vary model parameters to make a simplified assessment of the impact of water harvesting techniques on the rain-fed potential in the SAT. Maps of spatial yield results, constraints to agriculture, a climate change assessment, and some methodological details can be found in the appendices. The next sections will describe the methodology and results of the assessment of agricultural yield potential in the SAT, followed by a comparison of the results to actual yields, a discussion and description of the other types of results, and conclusions that can be drawn from the study.

Throughout this report, results will be shown in tables and figures for the semi-arid tropics as a whole, split into two regions, the dry SAT (dSAT) and moist SAT (mSAT), also referred to as SAT1 and SAT2, respectively. Tables and figures will also show four case study countries (India, Kenya, South Africa, and Ethiopia) with land in the SAT, and one case study country (Vietnam) that falls into the category of semi-humid tropics and therefore is not included in the SAT statistics. Spatial results for the entire SAT region are provided in the appendixes.

Yield Gaps in the Semi-Arid Tropics

To answer the questions brought up in the introduction, it is necessary to calculate the yield gap in the semi arid tropics, particularly in rain-fed areas, between what is actually being produced and what could possibly be produced under ideal management practices. Because we need to know what areas have the greatest potential, where the difficulties are the greatest, what the extents of these difficulties are and how serious they are, potential yields must be calculated and compared to actual yields in a spatially explicit manner, to the extent possible.

In the following sub-sections, the steps taken to calculate the yield gaps in the SAT will be laid out and the results of each step presented. First, the methodology for calculating potentially attainable rain-fed yields is discussed and results are shown. In the following section, simplified methods of accounting for soil-moisture management and rainwater harvesting in the modeling are discussed and the results of applying these techniques to the calculation of potential yield are shown. Finally, the yield gap between the modeled potential yields and the actual yields based on statistics are calculated.

Potentially Attainable Rain-fed Yield

The methodology used for the assessment of agricultural potential in the semi-arid tropics is called the Agro-Ecological Zones methodology, developed by IIASA and FAO over the past 30 years. The AEZ methodology used here is similar to, but slightly modified from, the version used for the global AEZ assessment for agriculture in the 21st century (IIASA, 2002). AEZ can be, and has been, used for both global studies and case studies. For the SAT, calculations are done at a 5 minute grid-cell scale, so that results can also be used locally and regionally. Details of the AEZ methodology have been described in a number of previous reports, so this section focuses only on changes made specifically for the requirements of this assessment of the SAT. Because the quality of the data is a very important factor in the quality of the results and conclusions that can be drawn, the sources of input data for AEZ are listed and briefly described in Appendix V. For the sake of global consistency and availability of data, datasets with global coverage were used in the analysis.

Many definitions of 'potential yield' are possible. This section is entitled 'potentially attainable rain-fed yield' to indicate that the calculation is not simply a maximum potential yield, but the calculated yield is limited to a more realistically obtainable yield by considering different levels of management practices, inputs, and naturally occurring yield reductions due to pest and disease incidence; water stress; extreme temperature events; and climatic factors that directly or indirectly affect yield, produce quality, efficiency of farm operations, and cost of production.

Although the calculated yield is limited by the reduction factors, the potentially obtainable yield calculated here is for optimal management practices and high inputs. In the context of AEZ, "high input levels and advanced management" mean that:

- the farming system is mainly market oriented,
- commercial production is a management objective,
- production is based on improved high-yielding varieties,
- production is fully mechanized,
- production has a low-labor intensity, and
- production uses optimum applications of nutrients and chemical pest, disease and weed control.

Intensive agriculture with high levels of inputs is not yet common on rain-fed land throughout the SAT, but the purpose here is to calculate an estimate of the maximum attainable rain-fed yield as a measure of the improvement in yields possible. Furthermore, the calculation of potentially obtainable yield that is shown in the following tables and figures, is based on a reference soil water content that can be used by the crop, or available water content (AWC) of 100 centimeters. This is done to make the impact of rainwater harvesting and soil moisture management more clear in following sections.

Yield potentials of major food crops in the SAT have been assessed.Crop types assessed specifically in the SAT for this report are presented in Table 1 below:

Table 1. Crop types assessed in the semi-arid tropics

Crops	Crop types	Climate zones
Cereals	*(10)*	
Maize	4	Tropics
Sorghum	4	Tropics
Pearl millet	2	Tropics
Legumes	*(6)*	
Soybean	3	Tropics
Groundnut	3	Tropics
Total	*16*	

Because several crop cultivars were simulated for each crop, the following rules were applied to obtain the potentially attainable yields.

- The highest yielding cultivar that can be produced 8 out of 10 years is selected for each 5 arc-minute grid cell.
- If all cultivars have less than 8 non-failure years out of 10, the cultivar with the lowest failure rate is selected, assuming that farmers will prefer to produce something in as many years as possible.
- If less than 50% of the years produce yield, the crop is not grown.

For this analysis, a failure year is a year that yields less than 20% of the average attainable yield.

Results

Calculated average potentially obtainable rain-fed yields for these crops in the SAT tropics and the case study countries are listed in Table 2 and plotted in Figure 4.

Table 2. Potential yield by crop, country, and SAT region in kg ha^{-1}

	India		Kenya		South Africa		Vietnam	Ethiopia		Total Sat	
	dSAT (1)	*mSAT (2)*	*dSAT (1)*	*mSAT (2)*	*dSAT (1)*	*mSAT (2)*	*SHT (3)*	*dSAT (1)*	*mSAT (2)*	*dSAT (1)*	*mSAT (2)*
Maize	3870	8020	1540	3480	2550	4980	4080	1960	4180	3410	7330
Groundnut	2590	4400	1330	2570	2290	3270	3410	1870	2910	2400	4080
Pearl millet	2870	3080	2130	2700	2260	3100	580	2540	2780	2660	2950
Sorghum	4560	6400	2680	3840	2540	3440	2150	2740	3660	4030	5910
Soybean	2850	5090	1020	2440	2030	3620	3000	1900	3440	2590	4760

Table 2 and Figure 4 show significant differences in the potential yield of a single crop among regions. Although the SAT is defined by growing period, the climatic and environmental conditions can be much different from one area within the SAT to another. Figure 2 shows the spatial variability in precipitation.

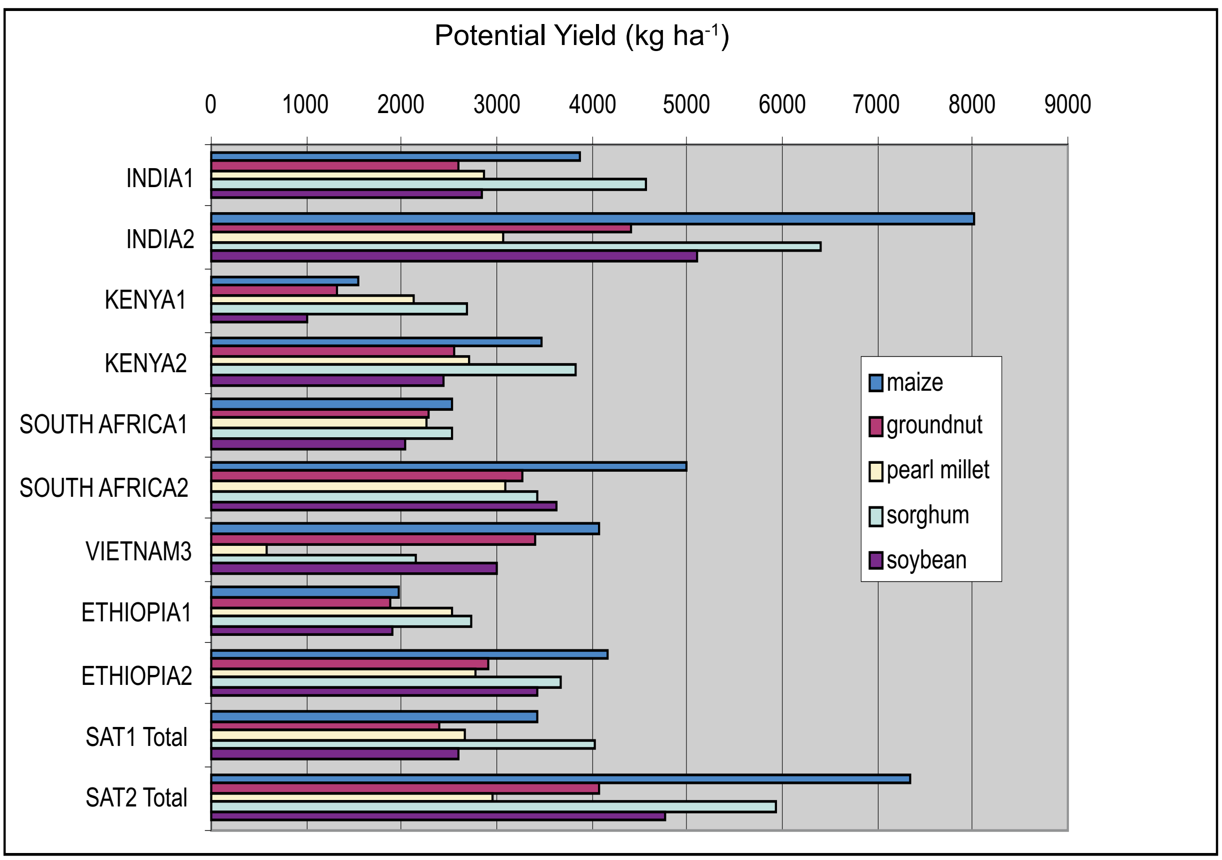

Figure 4. Potential Yields by crop, country and SAT region in kg ha^{-1}.

In addition to the summary tables and figures here that cover the SAT as a whole and the case study countries and crops, spatial maps of attainable yields under high inputs for the individual crop cultivars are presented in Appendix I. Maps of the variability in attainable yields, in terms of standard deviations, co-efficients of variation, and numbers of non-failure years, are also shown.

Attainable Yield with Moisture Regime and Dryland Management

Rain-fed yields in some areas of the semi-arid tropics are limited by insufficient water availability. Although this report is focused on rain-fed agriculture and not irrigated agriculture, there are relatively simple techniques to improve the availability of soil moisture with little investment. In addition, these same techniques also help to prevent soil erosion. Because simple soil and moisture conservation practices can be implemented at low cost and can have a significant benefit on much of the semi-arid tropics, it is worthwhile to try to quantify the impacts of these techniques on the potential yields of agriculture in the SAT.

Most water harvesting techniques involve shaping the soil surface to direct water to the plants and hold it in the soil, preventing direct surface runoff as much as possible. Examples go from broad beds and furrows on relatively flat land, contour furrows and bunds on slightly sloped land, to full step terraces on steeply sloped land. Additional moisture management techniques revolve around decreasing evaporative losses. Finally, more advanced water harvesting techniques act to re-route the watershed and store water in ponds for irrigation use later. When done on a large scale, water harvesting becomes full irrigation. Changes made to AEZ to quantify water harvesting and dryland moisture management can be considered to cover most of these practices including water harvesting with little pond or tank storage. Large scale water harvesting and full irrigation, where farmers have the possibility of adding water even after an extended drought period, are not included in the parameterization. The yield improvements due to water harvesting techniques are calculated within AEZ by increasing by 50% the soil water storage capacity in terms of the water content of the soil that is available to crops, since water harvesting schemes are designed to increase infiltration of precipitation into the soil.

In addition to water harvesting techniques that increase the capture of precipitation and enhance infiltration into the soil, another complementary set of techniques are designed to manage the moisture once it is in the soil and reduce losses. Additional alterations to the AEZ water balance were made to capture the impacts of these techniques as well. The modifications made to the AEZ water balance calculation in this respect, in combination with dryland specific land utilization types serve areas where rainfall is marginal and unreliable, but still sufficient to build up adequate soil moisture storage for successful growing of crops. These areas occur in the arid and dry semi-arid zones with typical annual rainfall between 300 and 600 mm and reference growing periods of 30-120 days, meaning that the dry semi-arid tropics, with growing periods between 75-120 days will most likely experience the greatest yield improvement within our study region. To give an idea of the extent of land affected both inside and outside the SAT, Figure 1 shows the full map of global growing periods. The area with growing periods between 30-120 days has a total extent of 3.2 billion hectares, about 24 % of the total world land surface (excluding Antarctica).

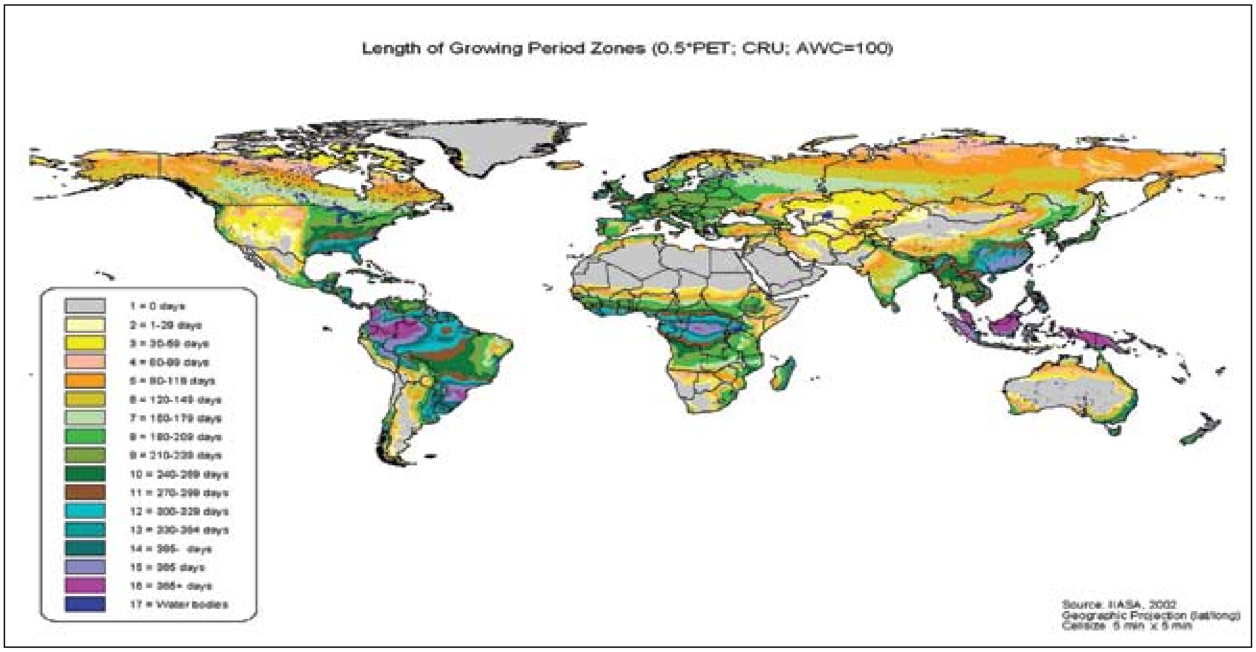

Figure 5. Reference length of growing period zones.

Enhanced Soil Moisture Balance

Reference evapotranspiration, stored soil moisture and rainfall are used together with crop transpiration water requirements of dryland cropping systems and evaporation losses during clean fallow (no-tillage or reduced tillage) in a year round water balance. Details of the calculation of potential evapotranspiration are presented in Fischer et al., 2002.

The growing period for crops grown on rain-fed land during the crop growth cycle depends to some extent on moisture stored in the soil profile. The amount of soil moisture stored in the soil profile, and available to a crop, varies, e.g., with depth of the soil profile, the soil physical characteristics, and the rooting pattern of the crop. Soil moisture storage capacity of soils (S_{max}) depends on soil physical and chemical characteristics, but above all on effective soil depth or volume. For the soil units of the Legend of the Soil Map of the World (FAO, 1974), FAO has developed procedures for the estimation of S_{max}[1] (FAO, 1995c). These estimates refer to crops relying on rainfall during the crop cycle and limited availability of soil moisture. Based on research evidence, the maximum available soil moisture (AWC) was set to 150 mm, assuming that the bulk of roots occur mainly in the top 100 cm of the soil profile (Fischer et al., 2002).

Empirical evidence from the USA and Bangladesh indicates that 200-250 mm of moisture can be used by crops that to a large extent are relying on residual soil moisture (Nielsen et al., 2002 and Brammer et al., 1988). The bulk of the roots in deep soils may move with retracting soil moisture up to a depth of about 150 cm. A first modification to the AEZ water balance model parameters concerns the AWC for crops grown on residual moisture. Table 3 below presents revised classes of available moisture holding capacity as related to the soil units and phases of the FAO/UNESCO Soil Map of the World.

1. It is assumed that S_{max} relates to plant available soil moisture in a ratio of approximately three to two

The S_{max} classes estimated for individual FAO soil units are presented in the Appendix IV. For each mapping unit (and each grid-cell) the composition in terms of soil units and the occurrence of soil depth/volume limiting soil phases is known from the DSMW. The relevant S_{max} values for individual soil units in a grid-cell were used to set limits to available soil moisture by soil unit, soil texture class, and soil phase.

Table 3. Available moisture storage capacity (AWC) classes derived for FAO soil units and for soil depth/volume limiting soil phases (based on rooting depths up to 150 cm)

CLASS	Soils with "no Phase" (mm)	Soils with Lithic Phase (mm)	Duripan Phase (mm)	Soils with Stony, Petric, Petrocalcic, Petrogypsic, Petroferric Phase (mm)
1	225 mm	50 mm	115/50 mm	145/85 mm
2	190 mm	40 mm	90/40 mm	115/70 mm
3	150 mm	35 mm	75/35 mm	95/55 mm
4	110 mm	25 mm	55/25 mm	75/45 mm
5	50 mm	15 mm	35/15 mm	35/15 mm
6	15 mm	n.a.	n.a.	n.a.

n.a = not available

The above soil specific AWC values were used in the growing period analysis. The daily water-balance, *W,* and actual evapotranspiration, *ETa,* is calculated as follows (see also Fischer et al., 2002):

$$W_{j+1} = min\left(W_j + P_j - ETa_j,\ dSa\right) \qquad (1)$$

$$ETa_j = \begin{cases} ETo_j & if\ (W_j + P_j) \cdot \geq Sa \cdot d \cdot (1 - p) \\ \rho ETo_j & else \end{cases} \qquad (2)$$

where,

$$\rho = \frac{ETa_j}{ETo_j} = \frac{W_j + P_j}{Sa \cdot d(1 - p)} \qquad (3)$$

ETO reference evapotranspiration

ETa actual evapotranspiration

j number of day in year

Sa available soil moisture holding capacity (mm/m)

d rooting depth (m)

p soil water depletion fraction below which *ETa* < *ETo*

ρ actual evapotranspiration proportionality factor.

Sa and *d* are defined by the respective values of the soil units in individual grid-cells, which have been adjusted from the original values for changed rooting patterns that develop under cropping on residual soil moisture.

Soil Evaporation Reduction Assumptions

Through application of water balances (with daily time steps) with historical data from locations in dry semi-arid areas and measured values of soil moisture at planting in the same locations, assumptions could be made on the efficiency of water conservation by means of zero tillage and reduced tillage systems (which include the use herbicides or mechanical means for the removal weeds to avoid additional transpiration losses) in terms of reduced soil evaporation rates. The water balance calculations and measured soil moisture data suggest a soil evaporation rate of approximate 20% of reference evapotranspiration during non-cropped periods.

"Independent simulations with the model CERES-Wheat (Tsuji et al., 1994) for Goodland, western Kansas, indicate that the assumption of soil-evaporation = 0.2* PET is indeed a good one, especially when temperatures are over 0°C. Five years of continuous water balance were simulated at Goodland KS, using observed weather, soil, cultivar, and management practice data previously collected for the US National Assessment study (Tubiello et al., 2002). Actual soil evaporation and model –computed potential ET were compared over different time-periods in order to assess AEZ performance in similar conditions."

A schematic overview of various steps of the water balance calculations as performed in the AEZ water balance module for both rainfall dependent crop growth (original) as well as crop growth relying on residual soil moisture is presented in Figure 2 that shows the various steps of AEZ water balance as influenced by temperature and cover.

Table 4. Water balance parameters by temperature and cover

Periods	P1a®	P1b®	P2a®	P2b®	P3 ®	P4 ®	P5 ®	P6 ®	P7 ®	P8 ®	P9 ®	P10®	P11®
Cover (1)				Fallow				Crop stage1	Crop stage2	Crop stage3		Fallow	
Mean temperature	Tm<0	Tm<0	Tm<0	Tm<0	Tm 0-5	Tm 0-5	Tm>5	Tm>5	Tm>5	Tm>5	Tm>5	Tm 0-5	Tm<0
Maximum temperature	Tmax <0	Tmax <0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0
Snow cover	Snow	No snow	Snow	No snow	Snow melt	No snow							
Evapo(transpi)ration	EVsnow	EVfroz1	EVsnow	EVfroz2	EVsnow	ETsoil/ EVsoil	ETsoil/ EVsoil	ETm	ETm	ETm	ETsoil/ EVsoil	ETsoil/ EVsoil	EVfroz
Rain-fed/ conventional tillage	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.3ETo	0.4ETo	kc* ETo	kc* ETo	kc* ETo	0.4ETo	0.3ETo	0.2ETo
Rain-fed/ zero tillage + weed removal or reduced tillage	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	kc* ETo	kc* ETo	kc* ETo	0.2ETo	0.2ETo	0.2ETo
Cover (2)							Fallow						
Evapo(transpi)ration	EVsnow	EVfroz1	EVsnow	EVfroz2	EVsnow	ETsoil/ EVsoil	ETsoil/ EVsoil	ETsoil/ EVsoil	ETsoil/ EVsoil	ETsoil/ EVsoil	ETsoil/ EVsoil	ETsoil/ EVsoil	EVfroz
Rain-fed/ conventional tillage	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.3ETo	0.4ETo	0.4ETo	0.4ETo	0.4ETo	0.4ETo	0.3ETo	0.2ETo
Rain-fed/ zero tillage + weed removal or reduced tillage	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo

Tm=mean temperature, Tmax=maximum temperature; ETo= reference evapotranspiration; EVsnow=sublimation rate of snow (= 0.2*ETo); EVfroz.= evaporation from frozen soil (= 0.2*ETo); EVsoil= evaporation from non frozen bare soil (= 0.2*ETo); ETsoil= evapotranspiration from non frozen soil and weeds (= 0.3 or 0.4*ETo). ETm= maximum crop evapotranspiration (= kc*ETo, where crop coefficient kc ranges are crop stage dependent).

Tillage Systems

In standard AEZ applications conventional tillage systems are assumed. In this case a closer look was taken at tillage systems that would help conserving as much soil moisture in the soil profile as possible. A number of factors have been considered namely: (i) improvement of soil moisture intake, (ii) reduction of soil evaporation losses, (iii) reduction of percolation losses and (vi) optimal use of soil moisture.

Improving soil moisture intake

Plant cover: Slows runoff

Crop stubble and debris: Slows runoff and captures drifting snow

Tillage: Improves infiltration into poorly permeable soils

Reduction of evaporation losses

Mulching: Reduces evaporation, discourages weed growth (transpiration)

Tillage of topsoil: May reduce evaporation by breaking soil capillary water movement towards soil surface.

Weeding: Reduces interception losses and evaporation.

Reducing of percolation losses

Increase of organic matter: Improve available water holding capacities of soil profile

Optimizing soil moisture

Reduce seed rate/increase spacing: Increases moisture available per plant

Fallowing: (Clean fallow reduces transpiration of weeds)

No tillage: Reduces evaporation losses

Reduced tillage: Reduces evaporation losses

Sub-tillage: Reduces evaporation losses and may reduce soil capillary water movement towards soil surface.

Several of the measures described in the box have been now accounted for in setting up the dryland version of AEZ. It has been assumed that depending on soil and terrain conditions adapted measures are taken to achieve optimal water conservation from rainfall while preventing soil erosion. Where possible (for instance in absence of problems like runoff due to low soil infiltration rates because of heavy topsoils or sealing characteristics of the soil surface) zero tillage with clean fallow is assumed. For soils with runoff due to low infiltration rates, prevalence of topsoil sealing and other specific topsoil characteristics and unfavorable soil capillary conditions, reduced tillage and sub-tillage systems are assumed (FAO, 1984). Also it is assumed that crop stubble, crop debris and mulching practices are used where practical and beneficial for soil moisture conservation. In summary best practice vis-à-vis soil moisture conservation is assumed in the AEZ water balance.

Results

Average modeled improvements to the potentially obtainable yields based on the water harvesting and soil moisture conservation techniques described above are shown for the SAT as a whole in Table 5 and Figure 6.

Table 5. Impact of soil moisture management techniques on potential yield in the semi-arid tropics as calculated by AEZ

Region and crop	Cultivated area (ha)	Reference potential yield (kg ha^{-1})	Increased AWC, 50%			Decreased evapotranspiration			Total		
			Yield (kg ha^{-1})	Difference (kg ha^{-1})	%	Yield (kg ha^{-1})	Difference (kg ha^{-1})	%	Yield (kg ha^{-1})	Difference (kg ha^{-1})	%
SAT1 Maize	424920	3410	4070	660	19%	4240	166	5%	4960	820	24%
SAT2 Maize	1434697	7330	7700	370	5%	7730	30	0.4%	7930	400	5%
SAT1 Groundnut	414100	2400	2730	330	14%	2830	103	4%	3080	430	18%
SAT2 Groundnut	1401833	4080	4160	80	2%	4180	16	0.4%	4210	100	2%
SAT1 Pearl millet	394063	2660	2720	60	2%	2770	51	2%	2780	110	4%
SAT2 Pearl millet	1367867	2950	2970	20	0.5%	2980	13	0.4%	2990	30	1%
SAT1 Sorghum	424920	4030	4450	420	10%	4620	175	4%	5080	590	15%
SAT2 Sorghum	1434697	5910	6110	190	3%	6130	28	0.5%	6240	220	4%
SAT1 Soybean	414100	2590	2920	330	13%	3060	148	6%	3330	480	18%
SAT2 Soybean	1401833	4760	4880	120	3%	4900	25	0.5%	4960	140	3%

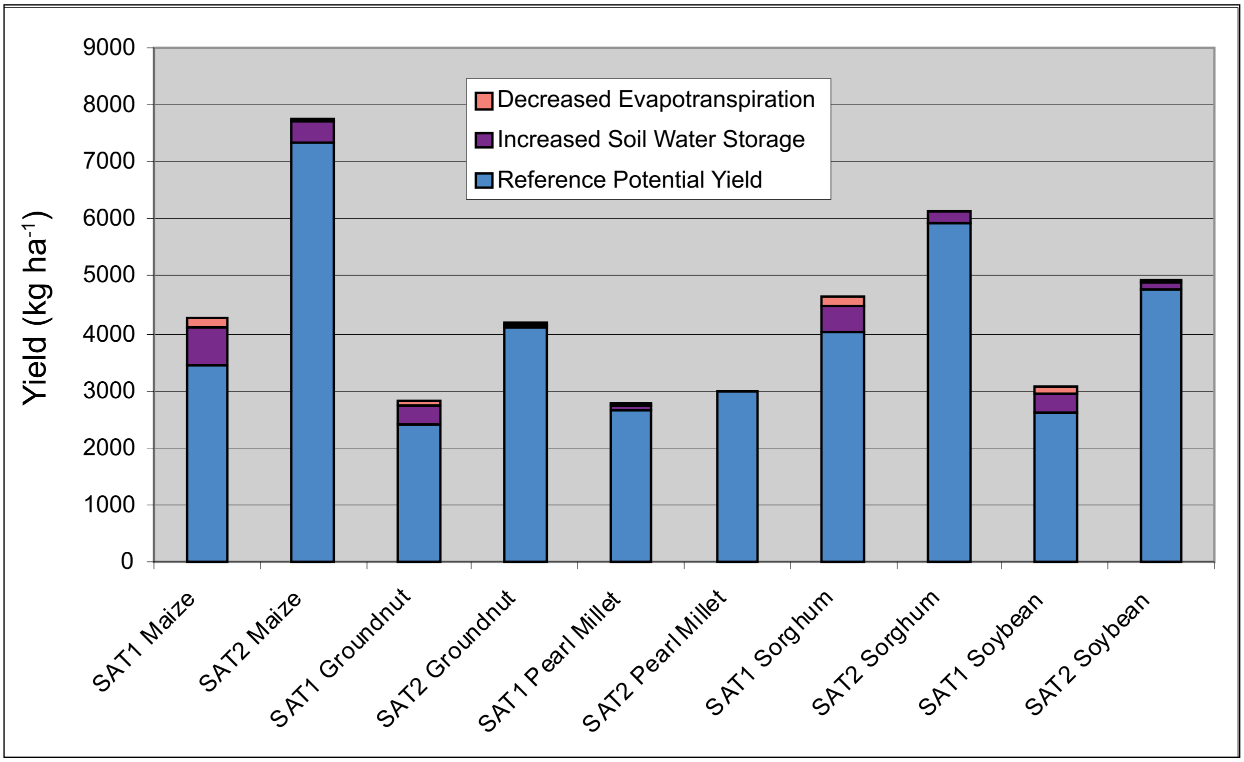

Figure 6. Impact of soil moisture management techniques on potential yield in the semi-arid tropics as calculated by AEZ.

The modeling of yield impacts of soil moisture management techniques produced many expected results. The impact of the dryland management techniques is greater in the drier regions of the SAT, the dSAT or SAT1 region, where the length of growing period is between 75 and 120 days as opposed to SAT2, where the LGP is between 120 and 180 days. The average yield increase in the dry semi-arid tropics over all crops was 15.8% but was only 3.1% in the moist semi-arid tropics. Also, a crop like maize that requires more water and is less drought-tolerant benefited much more from the additional soil moisture available than a crop like millet that is quite resistant to drought and showed only a slight benefit from the modeled moisture management. The increase in maize yield was 24.1% in the dSAT and 5.4% in the mSAT, but millet yield only improved by 4% in the dSAT and 1% in the mSAT.

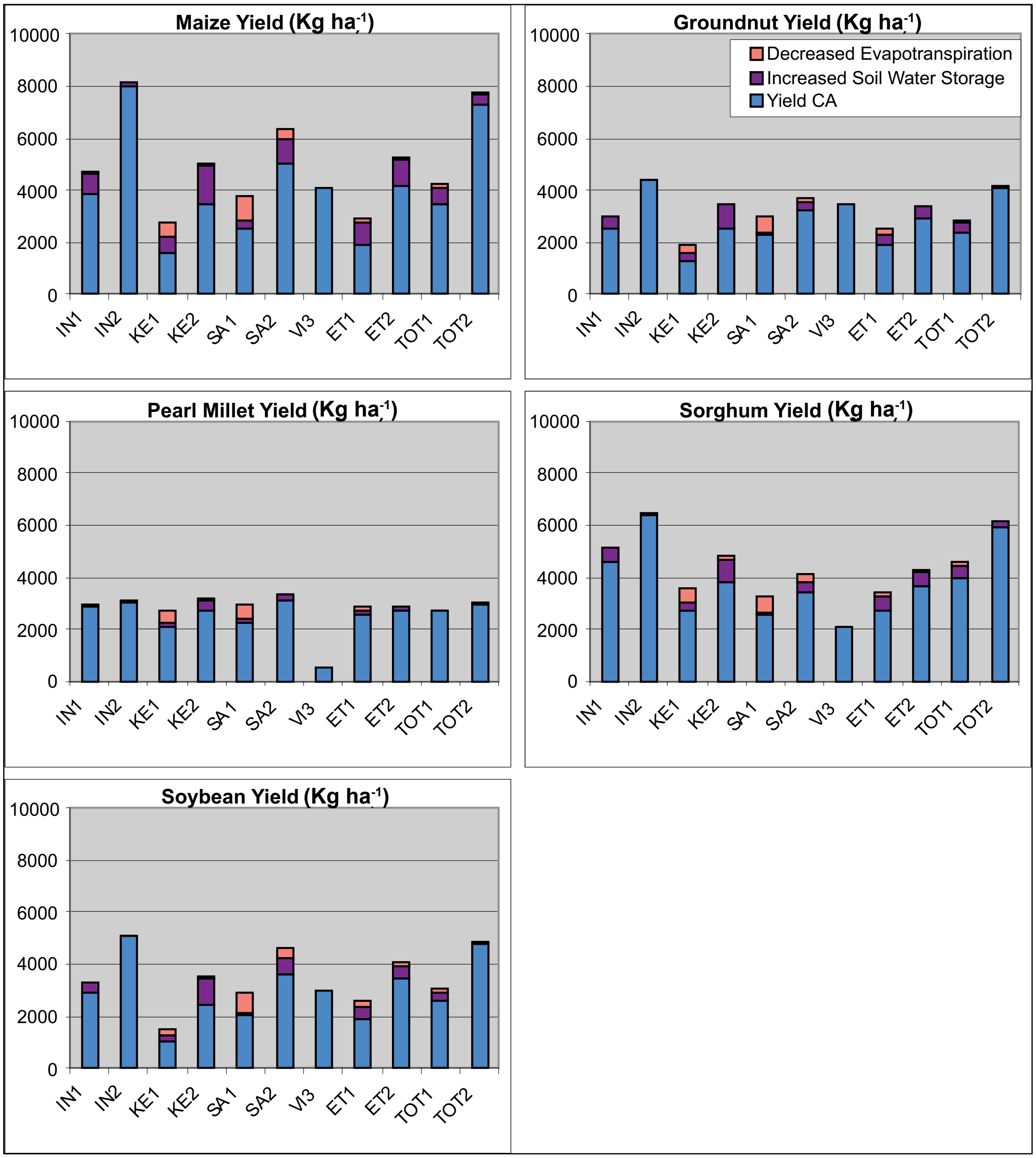

Figure 7. Country specific impact of soil moisture management techniques on potential yield in the semi-arid tropics as calculated by AEZ.

In the case study countries, yields increases varied from essentially zero percent in Vietnam and the wetter areas of the SAT, particularly in India, to an average increase of 80% for maize in the dSAT of Kenya. Figure 7 also shows that techniques that conserve moisture and reduce evaporation losses can have a larger impact in areas with high climatic variability and high evaporation rates than water harvesting techniques alone that only increase the soil moisture storage. In the dSAT of Kenya and South Africa, the yield increase due to efforts that reduce evaporation are many times the increase due to solely increasing soil moisture storage for several of the crops.

Comparison to National Statistics

Average national agricultural yields on rain-fed land from FAO (FAO, 2000 and FAO, 2008) were used as estimates of actual yield and compared with the potentially obtainable yields calculated in the previous sections. The yield gaps for the SAT as a whole are shown Table 6 and Figure 8.

Table 6. Comparison of actual yield from national-level statistics and calculated potential yield under high inputs

Region and crop	Cultivated area (ha)	Actual yield (kg ha^{-1})	Reference potential			Total		
			Yield (kg ha^{-1})	Difference (kg ha^{-1})	Quotient	Yield (kg ha^{-1})	Difference (kg ha^{-1})	Quotient
SAT1 Maize	424920	1460	3410	1950	2.3	4240	2780	2.9
SAT2 Maize	1434697	1460	7330	5870	5.0	7730	6270	5.3
SAT1 Groundnut	414100	980	2400	1420	2.5	2830	1850	2.9
SAT2 Groundnut	1401833	980	4080	3100	4.2	4180	3200	4.3
SAT1 Pearl millet	394063	690	2660	1980	3.9	2770	2080	4.0
SAT2 Pearl millet	1367867	690	2950	2270	4.3	2980	2290	4.3
SAT1 Sorghum	424920	1170	4030	2860	3.5	4620	3450	4.0
SAT2 Sorghum	1434697	1170	5910	4750	5.1	6130	4970	5.3
SAT1 Soybean	414100	1420	2590	1170	1.8	3060	1640	2.2
SAT2 Soybean	1401833	1420	4760	3340	3.3	4900	3480	3.4

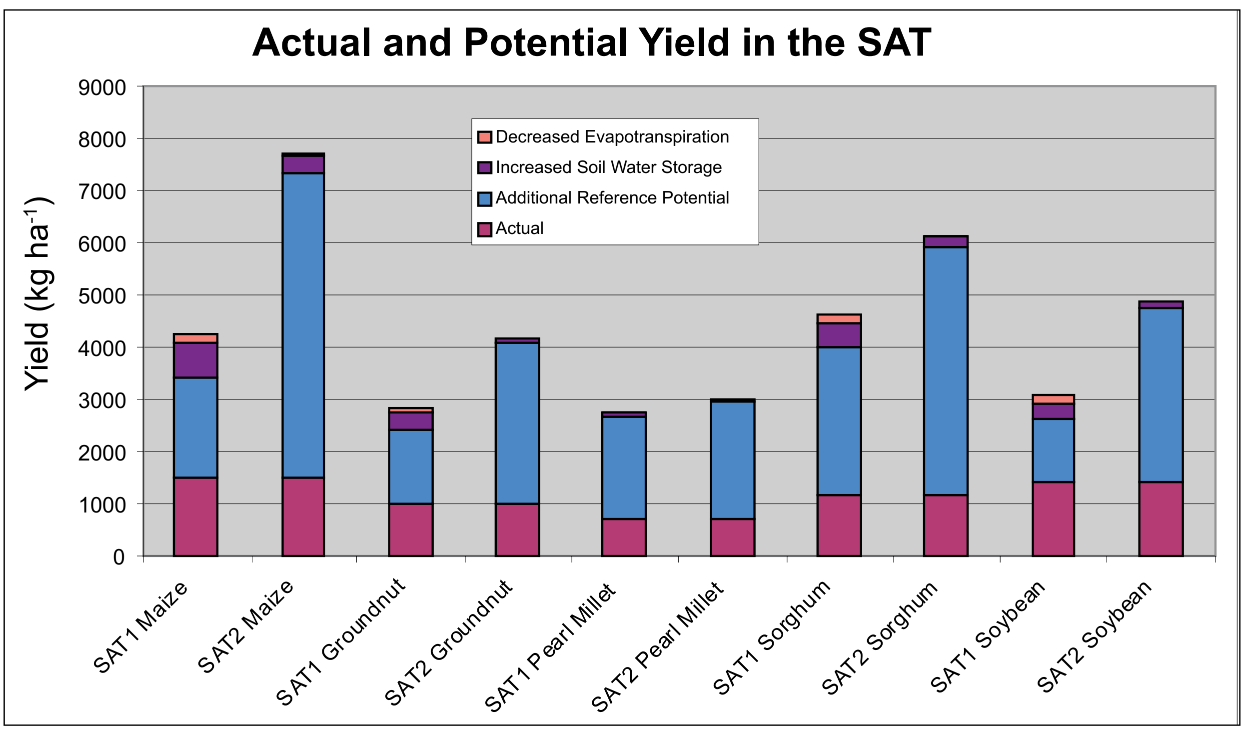

Figure 8. Comparison of actual yield from national-level statistics and calculated potential yield under high inputs, including potential yield increases from management of soil moisture and evapotranspiration.

Both Table 6 and in Figure 8 show that very large gains can potentially be made to yields in the SAT. In all cases, if high inputs and dryland management techniques are applied to the rain-fed lands, yields can be more than doubled. At the upper extreme, in the case of wheat and sorghum, yields can potentially be improved to the point that they are more than five times the current average national yields produced in purely rain-fed areas.

Figure 9 shows the yield gaps for the case-study crops and countries. In some cases, primarily in South Africa and Vietnam, statistics were not available for yields on only rain-fed land.

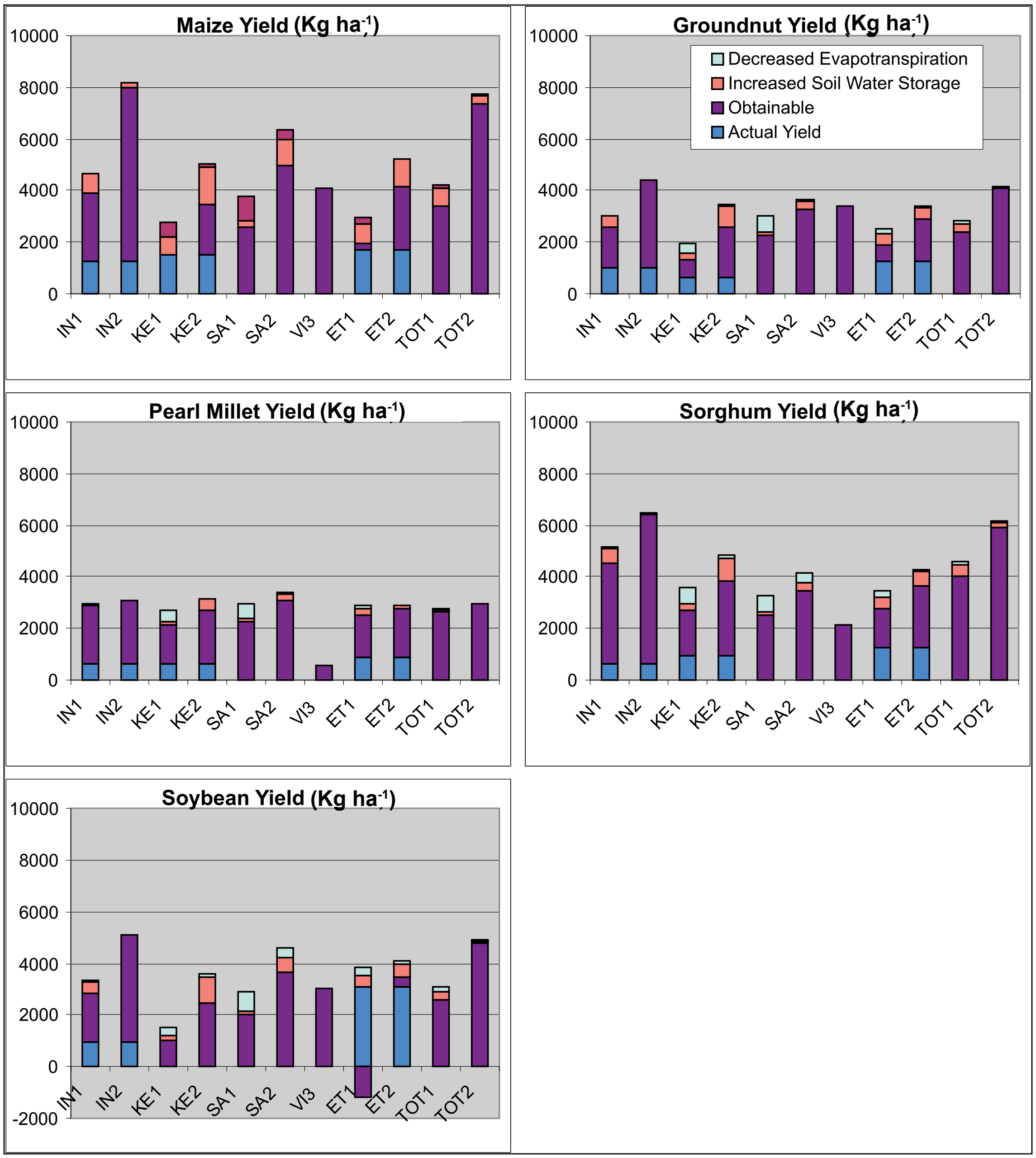

Figure 9. country specific impact of soil moisture management techniques on potential yield in the semi-arid tropics as calculated by AEZ.

Discussion

In this report, yield gaps have been assessed in the semi-arid tropics by first calculating the attainable yield under high levels of input and advanced management and by comparing these calculated pseudo-maximum average yields to the average rain-fed yields recorded in countries in the SAT. Furthermore, a methodology was developed for estimating possible improvements to the attainable yield through the use of water harvesting and other soil water management techniques. This methodology was then applied to the modeling of attainable yields to assess the improvement these dryland management techniques might have on average yield above the already modeled yields attainable under advanced management and high input levels.

Modeled attainable yields for maize, groundnut, pearl millet, sorghum, and soybean were presented in Table 2 and Figure 4, which show them to reach 3.4, 2.4, 2.7, 4.0, and 2.6 t ha^{-1} on average over the region here called the dry semi-arid tropics with growing periods of between 75-120 days, respectively. In the moist semi-arid tropics, with growing periods between 120-180 days, the modeled yields reach 7.3, 4.1, 3.0, 5.9, and 4.8 t ha^{-1}. Because the modeling results in this case assume advanced management and high input levels, these modeled yields reach or exceed average rain-fed yields found in industrialized nations with advanced agricultural systems. Due to differing climatic and bio-physical conditions in different regions of the SAT, modeled attainable yields differ considerably among the SAT areas within the case-study countries. Attainable maize yields in the SAT vary from 1.5 t ha^{-1} in the dSAT in Kenya to 8.0 in the mSAT in India, for instance, while attainable millet yields were calculated to be only 0.6 t ha^{-1} in Vietnam vs. 3.1 in South Africa. In both cases, attainable yields differ by a factor of 5 or more among our few case study countries.

As the name implies, the semi-arid tropics are not water rich. Because water is a major limiting factor in crop production in the SAT, a variety of techniques have been developed and practiced in places over thousands of years to improve infiltration and water retention in the soil, limit evaporation and thereby improve yields. Adjustments have been made to AEZ to model the impact of some of these dryland management practices on rain-fed yields. Table and Figure 6 show that the modeled impact of these dryland management techniques on average yields in the dSAT is an increase in yield of about 24% while it is only 5% on average in the mSAT.

The increase in yield with dryland management techniques may seem low, particularly when compared to reports that show yield increases of more than 100% on research fields that practice rainwater harvesting (Wani et.al., 2002, 2009, Oweis et.al., 1999, Tumbo et. al., 2005). However, the increases modeled here are average increases over all the land that is suitable for the crop over an entire region, not a possible increase on an individual farm. The modeled average yield increase is also limited by two other factors in the modeling. One, dryland management and limited water harvesting techniques were modeled as an increase in the soil's moisture holding capacity as well as a reduction in evaporation through management practices, but the model does not account for more advanced water harvesting techniques that start to resemble full irrigation with the possibility of storing water for extended periods of time. This limitation seems reasonable considering that average yields over large areas are being considered and crops are grown by the model in all land capable of producing yield. Some water harvesting practices require additional land area to harvest the water. If this takes some land out of production in some areas, yields on the planted plot may increase and become more reliable, but overall production will increase to only a smaller extent because less land is yielding crops. Furthermore, the most productive techniques may not be possible throughout an entire area so that average yield increases will not approach the yields possible on individual test plots. The second factor limiting the modeled increase in yields is that attainable yields were modeled from the beginning for advanced management and high levels of input. Already, the high levels of input and advanced management partially offset the water scarcity, resulting in quite high yields even before dryland management techniques were applied.

Even with these considerations, though, the modeled average increase in yield due to dryland management techniques, above the already high input attainable yields, was significant at 15% or more on average throughout the entire dSAT for all the case study crops with the exception of millet, which is quite drought resistant. The largest yield increases were in the dry SAT, where any additional water is helpful. The assessment of yield increases in the case study countries showed the largest modeled average yield increase was 80% for maize over the entire dSAT area of Kenya. In general, the African case-study countries, which are in dry regions with large variability, benefited the most from dryland management practices. Similarly, the crops requiring more water such as maize benefited more than crops like millet that are already drought tolerant. In addition to the yield increases, year-to-year variability in attainable yields decreases in all cases, reducing the risk for farmers and providing opportunities for a steadier income stream.

The results of the modeling of yield improvement due to dryland management were split into water harvesting techniques that increase the water stored in the soil by improving capture and infiltration and those which aim to manage the existing soil moisture and reduce evaporation. In most areas, increasing water storage has a larger impact than techniques that reduce evaporation. On average the percentage increase in yield was five times greater for a modeled 50% increase in soil available water content than it was for the evaporation reduction methods. However, in very dry and hot areas with especially high evaporation rates and high climatic variability, controlling evaporation will have the larger impact. Kenya and South Africa are two such areas where minimizing evaporation produces greater yield improvements than simply increasing soil water storage capacity.

Finally, modeled attainable yields were compared to yield statistic from FAO. The results suggest that sizable improvements in yields, up to 5 times current yields, are possible with existing technology through improvements in agricultural management practices and more intensive farming with higher inputs. Dryland management practices further improve these yields. The analysis of yield gaps, though, was somewhat limited by lack of available and consistent statistical data on actual yields in rain-fed areas of the Semi-Arid Tropics. Therefore, a direct comparison of rain-fed yields in these exact regions was not made. Instead, average rain-fed yield data by country from FAO was used to represent actual rain-fed yields in the SAT. An interesting consequence is shown in the case study country results in Figure 9, where the actual yield of soybean is shown to be higher than the attainable yield in the dSAT of Ethiopia. This does not mean they are achieving average yields in the dSAT above the modeled attainable yield. It means only that data was not available on actual rain-fed yields that were specifically in the dSAT areas of Ethiopia for this study, and that the average country-level rain-fed yield of soybean that is shown is higher than what the model estimates is obtainable in the dry SAT areas. Figure 9 also shows that rain-fed-only yield data on all crops were also not available for all countries. The actual yield numbers available do provide a useful estimate for comparison with attainable yield and are enough to understand the situation and draw conclusions, but more detailed data on actual rain-fed yields would of course enable more accurate yield gap analysis. More information will soon become available, since IIASA is currently working on an update of its GAEZ methodology including a global coverage of downscaled yield statistics and a global yield gap analysis.

One significant mounting threat to agriculture worldwide is climate change. An example of potential climate change impacts on yields in the SAT is provided in Appendix III for a time frame around 2025. The results show a mixed picture in which yields improve in some areas with the climate change model and scenario selected and decrease in other areas. Both increasing and decreasing yields are shown on all continents with areas in the SAT. SAT areas within countries in South America, particularly Brazil and Venezuela, and in the southernmost parts of Africa, South Africa, Mozambique, Botswana, and Namibia, suffer the largest declines in attainable yield, while Zimbabwe, Congo, Guinea-Bissau, and Malawi gain the most. In many countries, as in the global SAT as a whole, the potentially obtainable yield doesn't change substantially on average, but regions within the country gain or lose. The impacts of climate change from this example are significant and could be problematic in areas where attainable yields are calculated as declining, particularly if agricultural improvements are not made in these areas. In many cases, the regions where attainable yields are declining are regions with very low attainable yields to begin with, areas that are not very suitable for agriculture now and may not be suitable in the future. However, the declines in attainable yield throughout the SAT are relatively small in comparison to the gains in yield that can potentially be achieved through improvements in farming practices, moving toward higher input levels and advanced management.

In conclusion, this report shows that despite the challenges posed to rain-fed agriculture in the semi-arid tropics, there is vast unmet potential for large yield improvements. With advanced management and high input levels, yields can potentially improve at three to four times current levels. Specialized dryland management practices such as water harvesting and reduction of soil moisture losses can increase yields by an additional 5-15% on average over the entire global SAT, but can do even more in certain regions, such as the 80% improvement in yields calculated for the dSAT of Kenya. These dryland management practices, including water harvesting, also reduce the variability from year to year producing a more reliable yield. So, the potential exists for vast agricultural production improvements in the SAT that can feed the population of the SAT and much more. However, although a detailed analysis of social issues in the SAT is beyond the scope of this study, it is hard to imagine that advanced management techniques and high input levels can be used to meet the agricultural potential until social and political problems that continue in some parts of the SAT are dealt with, including poverty, lack of educational opportunities, lack of political stability and good agricultural institutions.

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Appendix I: Spatial SAT Yield Results

This appendix provides global maps at 5 arc-minute resolution of modeled attainable yields under advanced management practices, the standard deviation and coefficient of variation in these modeled attainable yields over a 40-year period from 1961-2000 and the number of years of successful production (non-failure years) during this period. Maps of yield improvements and improvements in variability due to dryland management practices are also included.

Attainable yields and variability for 90-day lowland maize cultivars

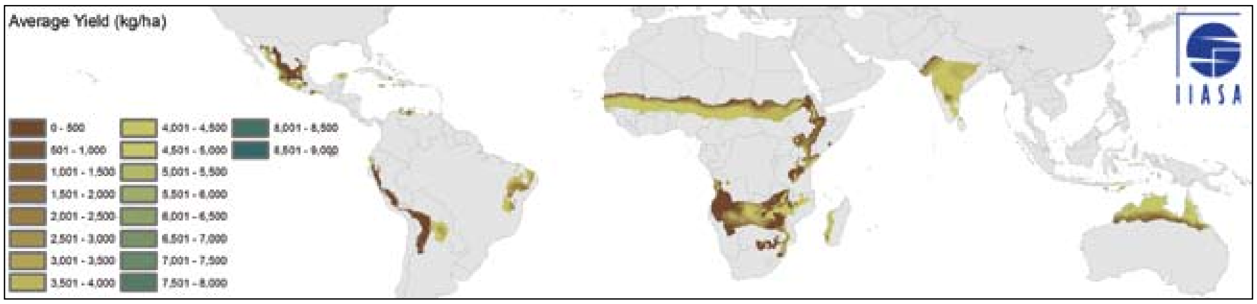

Figure 10. Modeled attainable yield for lowland maize with a 90-day growing period.

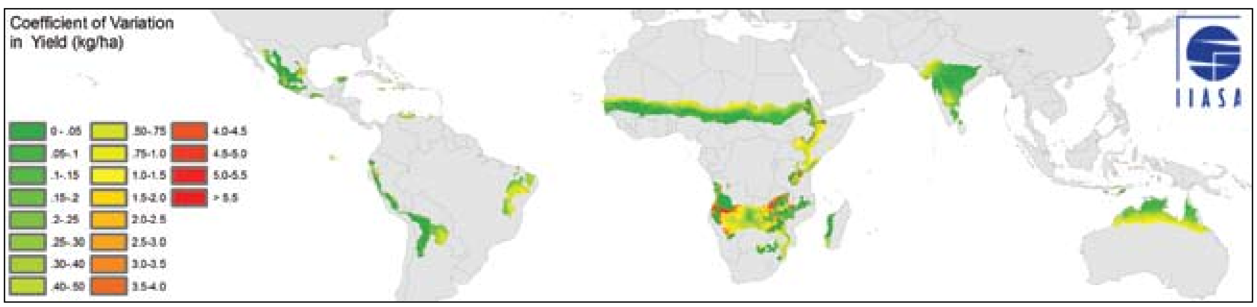

Figure 11. Modeled coefficient of variation in attainable yield for lowland maize with a 90-day growing period.

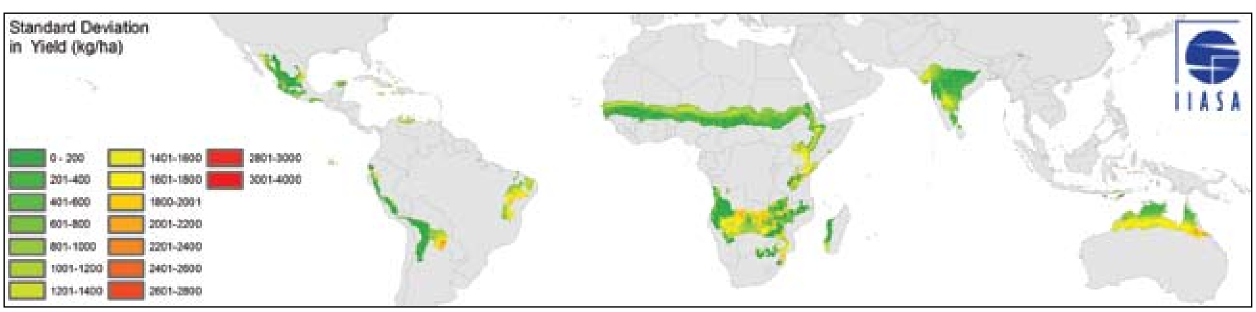

Figure 12. Modeled standard deviation in attainable yield for lowland maize with a 90-day growing period.

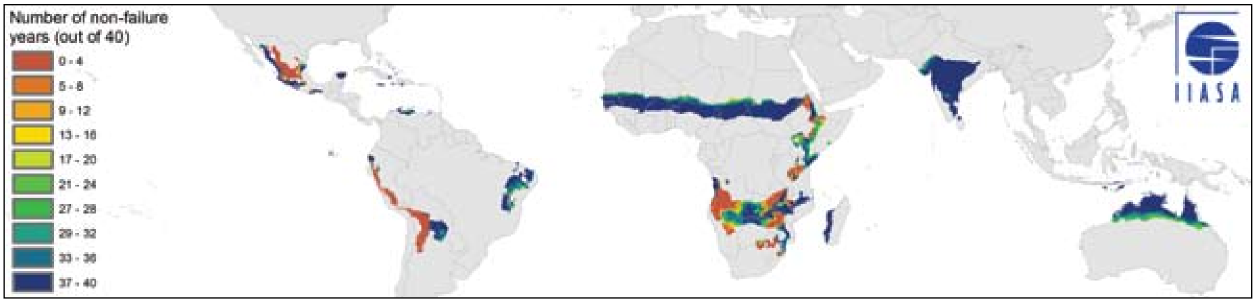

Figure 13. Modeled number of non-failure years of lowland maize with a 90-day growing period.

Changes in attainable yields and variability for 90-day lowland maize cultivars under water harvesting and dryland management practices

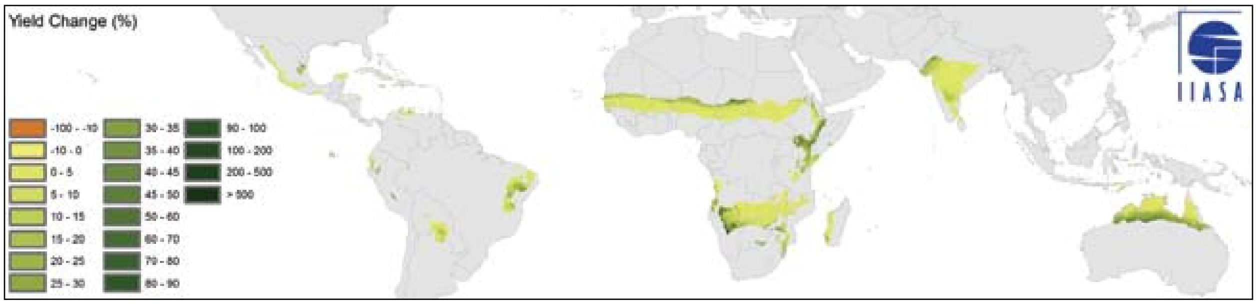

Figure 14. Percentage change in attainable yield for lowland maize with a 90-day growing period when dryland management practices are implemented.

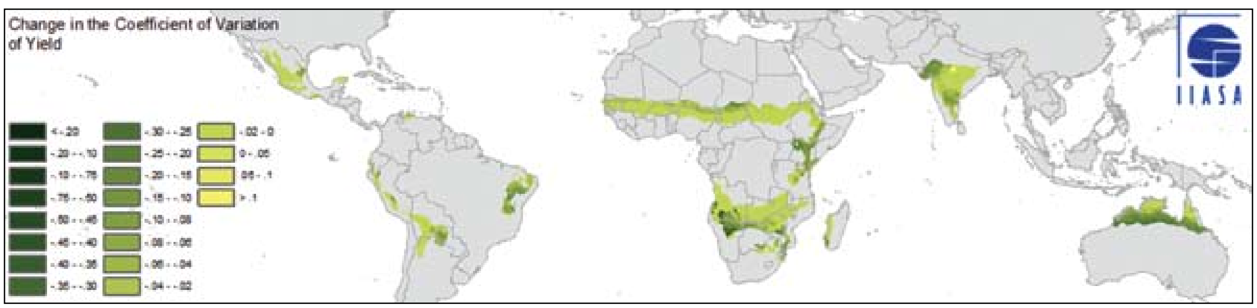

Figure 15. Change in the coefficient of variation of attainable yield for lowland maize with a 90-day growing period when dryland management practices are implemented.

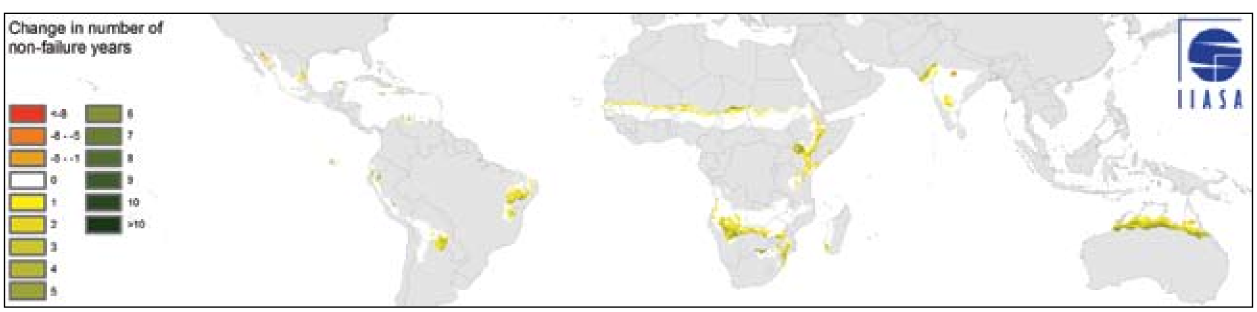

Figure 16. Change in the number of non-failure years of lowland maize with a 90-day growing period when dryland management practices are implemented.

Attainable yields and variability for 105-day lowland maize cultivars

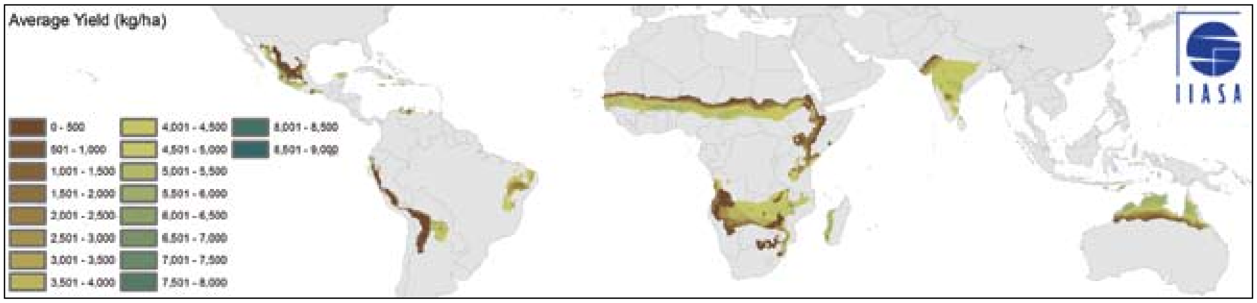

Figure 17. Modeled attainable yield for lowland maize with a 105-day growing period.

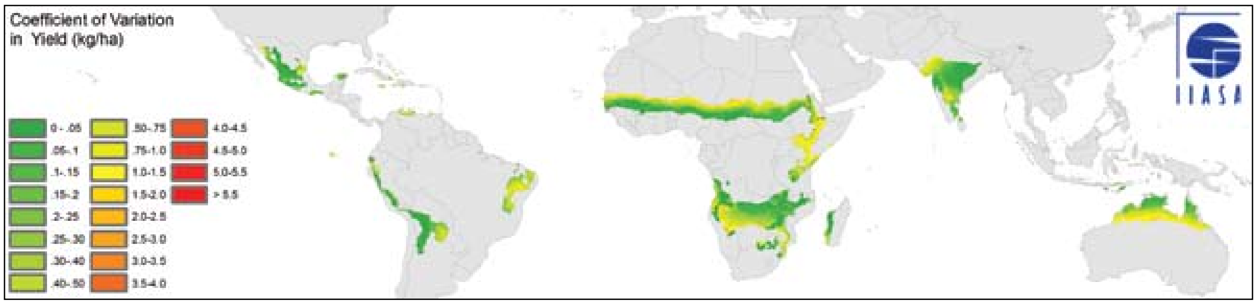

Figure 18. Modeled coefficient of variation in attainable yield for lowland maize with a 105-day growing period.

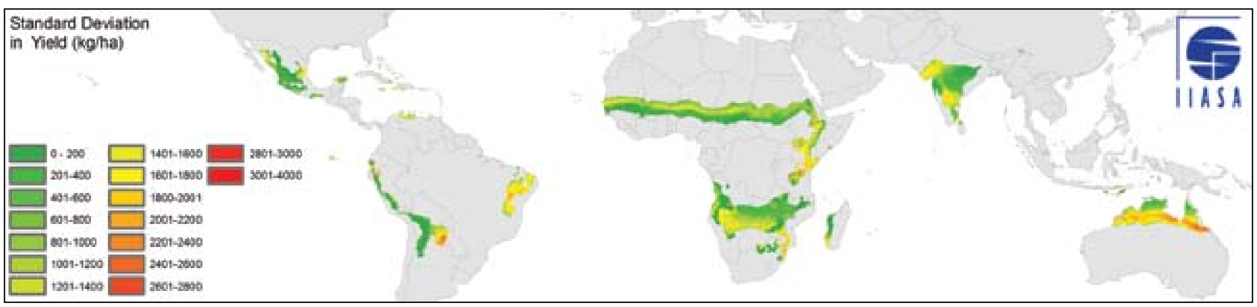

Figure 19. Modeled standard deviation in attainable yield for lowland maize with a 105-day growing period.

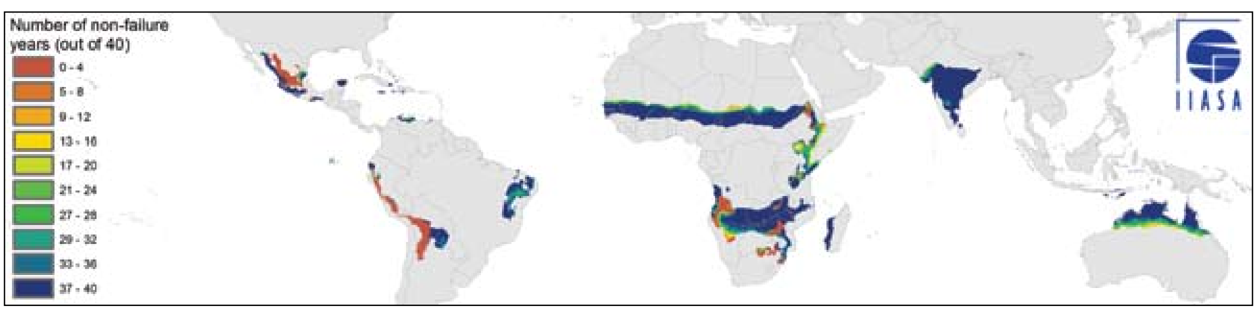

Figure 20. Modeled number of non-failure years of lowland maize with a 105-day growing period.

Changes in attainable yields and variability for 105-day lowland maize cultivars under water harvesting and dryland management practices

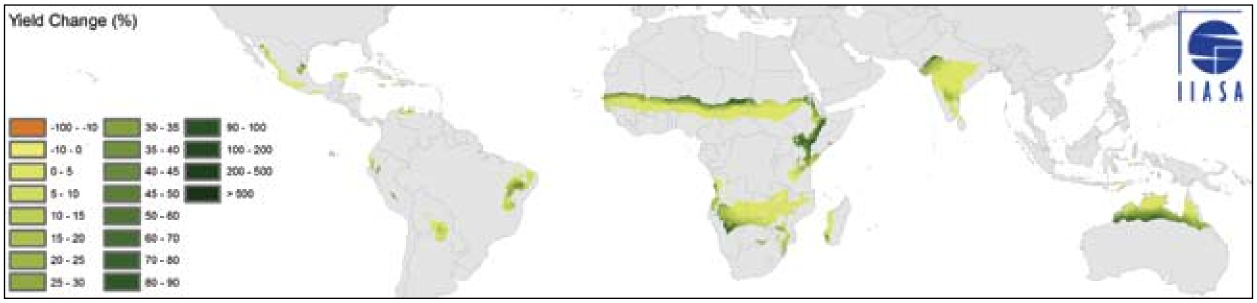

Figure 21. Percentage change in attainable yield for lowland maize with a 105-day growing period when dryland management practices are implemented.

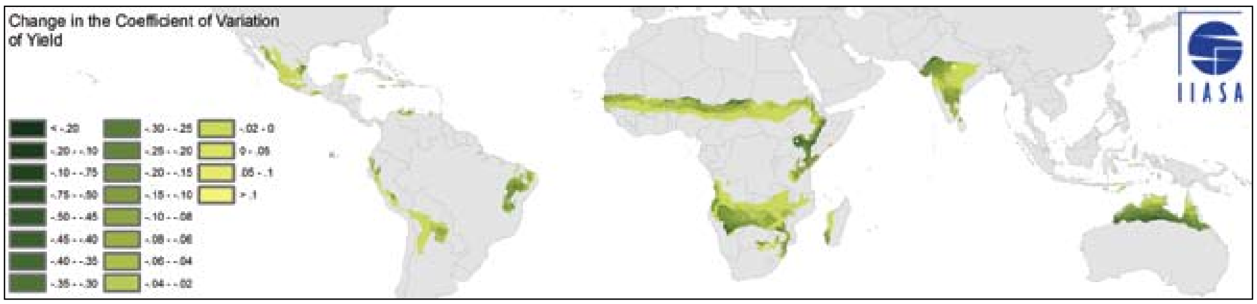

Figure 22. Change in the coefficient of variation of attainable yield for lowland maize with a 105-day growing period when dryland management practices are implemented.

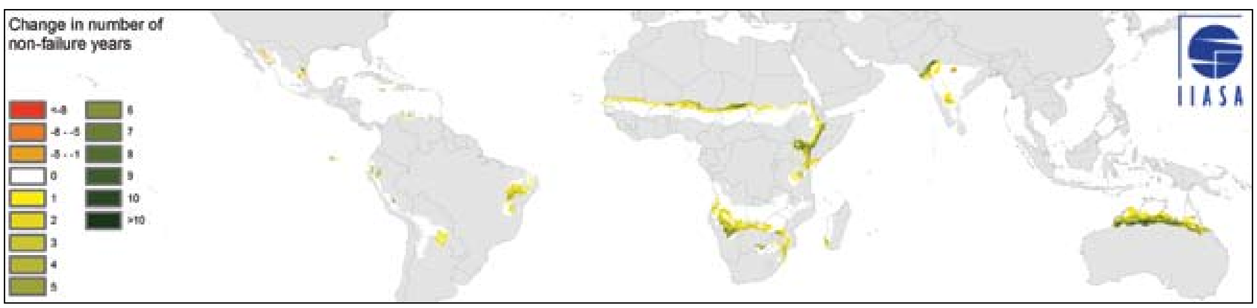

Figure 23. Change in the number of non-failure years of lowland maize with a 105-day growing period when dryland management practices are implemented.

Attainable yields and variability for 120-day lowland maize cultivars

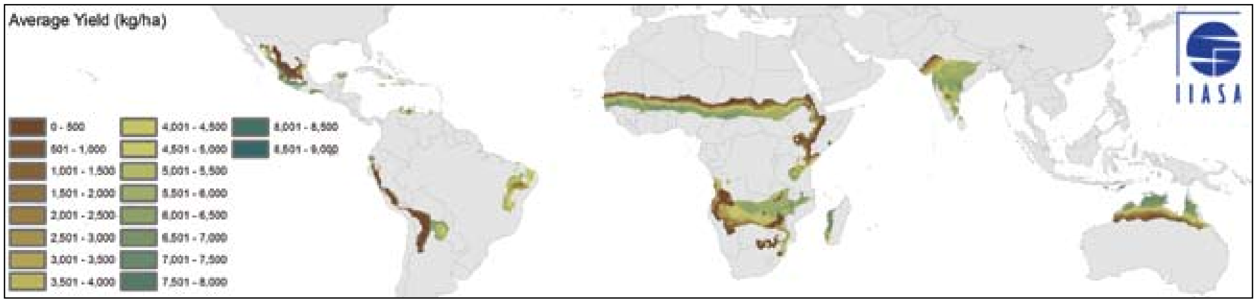

Figure 24. Modeled attainable yield for lowland maize with a 120-day growing period.

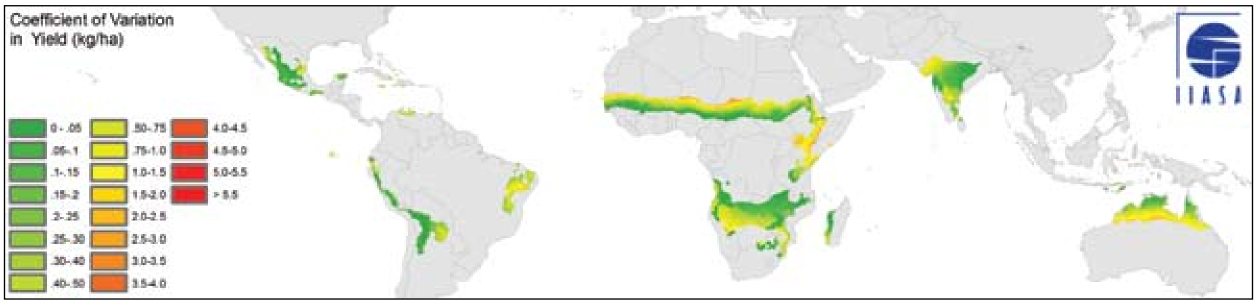

Figure 25. Modeled coefficient of variation in attainable yield for lowland maize with a 120-day growing period.

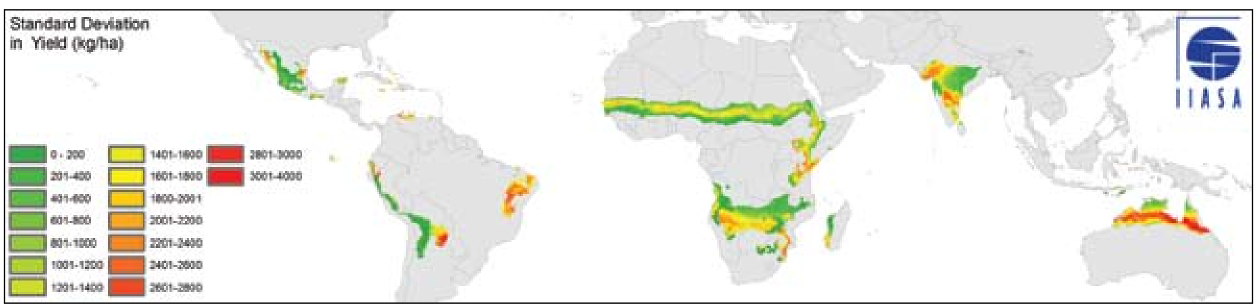

Figure 26. Modeled standard deviation in attainable yield for lowland maize with a 120-day growing period.

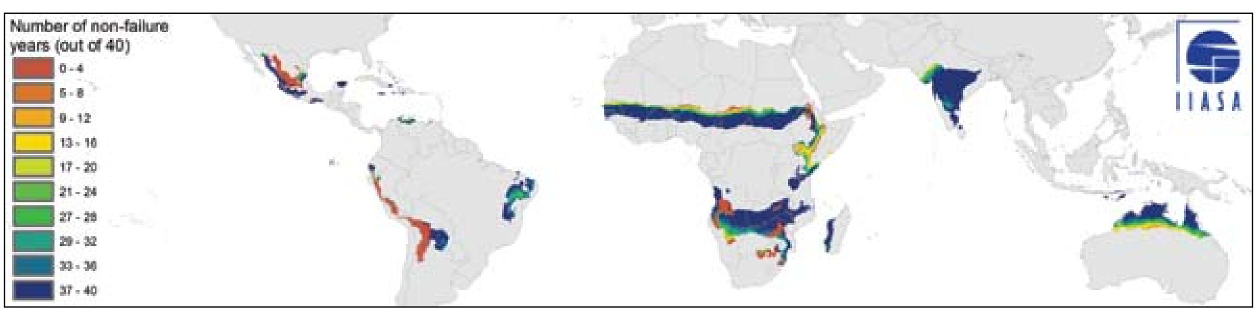

Figure 27. Modeled number of non-failure years of lowland maize with a 120-day growing period.

Changes in attainable yields and variability for 120-day lowland maize cultivars under water harvesting and dryland management practices

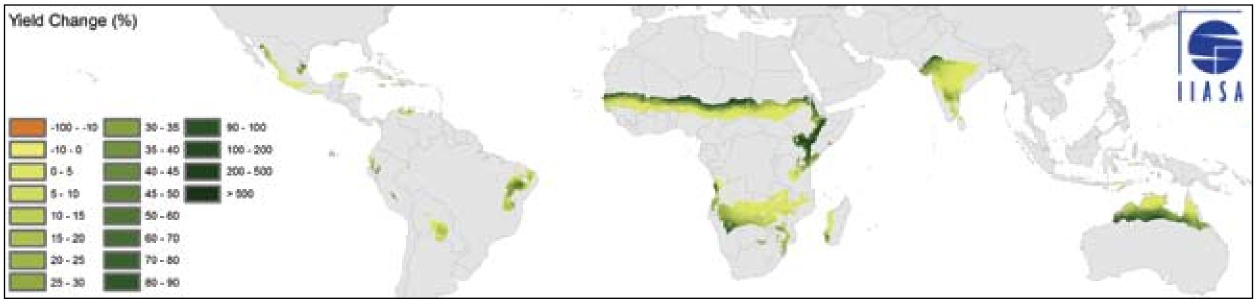

Figure 28. Percentage change in attainable yield for lowland maize with a 120-day growing period when dryland management practices are implemented.

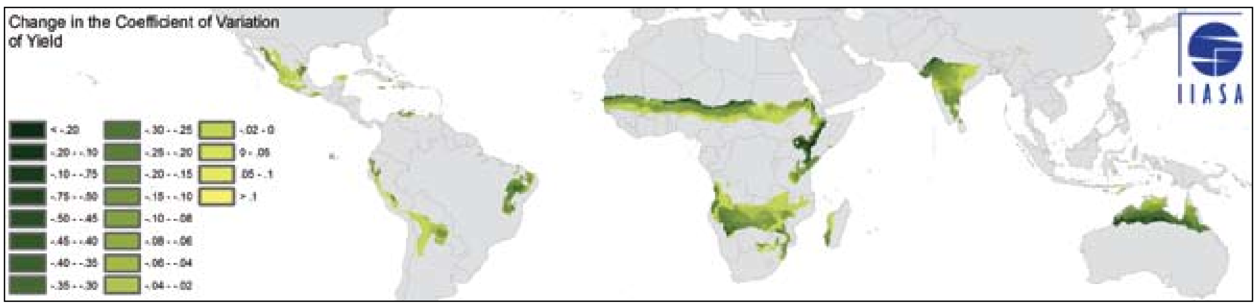

Figure 29. Change in the coefficient of variation of attainable yield for lowland maize with a 120-day growing period when dryland management practices are implemented.

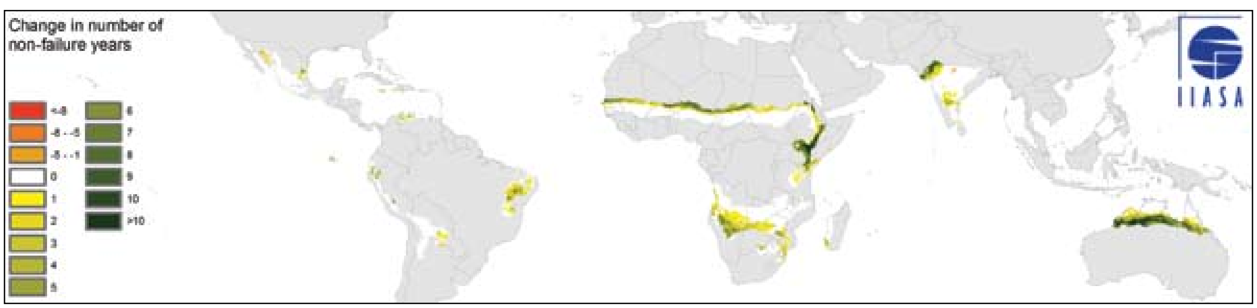

Figure 30. Change in the number of non-failure years of lowland maize with a 120-day growing period when dryland management practices are implemented.

Attainable yields and variability for 135-day lowland maize cultivars

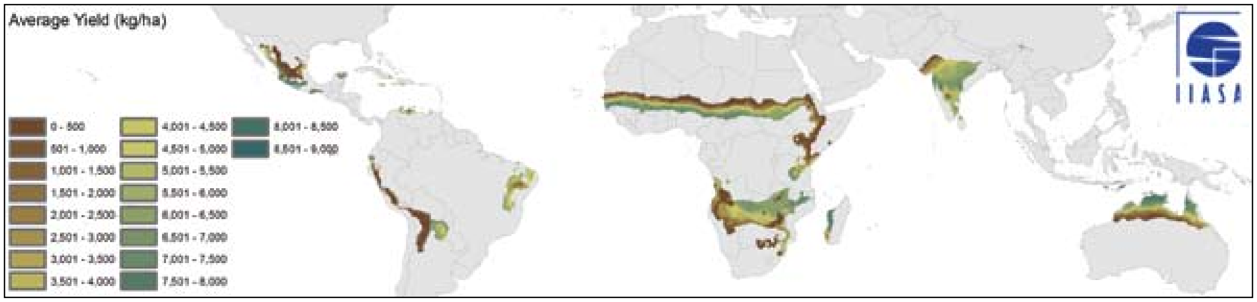

Figure 31. Modeled attainable yield for lowland maize with a 135-day growing period.

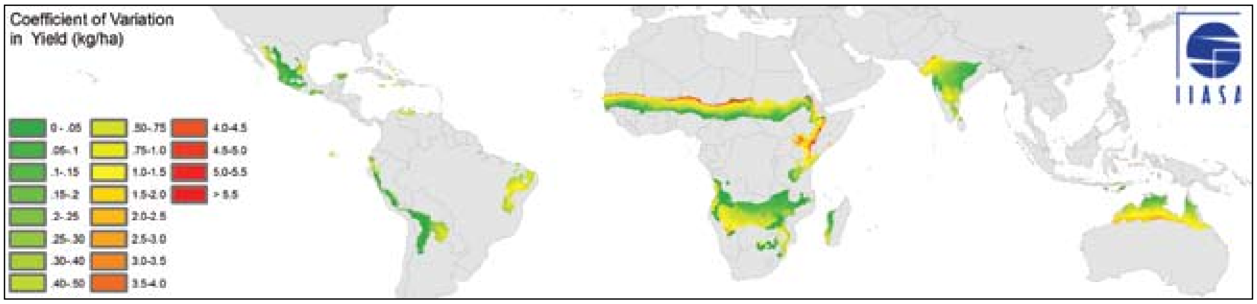

Figure 32. Modeled coefficient of variation in attainable yield for lowland maize with a 135-day growing period.

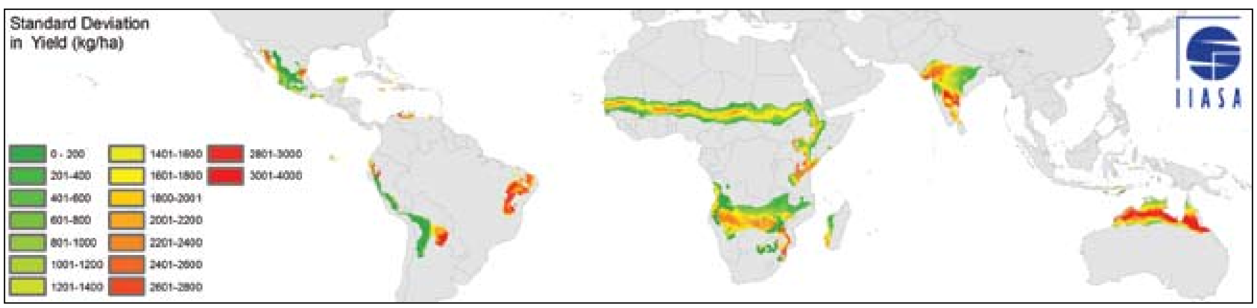

Figure 33. Modeled standard deviation in attainable yield for lowland maize with a 135-day growing period.

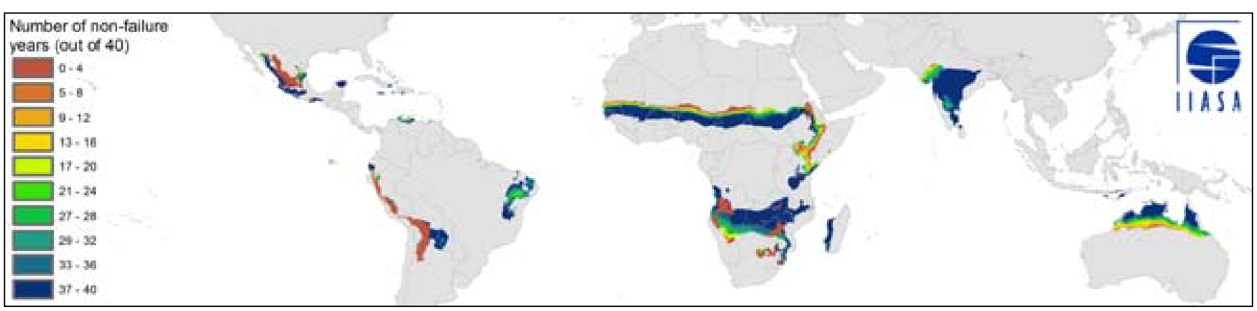

Figure 34. Modeled number of non-failure years of lowland maize with a 135-day growing period.

Changes in attainable yields and variability for 135-day lowland maize cultivars under water harvesting and dryland management practices

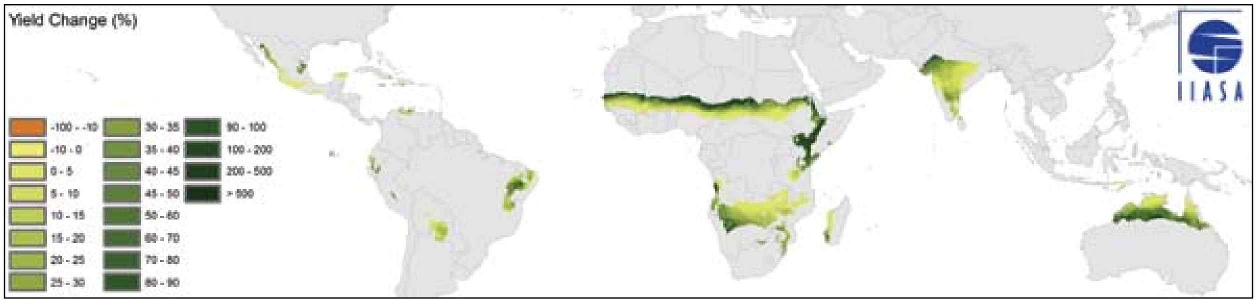

Figure 35. Percentage change in attainable yield for lowland maize with a 135-day growing period when dryland management practices are implemented.

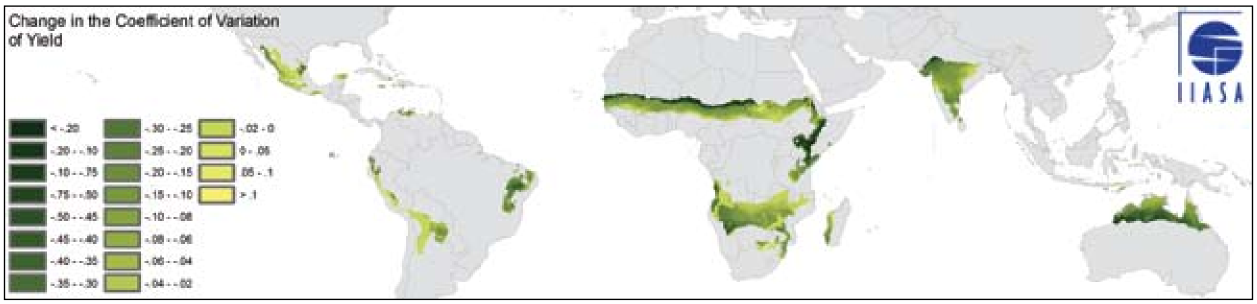

Figure 36. Change in the coefficient of variation of attainable yield for lowland maize with a 135-day growing period when dryland management practices are implemented.

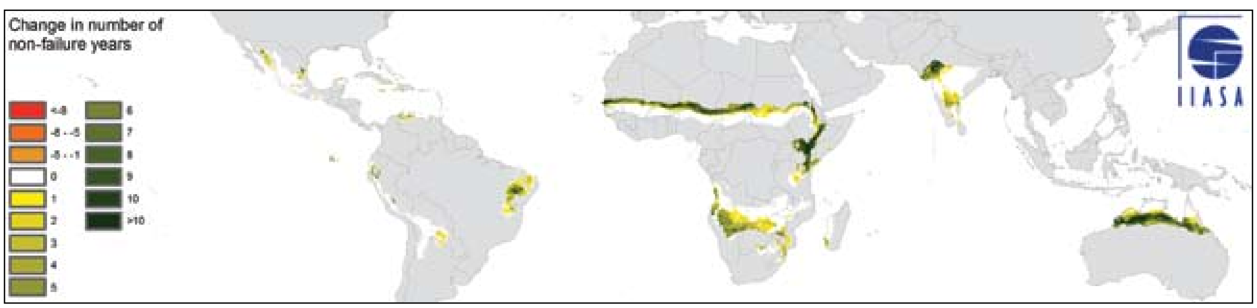

Figure 37. Change in the number of non-failure years of lowland maize with a 135-day growing period when dryland management practices are implemented.

Attainable yields and variability for 90-day lowland sorghum cultivars

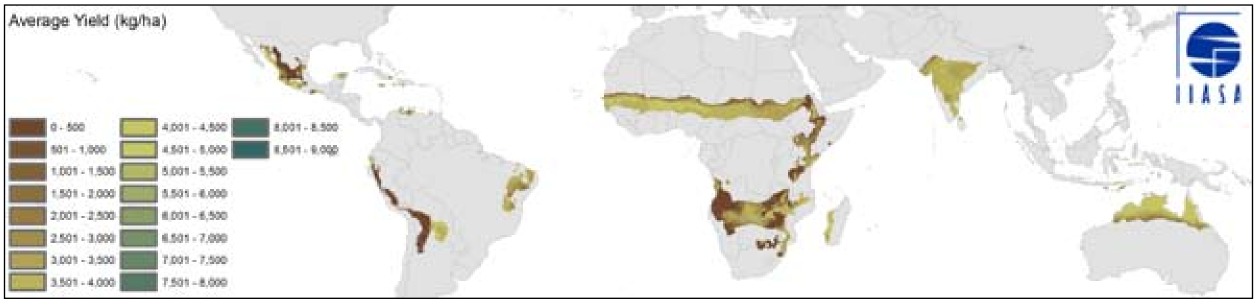

Figure 38. Modeled attainable yield for lowland sorghum with a 90-day growing period.

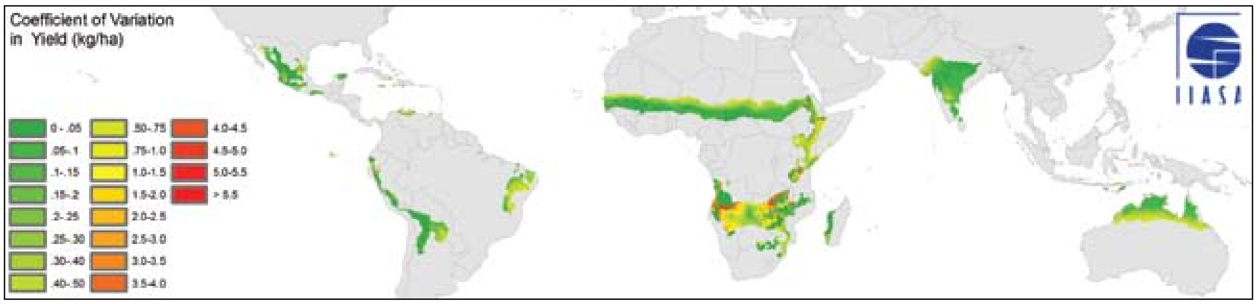

Figure 39. Modeled coefficient of variation in attainable yield for lowland sorghum with a 90-day growing period.

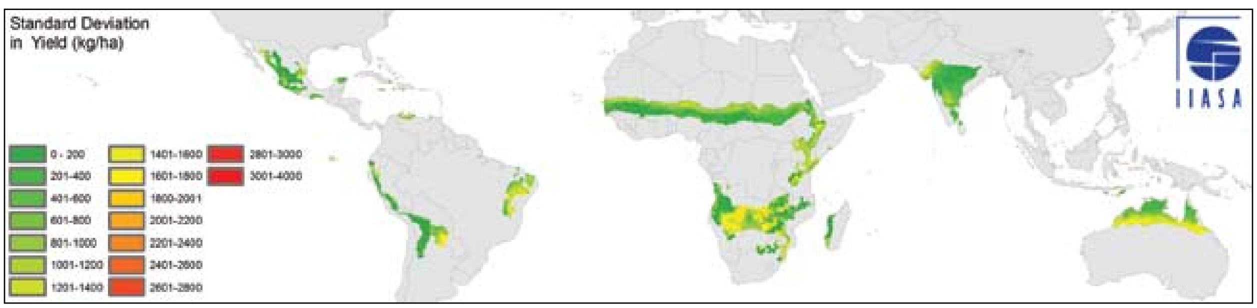

Figure 40. Modeled standard deviation in attainable yield for lowland sorghum with a 90-day growing period.

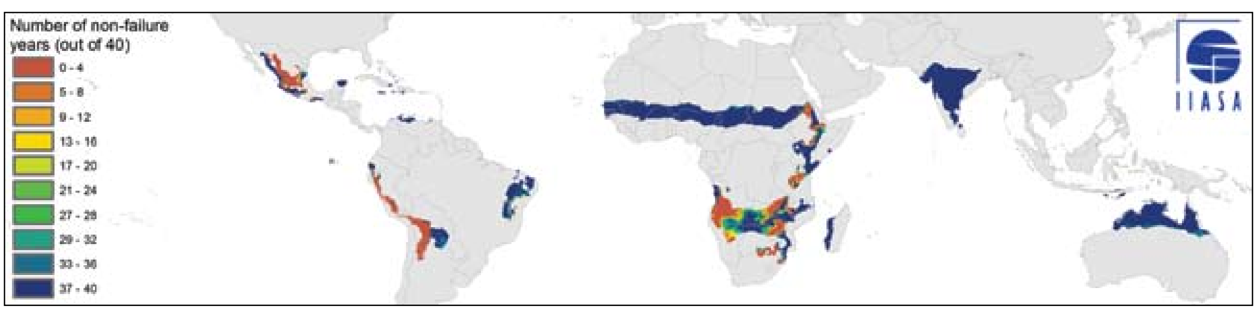

Figure 41. Modeled number of non-failure years of lowland sorghum with a 90-day growing period.

Changes in attainable yields and variability for 90-day lowland sorghum cultivars under water harvesting and dryland management practices

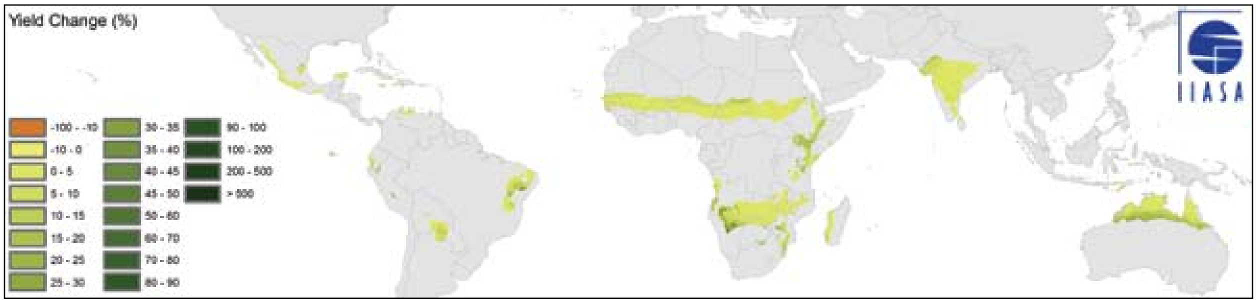

Figure 42. Percentage change in attainable yield for lowland sorghum with a 90-day growing period when dryland management practices are implemented.

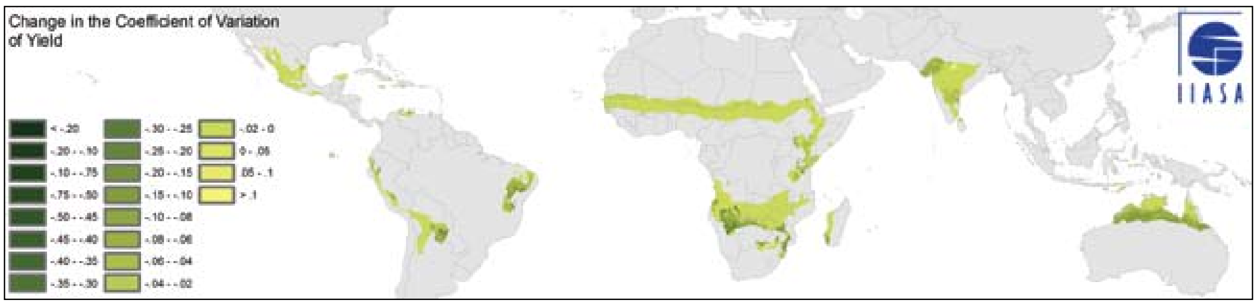

Figure 43. Change in the coefficient of variation of attainable yield for lowland sorghum with a 90-day growing period when dryland management practices are implemented.

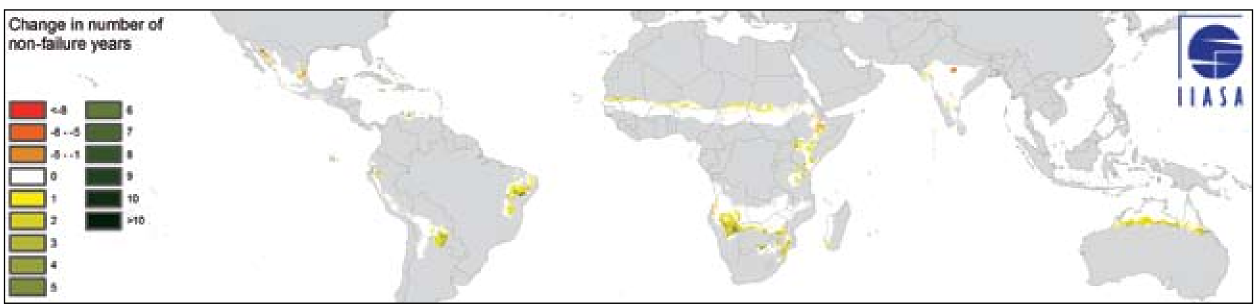

Figure 44. Change in the number of non-failure years of lowland sorghum with a 90-day growing period when dryland management practices are implemented.

Attainable yields and variability for 105-day lowland sorghum cultivars

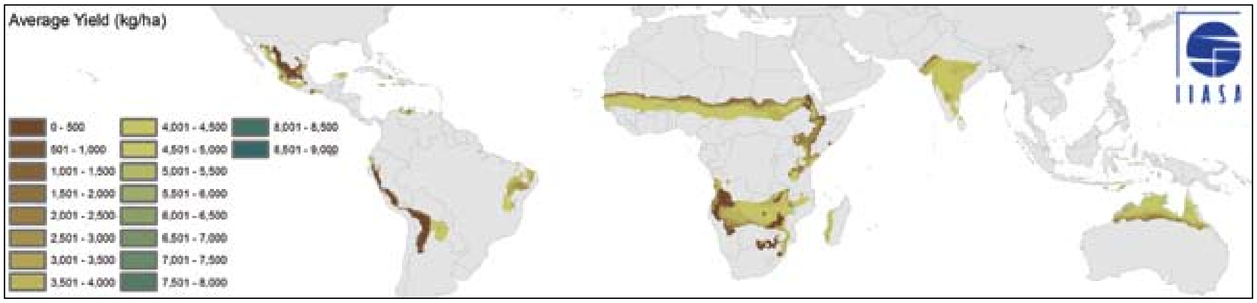

Figure 45. Modeled attainable yield for lowland sorghum with a 105-day growing period.

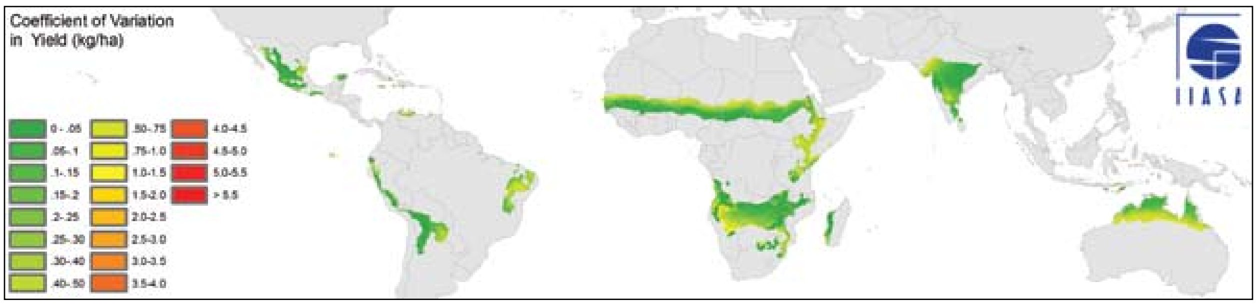

Figure 46. Modeled coefficient of variation in attainable yield for lowland sorghum with a 105-day growing period.

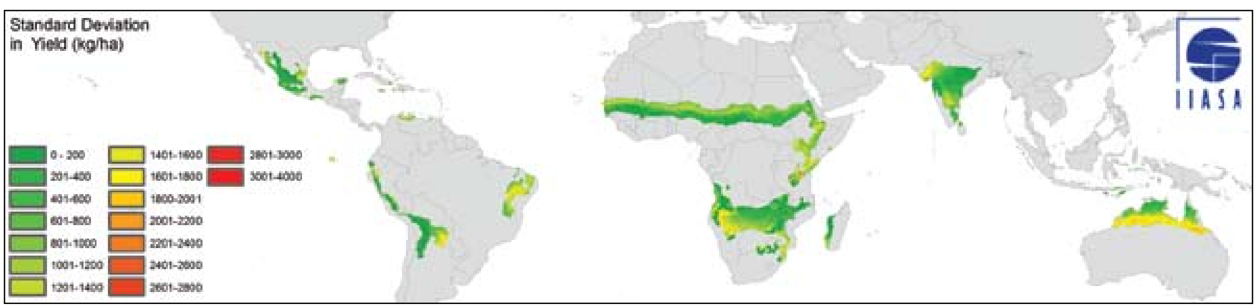

Figure 47. Modeled standard deviation in attainable yield for lowland sorghum with a 105-day growing period.

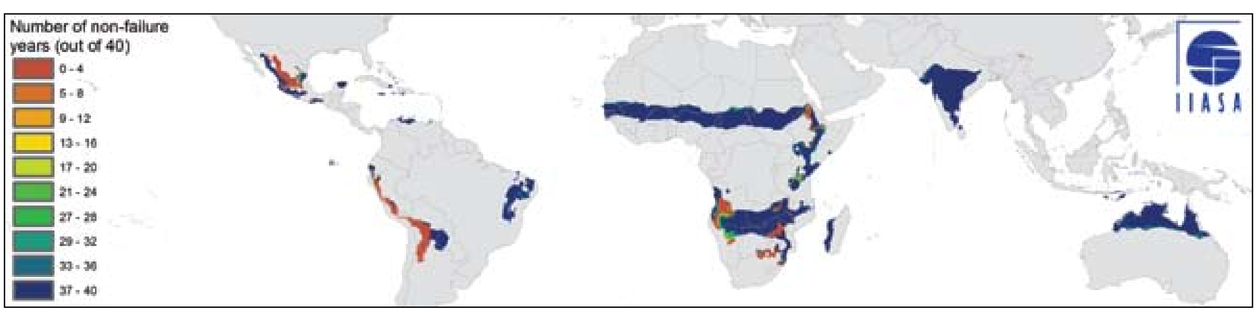

Figure 48. Modeled number of non-failure years of lowland sorghum with a 105-day growing period.

Changes in attainable yields and variability for 105-day lowland sorghum cultivars under water harvesting and dryland management practices

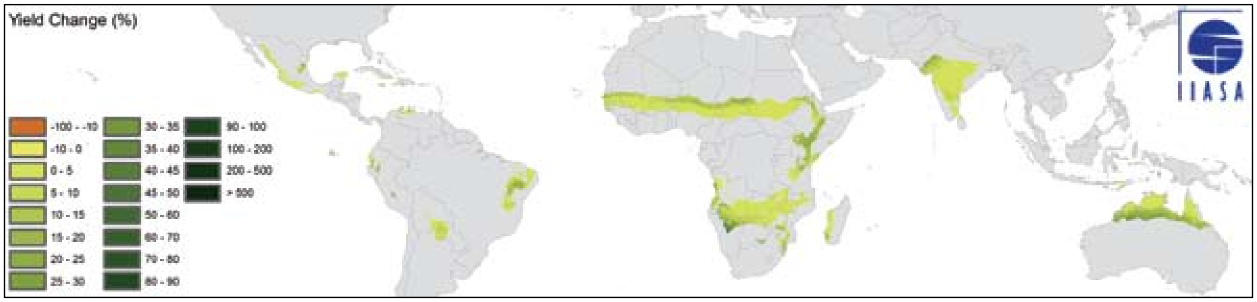

Figure 49. Percentage change in attainable yield for lowland sorghum with a 105-day growing period when dryland management practices are implemented.

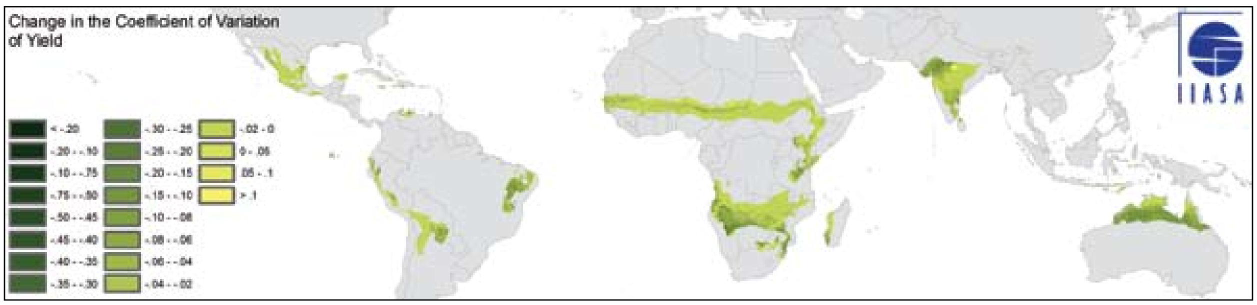

Figure 50. Change in the coefficient of variation of attainable yield for lowland sorghum with a 105-day growing period when dryland management practices are implemented.

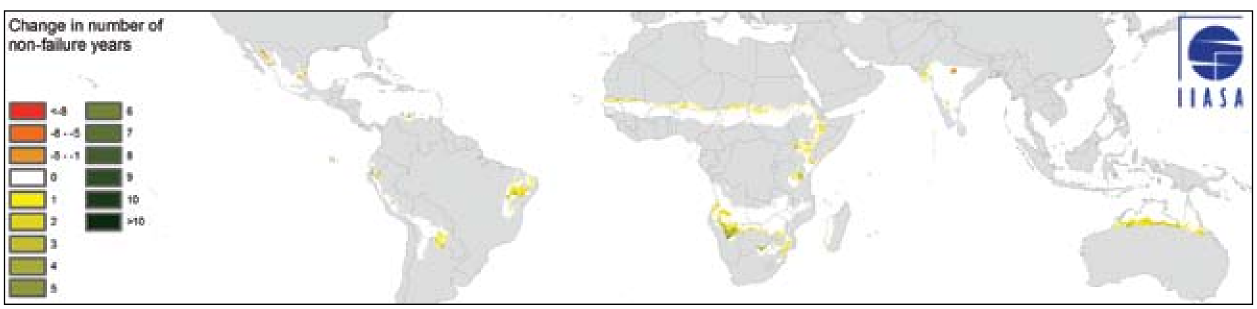

Figure 51. Change in the number of non-failure years of lowland sorghum with a 105-day growing period when dryland management practices are implemented.

Attainable yields and variability for 120-day lowland maize cultivars

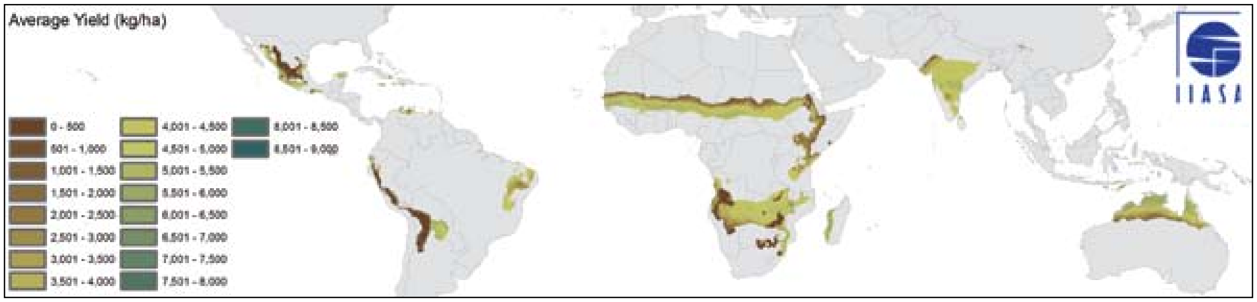

Figure 52. Modeled attainable yield for lowland sorghum with a 120-day growing period.

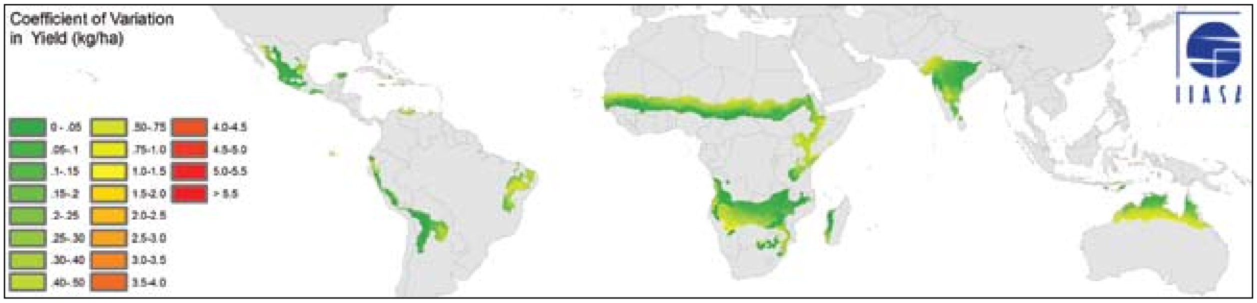

Figure 53. Modeled coefficient of variation in attainable yield for lowland sorghum with a 120-day growing period.

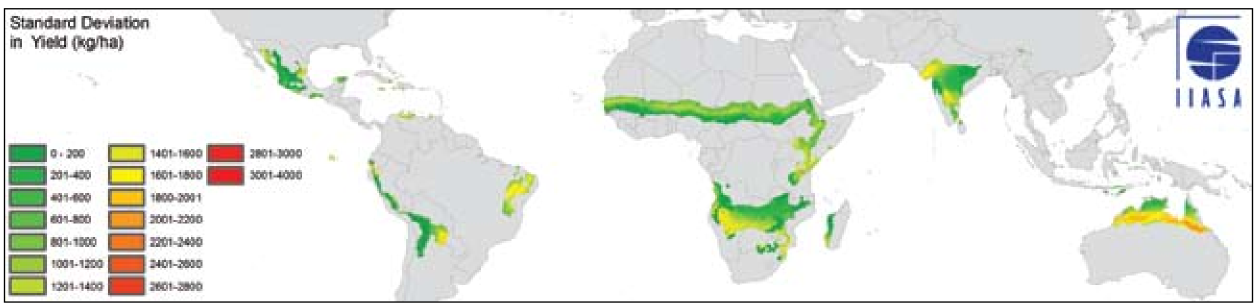

Figure 54. Modeled standard deviation in attainable yield for lowland sorghum with a 120-day growing period.

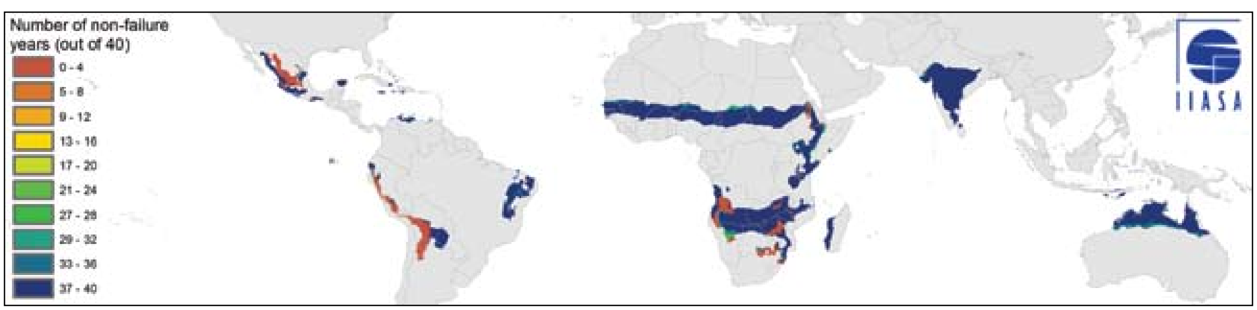

Figure 55. Modeled number of non-failure years of lowland sorghum with a 120-day growing period.

Changes in attainable yields and variability for 120-day lowland sorghum cultivars under water harvesting and dryland management practices

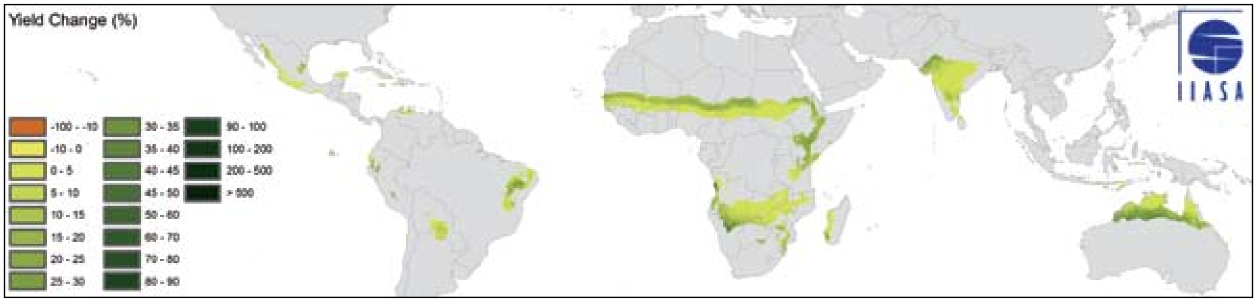

Figure 56. Percentage change in attainable yield for lowland sorghum with a 120-day growing period when dryland management practices are implemented.

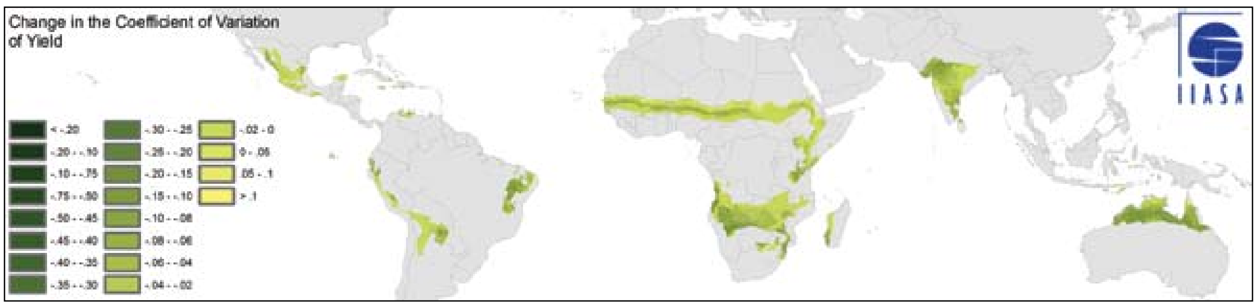

Figure 57. Change in the coefficient of variation of attainable yield for lowland sorghum with a 120-day growing period when dryland management practices are implemented.

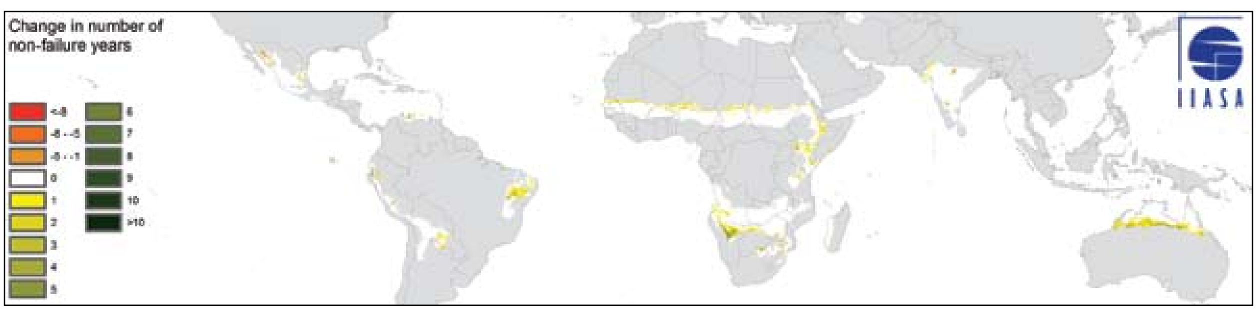

Figure 58. Change in the number of non-failure years of lowland sorghum with a 120-day growing period when dryland management practices are implemented.

Attainable yields and variability for 135-day lowland sorghum cultivars

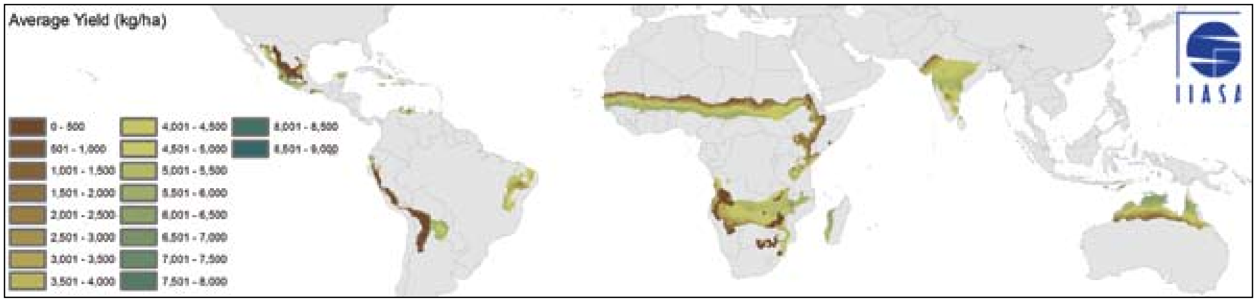

Figure 59. Modeled attainable yield for lowland sorghum with a 135-day growing period.

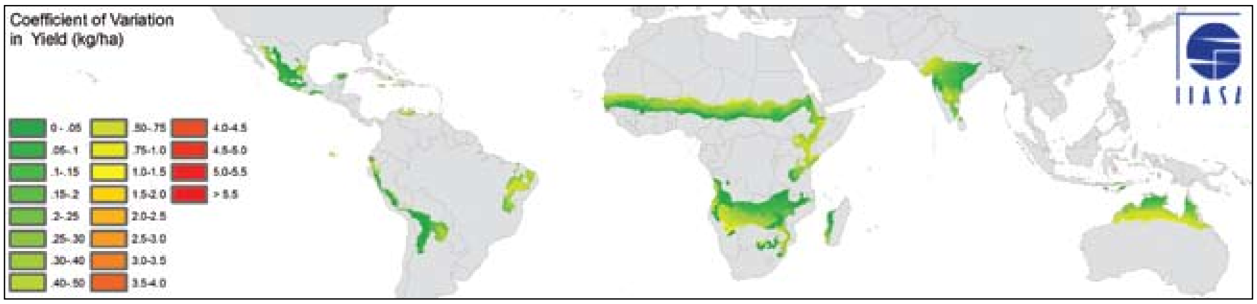

Figure 60. Modeled coefficient of variation in attainable yield for lowland sorghum with a 135-day growing period.

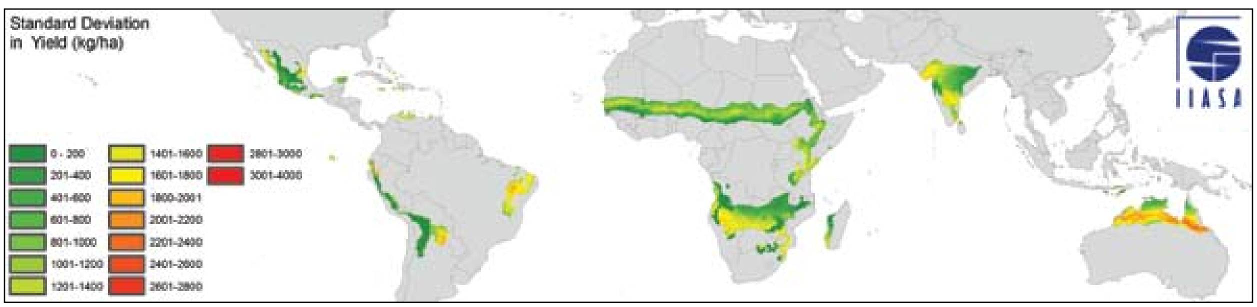

Figure 61. Modeled standard deviation in attainable yield for lowland sorghum with a 135-day growing period.

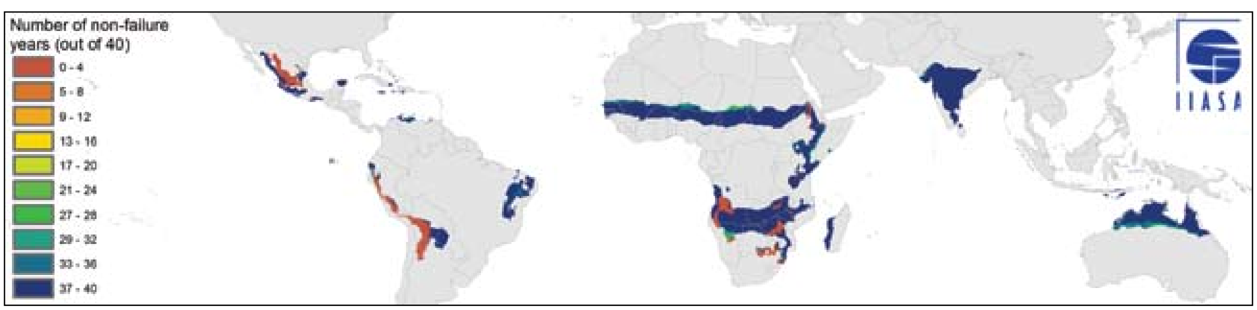

Figure 62. Modeled number of non-failure years of lowland sorghum with a 135-day growing period.

Changes in attainable yields and variability for 135-day lowland sorghum cultivars under water harvesting and dryland management practices

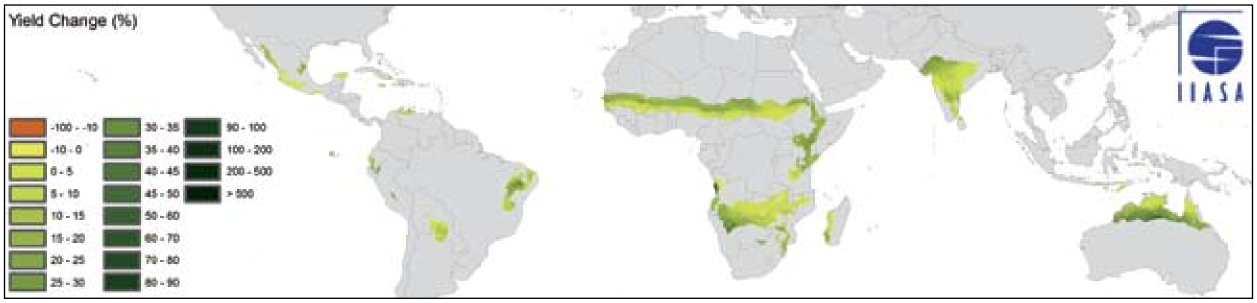

Figure 63. Percentage change in attainable yield for lowland sorghum with a 135-day growing period when dryland management practices are implemented.

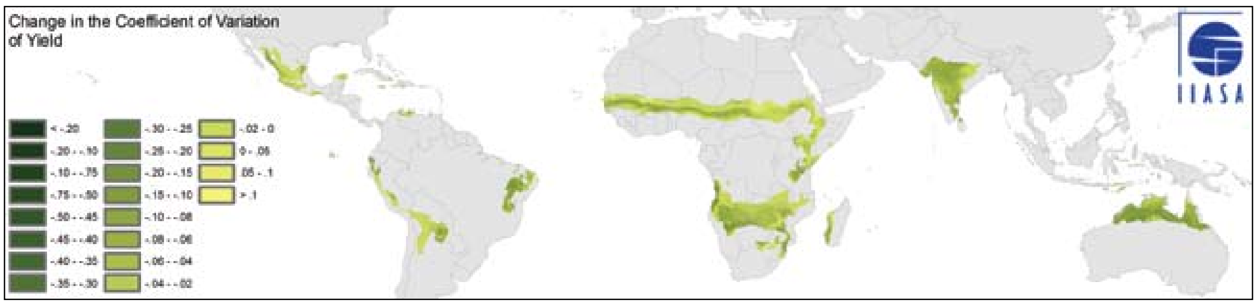

Figure 64. Change in the coefficient of variation of attainable yield for lowland sorghum with a 135-day growing period when dryland management practices are implemented.

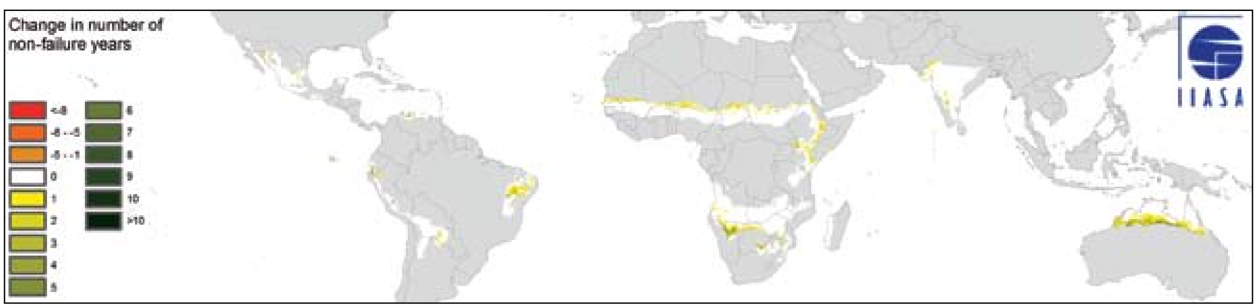

Figure 65. Change in the number of non-failure years of lowland sorghum with a 135-day growing period when dryland management practices are implemented.

Attainable yields and variability for 70-day pearl millet cultivars

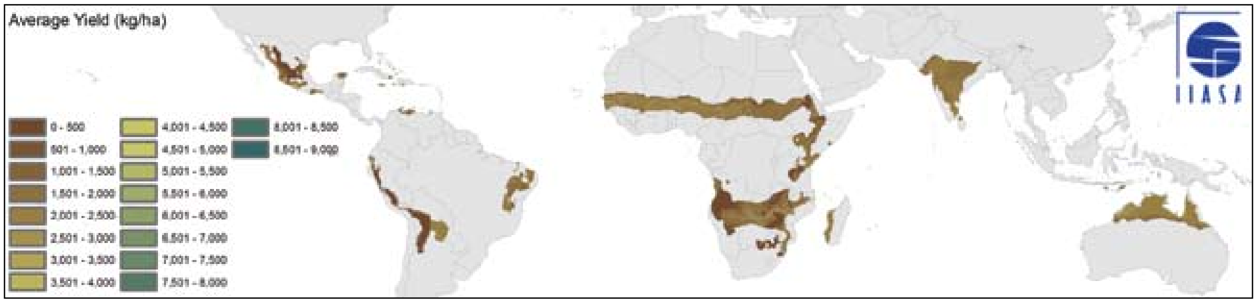

Figure 66. Modeled attainable yield for pearl millet with a 70-day growing period.

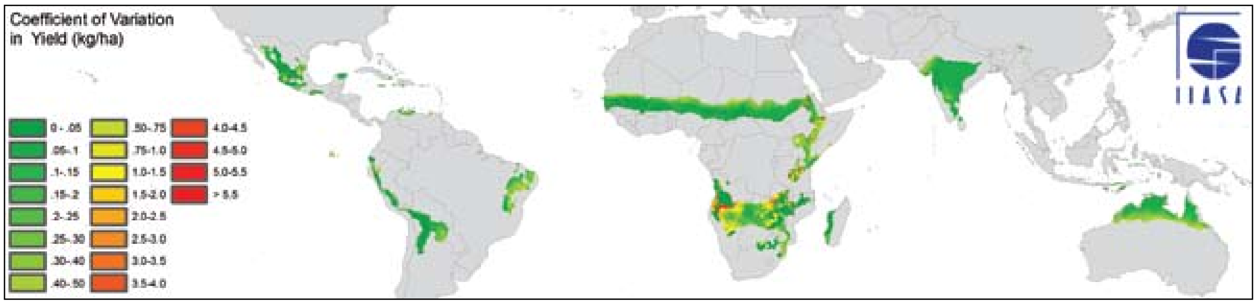

Figure 67. Modeled coefficient of variation in attainable yield for pearl millet with a 70-day growing period.

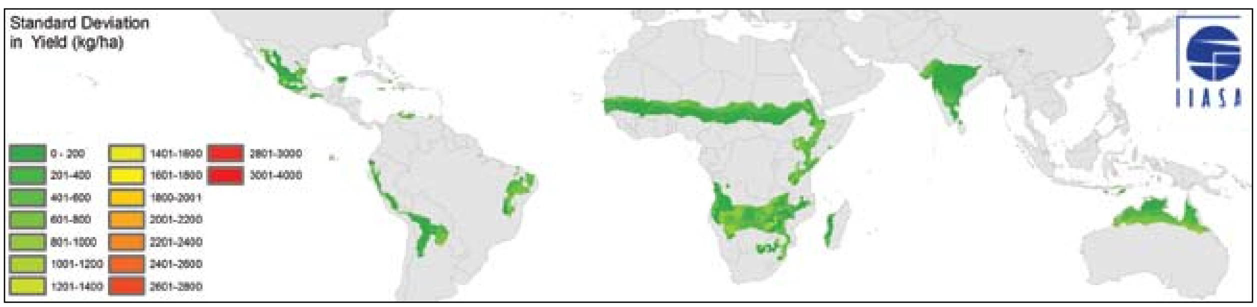

Figure 68. Modeled standard deviation in attainable yield for pearl millet with a 70-day growing period.

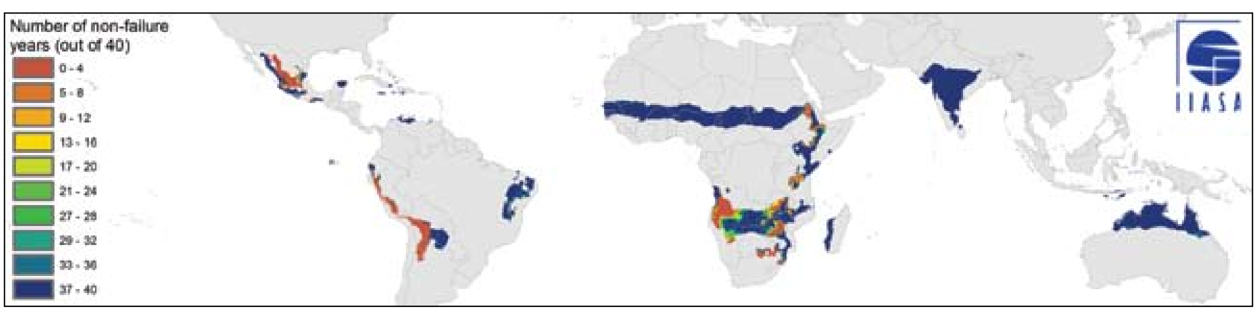

Figure 69. Modeled number of non-failure years of pearl millet with a 70-day growing period.

Changes in attainable yields and variability for 70-day pearl millet cultivars under water harvesting and dryland management practices

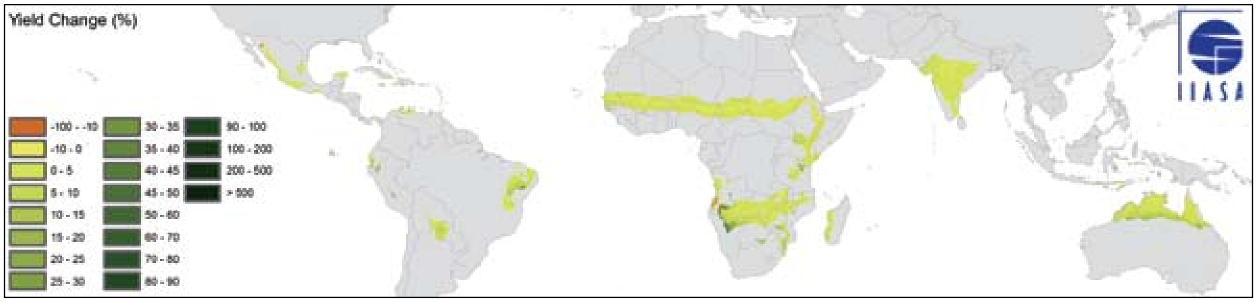

Figure 70. Percentage change in attainable yield for pearl millet with a 70-day growing period when dryland management practices are implemented.

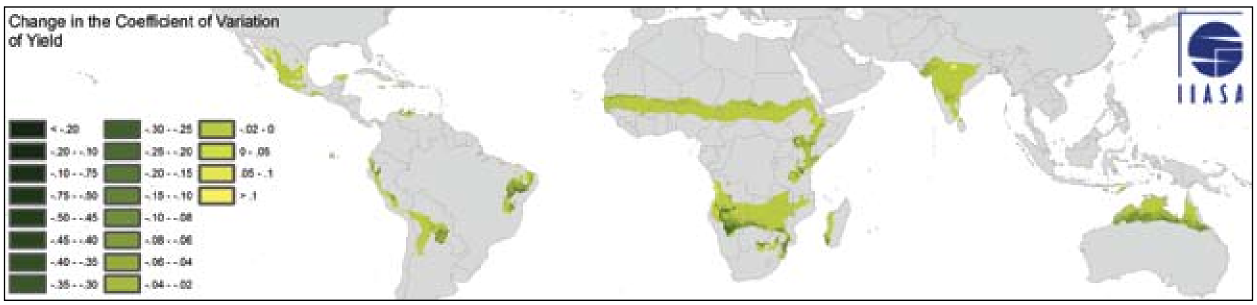

Figure 71. Change in the coefficient of variation of attainable yield for pearl millet with a 70-day growing period when dryland management practices are implemented.

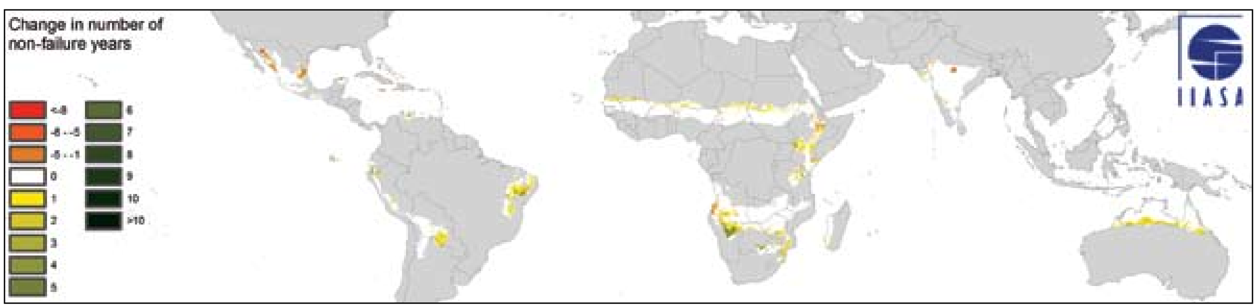

Figure 72. Change in the number of non-failure years of pearl millet with a 70-day growing period when dryland management practices are implemented.

Attainable yields and variability for 90-day pearl millet cultivars

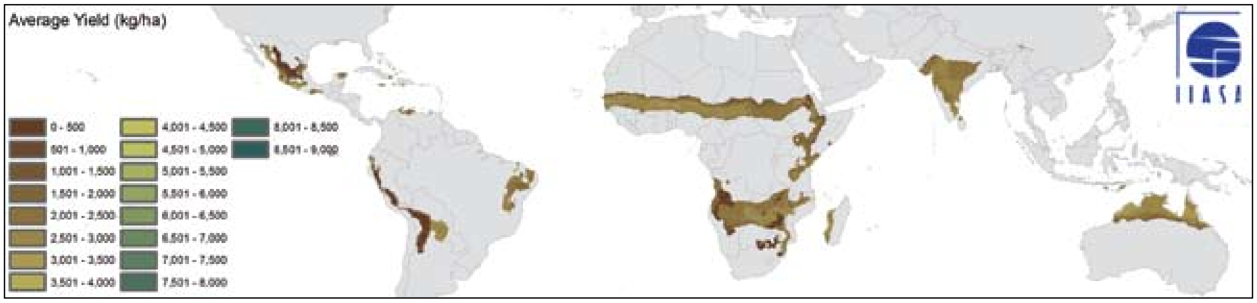

Figure 73. Modeled attainable yield for pearl millet with a 90-day growing period.

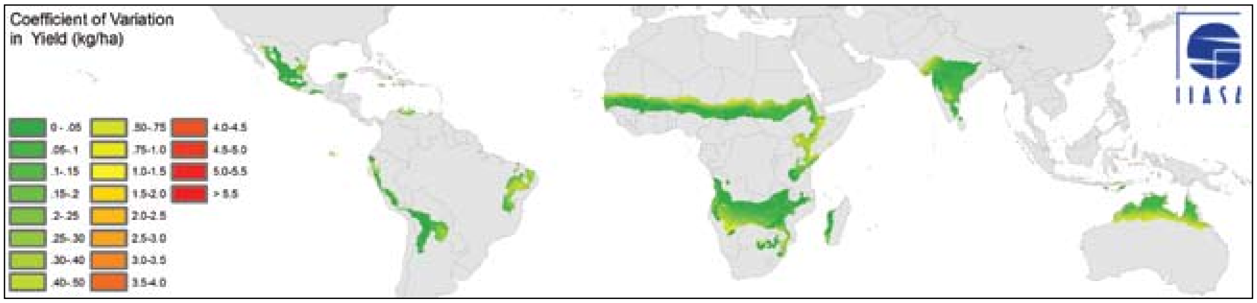

Figure 74. Modeled coefficient of variation in attainable yield for pearl millet with a 90-day growing period.

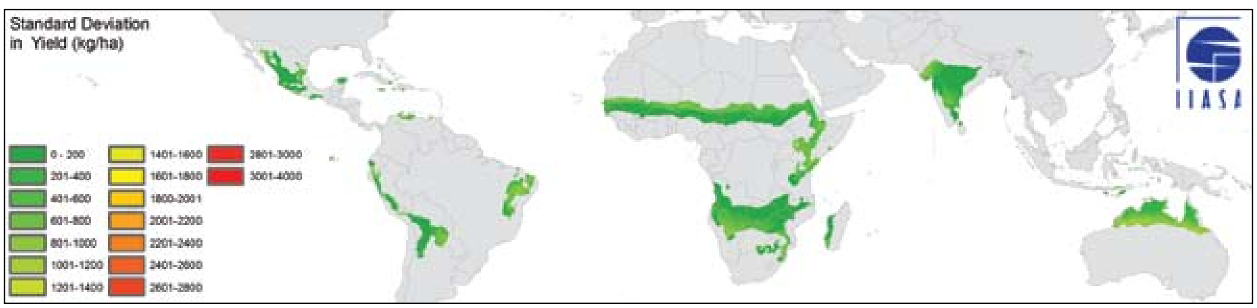

Figure 75. Modeled standard deviation in attainable yield for pearl millet with a 90-day growing period.

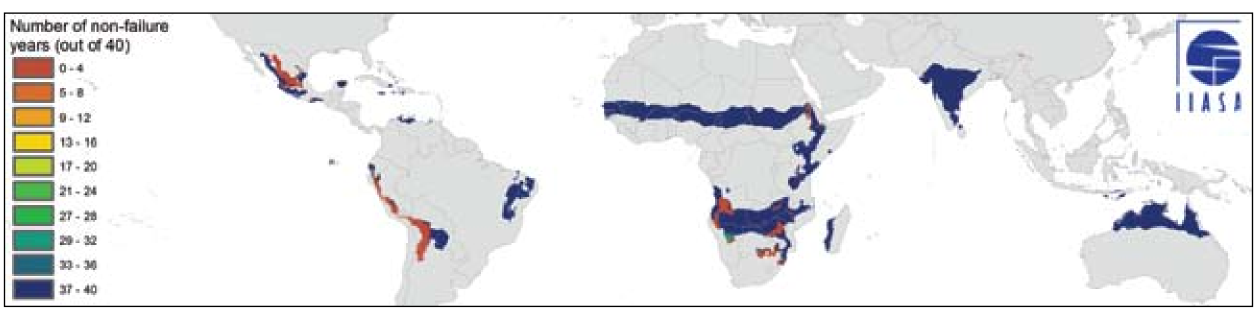

Figure 76. Modeled number of non-failure years of pearl millet with a 90-day growing period.

Changes in attainable yields and variability for 90-day pearl millet cultivars under water harvesting and dryland management practices

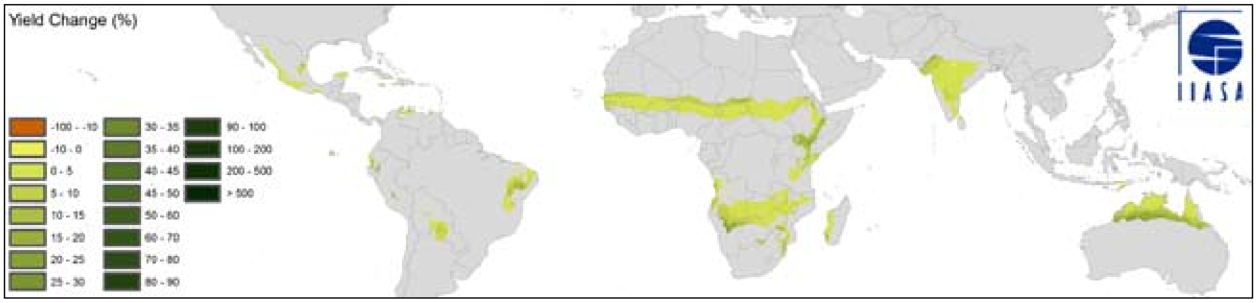

Figure 77. Percentage change in attainable yield for pearl millet with a 90-day growing period when dryland management practices are implemented.

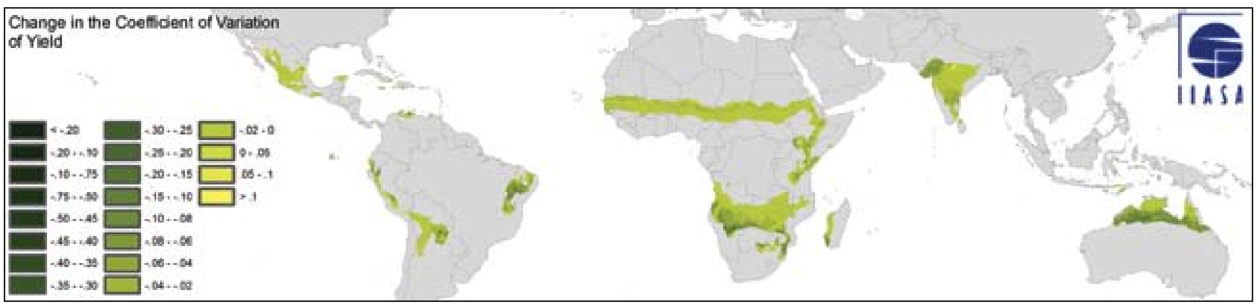

Figure 78. Change in the coefficient of variation of attainable yield for pearl millet with a 90-day growing period when dryland management practices are implemented.

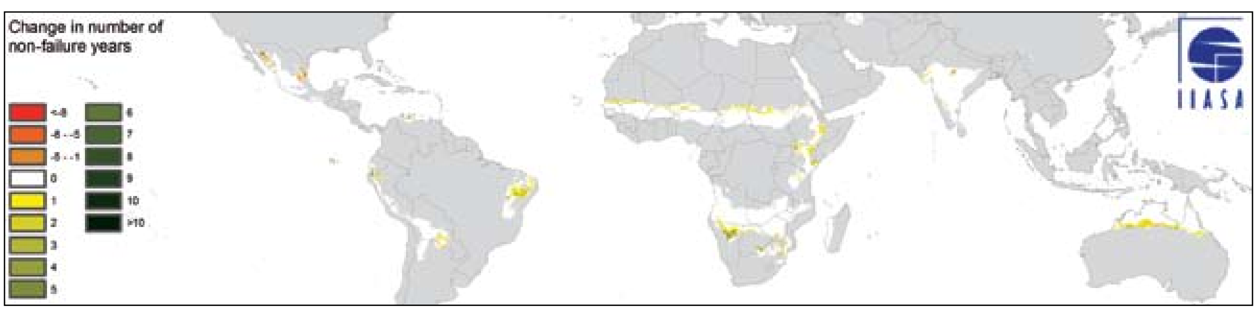

Figure 79. Change in the number of non-failure years of pearl millet with a 90-day growing period when dryland management practices are implemented.

Attainable yields and variability for 90-day groundnut cultivars

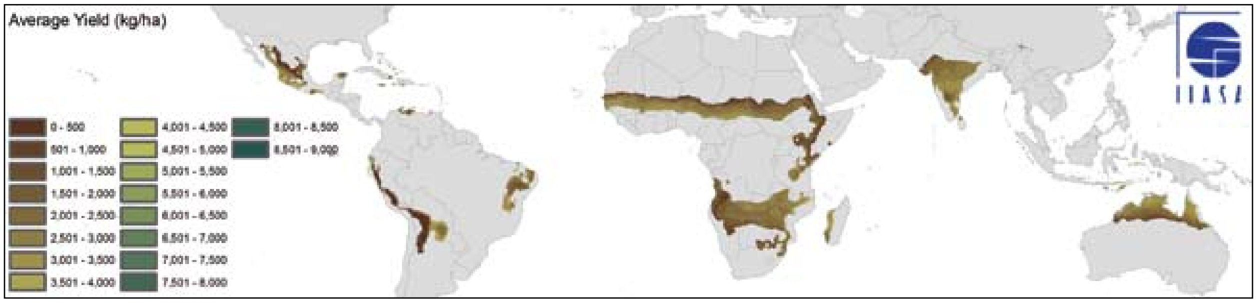

Figure 80. Modeled attainable yield for lowland groundnut with a 90-day growing period.

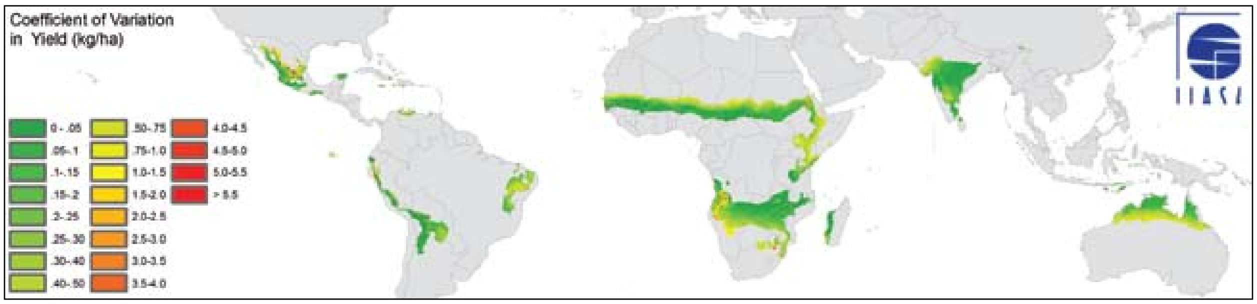

Figure 81. Modeled coefficient of variation in attainable yield for lowland groundnut with a 90-day growing period.

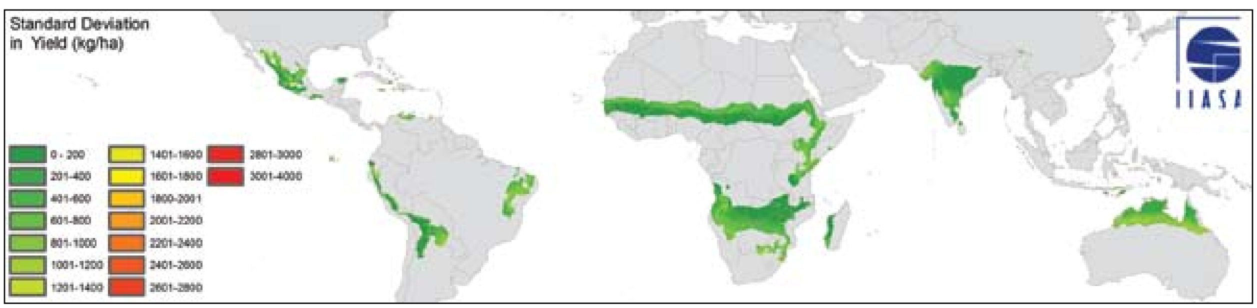

Figure 82. Modeled standard deviation in attainable yield for lowland groundnut with a 90-day growing period.

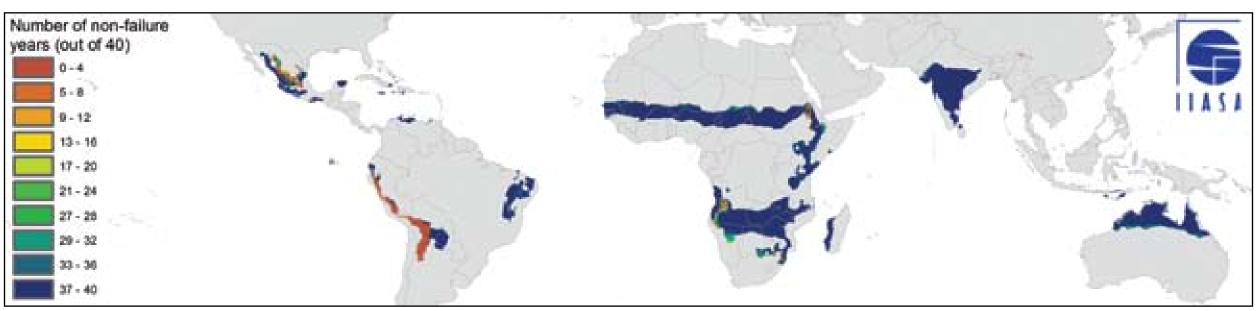

Figure 83. Modeled number of non-failure years of lowland groundnut with a 90-day growing period.

Changes in attainable yields and variability for 90-day groundnut cultivars under water harvesting and dryland management practices

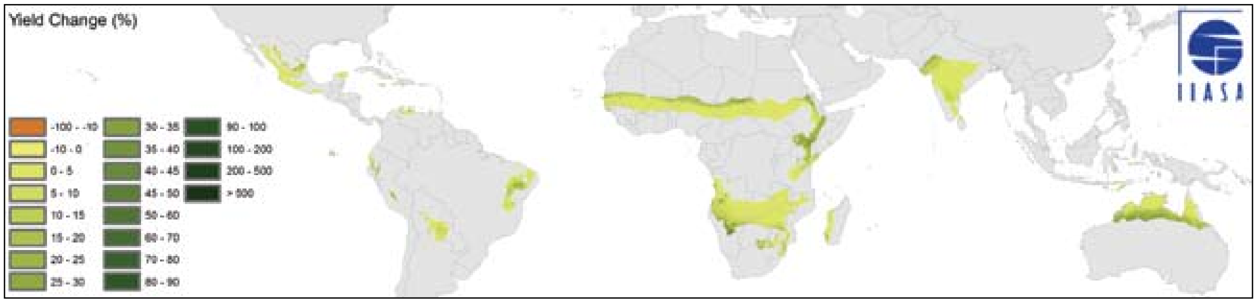

Figure 84. Percentage change in attainable yield for groundnut with a 90-day growing period when dryland management practices are implemented.

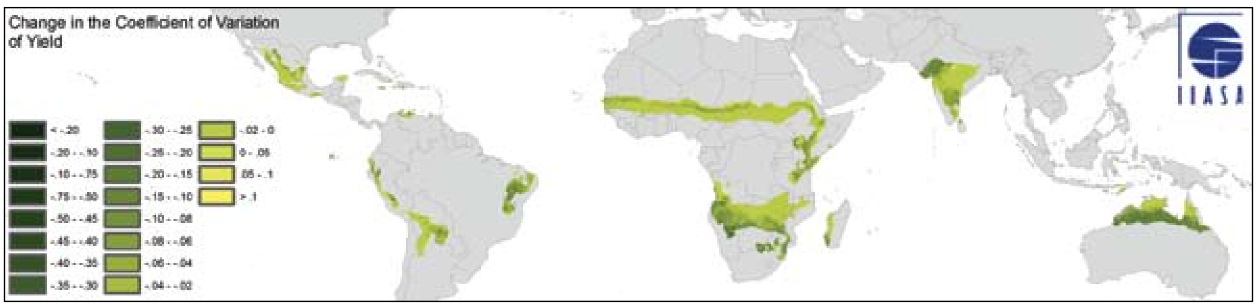

Figure 85. Change in the coefficient of variation of attainable yield for groundnut with a 90-day growing period when dryland management practices are implemented.

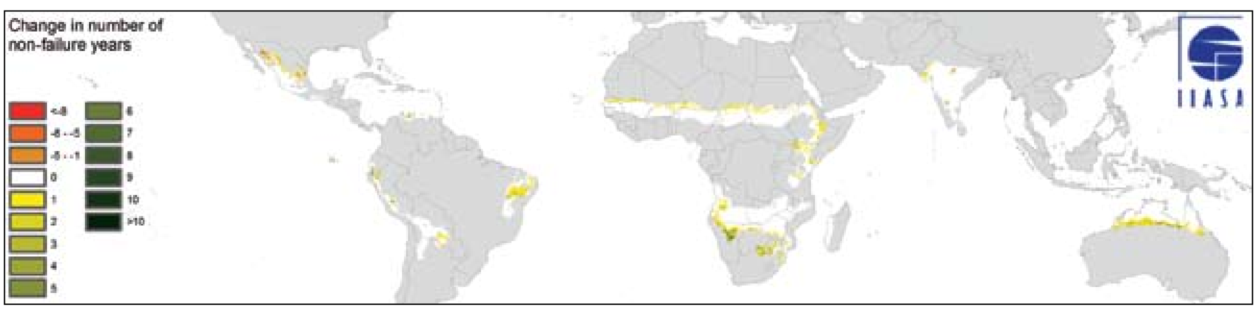

Figure 86. Change in the number of non-failure years of groundnut with a 90-day growing period when dryland management practices are implemented.

Attainable yields and variability for 105-day groundnut cultivars

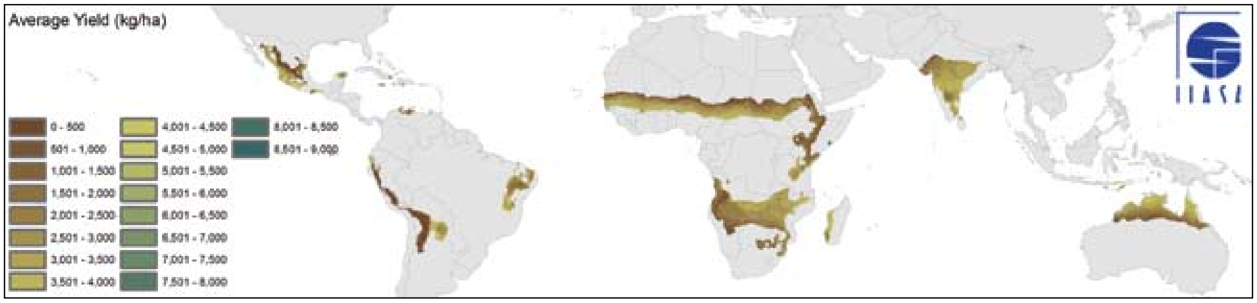

Figure 87. Modeled attainable yield for lowland groundnut with a 105-day growing period.

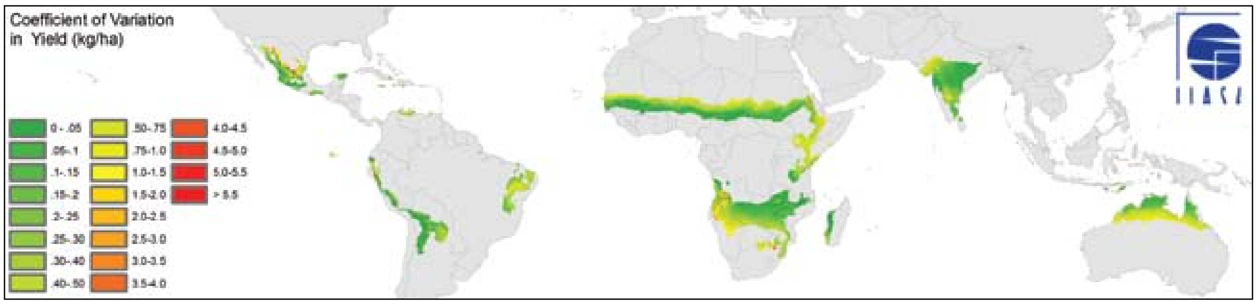

Figure 88. Modeled coefficient of variation in attainable yield for lowland groundnut with a 105-day growing period.

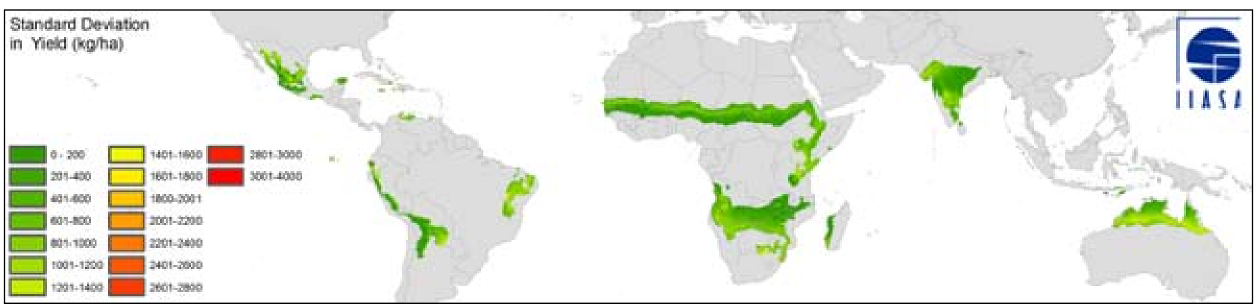

Figure 89. Modeled standard deviation in attainable yield for lowland groundnut with a 105-day growing period.

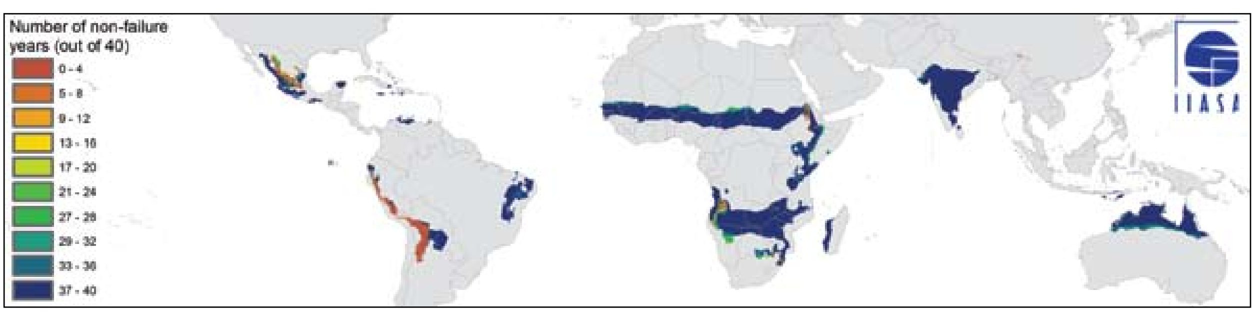

Figure 90. Modeled number of non-failure years of lowland groundnut with a 105-day growing period.

Changes in attainable yields and variability for 105-day groundnut cultivars under water harvesting and dryland management practices

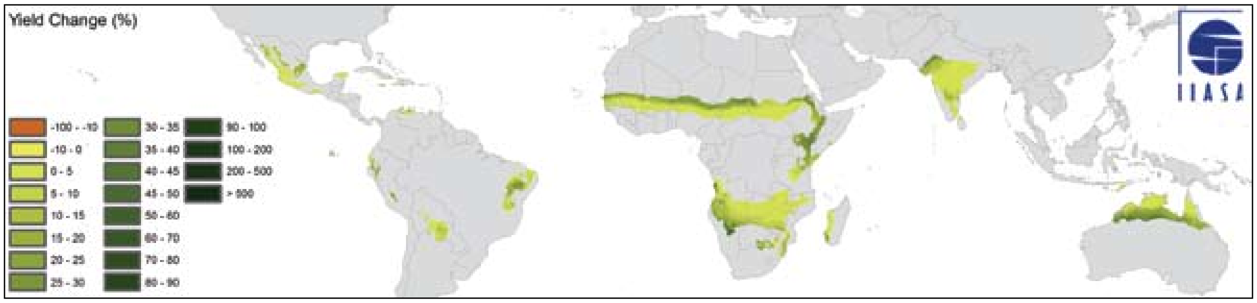

Figure 91. Percentage change in attainable yield for groundnut with a 105-day growing period when dryland management practices are implemented.

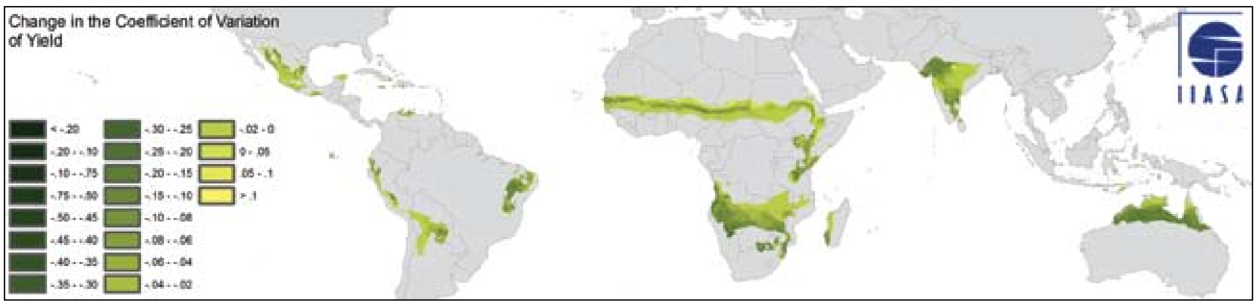

Figure 92. Change in the coefficient of variation of attainable yield for groundnut with a 105-day growing period when dryland management practices are implemented.

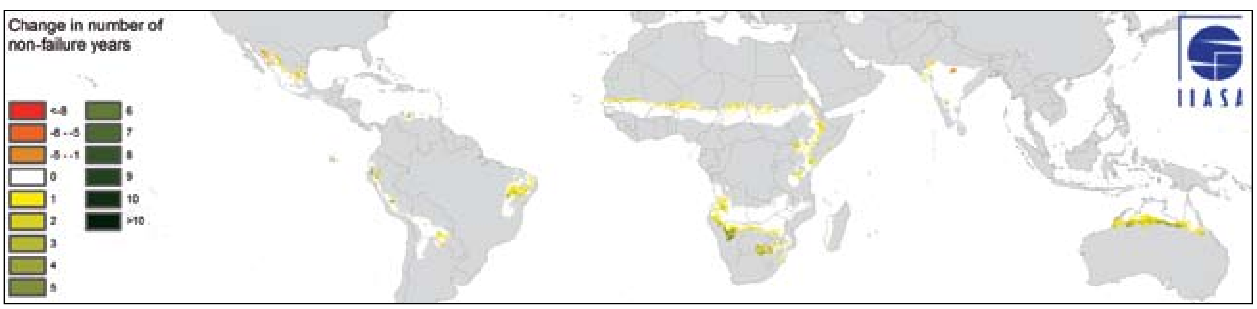

Figure 93. Change in the number of non-failure years of groundnut with a 105-day growing period when dryland management practices are implemented.

Attainable yields and variability for 120-day groundnut cultivars

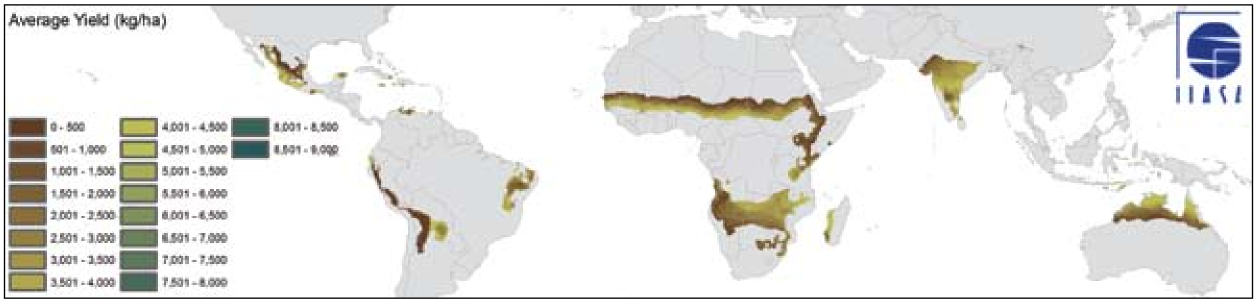

Figure 94. Modeled attainable yield for lowland groundnut with a 120-day growing period.

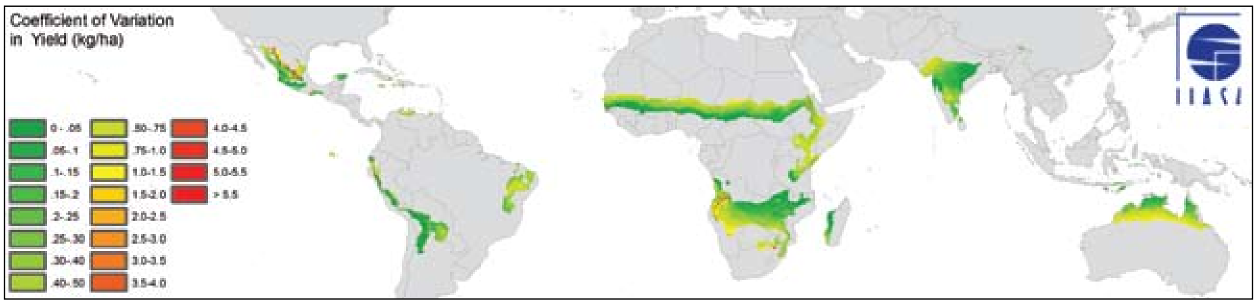

Figure 95. Modeled coefficient of variation in attainable yield for lowland groundnut with a 120-day growing period.

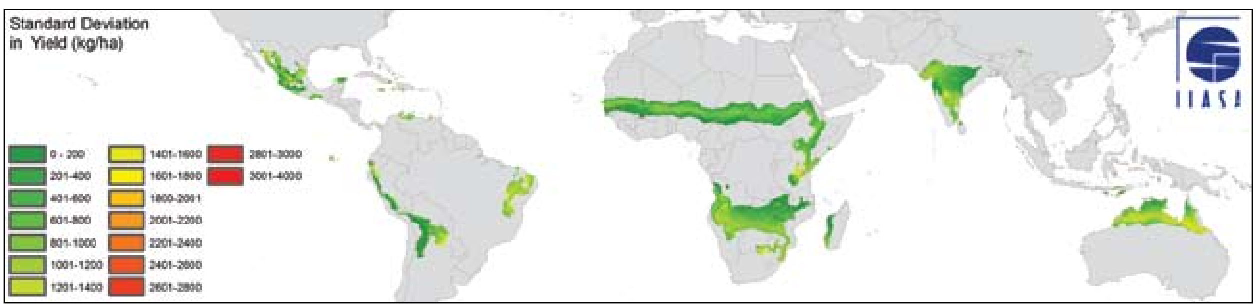

Figure 96. Modeled standard deviation in attainable yield for lowland groundnut with a 120-day growing period.

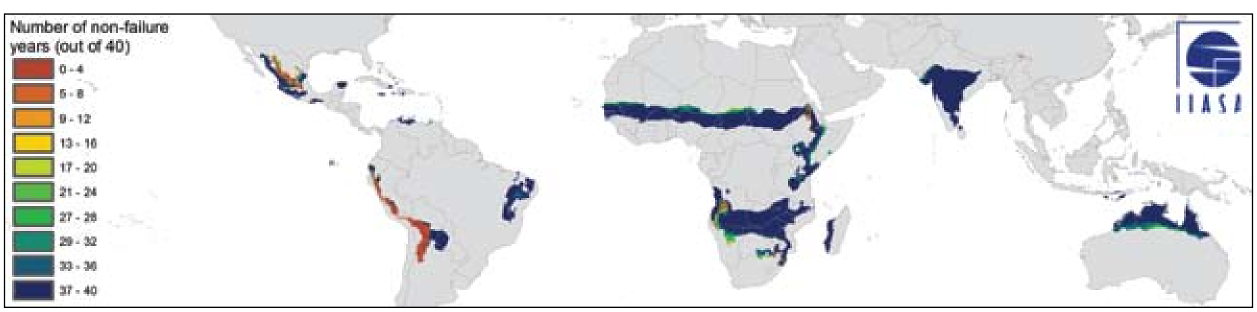

Figure 97. Modeled number of non-failure years of lowland groundnut with a 120-day growing period.

Changes in attainable yields and variability for 120-day groundnut cultivars under water harvesting and dryland management practices

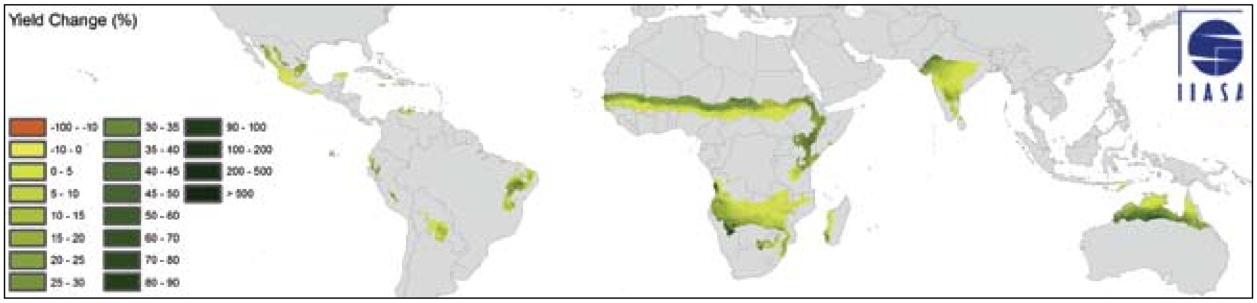

Figure 98. Percentage change in attainable yield for groundnut with a 120-day growing period when dryland management practices are implemented.

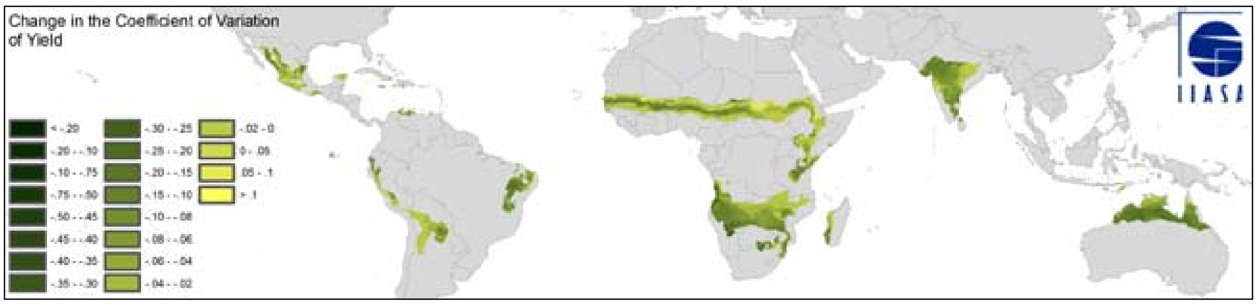

Figure 99. Change in the coefficient of variation of attainable yield for groundnut with a 120-day growing period when dryland management practices are implemented.

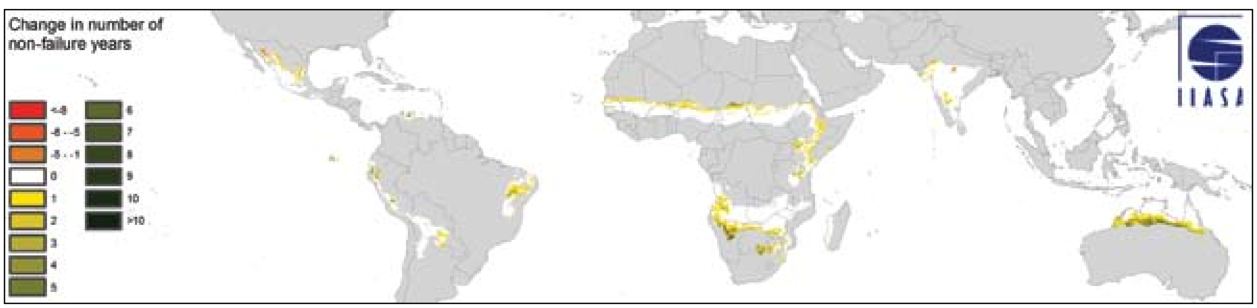

Figure 100. Change in the number of non-failure years of groundnut with a 120-day growing period when dryland management practices are implemented.

Appendix II: AEZ Assessment of Constraints to Agriculture in the Semi-Arid Tropics

Climatic Constraints

Climate constraints in AEZ are classified according to length of periods with cold temperatures and moisture limitations. Temperature constraints are related to the length of the temperature growing period LGPt=5, i.e., the number of days with mean daily temperature above 5◦C. An LGPt=5 of less than 120 days is considered a severe constraint, while an LGPt=5 of less than 180 days is considered as posing a moderate constraint to crop production. Hyper-arid and arid moisture regimes (LGP < 60 days) are considered severe constraints, and dry semi-arid moisture regimes (LGP 60–119 days) are moderate constraints. By definition, therefore, the dry SAT has moisture-related climate constraints. The map of climatic constraints to agriculture in the SAT is shown below, repeated from the introductory section of this report.

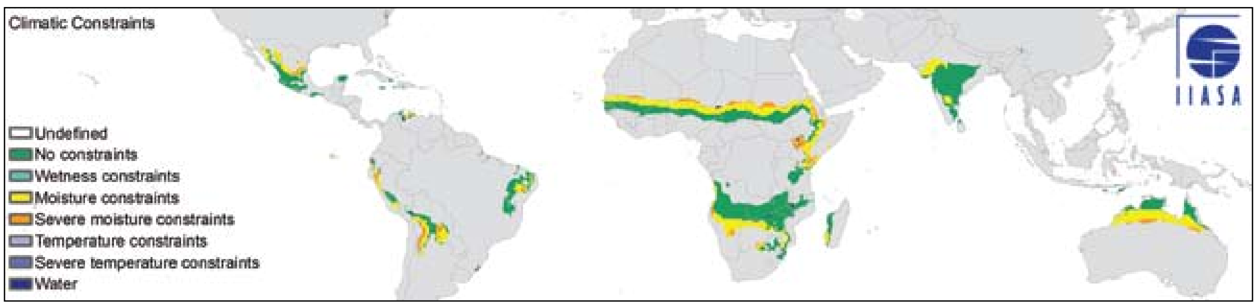

Figure 101. Climatic constraints to agriculture in the SAT.

Soil and Terrain Constraints

In addition to climatic constraints, the land resources inventory allows characterization of various regions according to the prevailing soil and terrain constraints. A constraint classification has been formulated and has been applied to each grid-cell of the land resources inventory. The constraints considered include:

- Terrain-slope constraints
- Soil depth constraints
- Soil fertility constraints
- Soil drainage constraints
- Soil texture constraints
- Soil chemical constraints
- Presence of miscellaneous land units

The definition of these constraints, followed by a map of these constraints within the SAT, is provided in the following sections.

Terrain Slope Constraints

Table 7. Terrain constraint classifications for soil units according to FAO '74 and FAO '90

	Rain-fed	Gravity irrigation*	Sprinkler irrigation
Severe constraints	slopes > 30%	slopes > 8%	slopes > 16%
Constraints	slopes 16-30%	slopes 5-8%	slopes 8-16%
Slight constraints	slopes 8-16%	slopes 2-5%	slopes 5-8%
No constraints	slopes 0-8%	slopes 0-2%	slopes 0-5%

*Applicable to non-terraced land

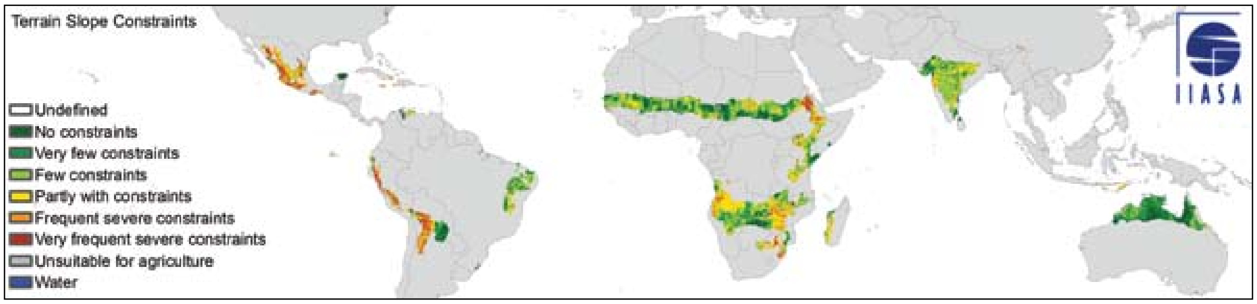

Figure 102. Terrain slope constraints in the SAT.

Soil Depth Constraints

Table 8. Soil depth constraint classifications for soil units according to FAO '74 and FAO '90

	FAO '74	FAO '90
Severe constraints	All soils with depth limitations within 50 cm of the surface caused by the presence of coherent hardrock or hard-pans (shallow soils): Lithosols (I), Renzinas (E), Rankers (U), all soils with Lithic phase.	All soils with depth limitations within 50 cm of the surface caused by the presence of coherent hardrock or hard-pans (shallow soils): Leptosols (LP), all soils with Lithic phase
Constraints	All soils with depth limitations within 100 cm of the surface by presence of Petrocalcic, Petrogypsic, Petroferric and Duripan phases.	All soils with depth limitations within 100 cm of the surface by presence of Petroferric and Duripan phases.
No constraints	Deep soils: all other soils	Deep soils: all other soils

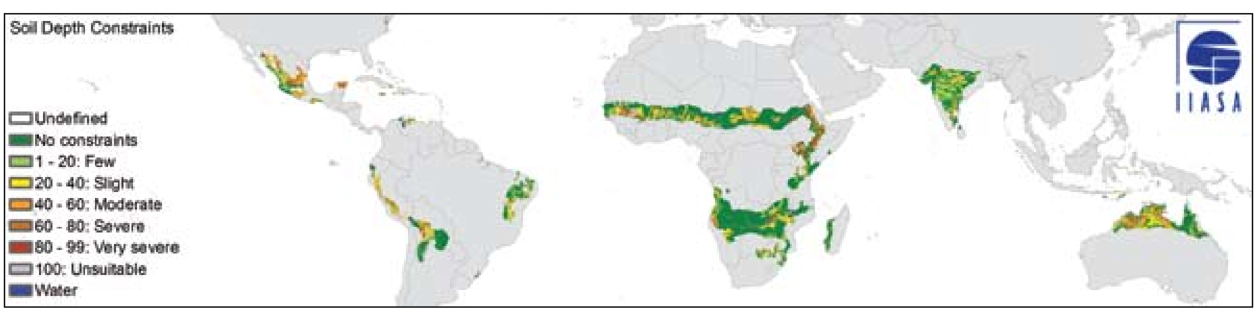

Figure 103. Soil depth constraints in the SAT.

Natural Fertility Constraints

Table 9. Soil fertility constraint classifications for soil units according to FAO '74 and FAO '90

	FAO '74	FAO '90
Severe constraints	Soils with low natural fertility and soils where a major land improvement is required before cultivation is possible: all other soils	Soils with low natural fertility and soils where a major land improvement is required before cultivation is possible: all other soils.
Constraints	Soils with moderate natural fertility: Jd, Gh, Gd, Rd, Q, Qc, Ql, T, To, Th, Xy, M, Mo, Mg, Bc, Bd, Bh, Bg, Bf, Lf, Lp, Lc, Lg, D, De,Dg, Pl, W, We, Wh, A, Ao, Ah, Nd, Nh, Fr and Fh.	Soils with moderate natural fertility: FLd, FLs, GLd, RGd, AR, ARh, ARb, ARl, ARc ARg, ANg, VRd, CMd, CMg, CMo, CL, CLh, CLl, CHg, PHg, PHj, GRg, LVf, LVa, LVg, LVj, PL, PLe, PLd, PLm, PLu, PDd, PDg, PDj, PZ, PZh, LX, LXh, AC, ACh, ACu, NTu, FR, FRh, FRr, FRu, HS, HSl, HSs, HSf, ATf
No constraints	Soils with high natural fertility: J, Je, G, Ge, Gc, Gm, R, Re, Rc, E, Tm, V, VP, Vc, Sm, Y, Yh, Yk, Yl, X, Xh, Xk, Xl, K, Kh, Kk, Kl, C, Ch, Ck, Cl, Cg, H, Hh, Hc, Hl, Hg, B, Be, Bk, Bv, L, Lo, Lk, Lv, Wm, N and Ne.	Soils with high natural fertility: FL, FLe, FLc, FLm, FLu, GL, GLe, GLk, GLa, GLm, GLu, RG, RGe, RGc, Rgu, AN, ANm, ANh, ANu, VR, VRe, VRk, CM, CMe, CMu, CMc, CMx, CMv, KS, KSh, KSl, KSk, CH, CHh, CHk, CHl, CHw, PH, PHh, PHc, PHl, GR, GRh, LV, LVh, LVx, LVk, LVv, PD, PDe, NT, NTh, NTr, AT, ATa, Atc.

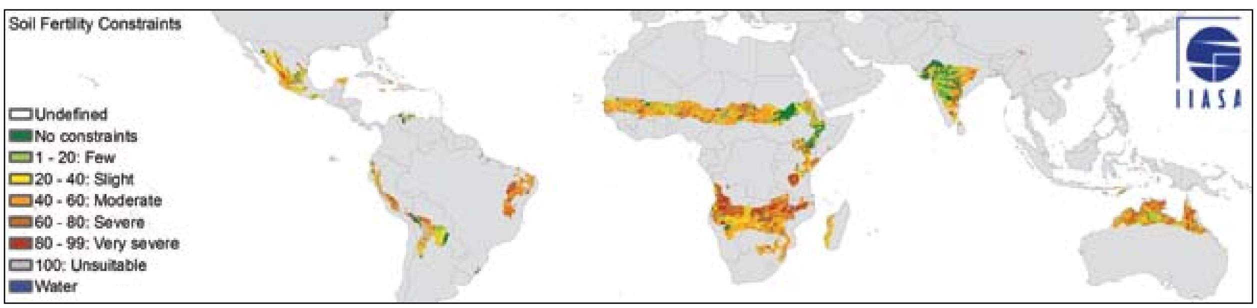

Figure 104. Soil fertility constraints in the SAT.

Soil Drainage Constraints

Table 10. Soil drainage constraint classifications for soil units according to FAO '74 and FAO '90

	FAO '74	FAO '90
Severe constraints	Poorly and imperfectly drained soils: All Gleysols (G, Ge, Gc, Gd, Gm, Gh, Gp and Gx), all Planosols (W, We, Wd, Wm, Wh, Ws, Wx) and all gleyic sub-groups (Zg, Sg, Mg, Hg, Lg, Dg, Pg and Ag), except Bg	Poorly and imperfectly drained soils: All Gleysols (GL, GLe, GLk, GLd, GLa, GLm, Glu, GLt, GLi), all planosols (PL, PLe, PLd, PLm, PLu, PLi) and soils with antraquic phases
Constraints		All soil with gleyic and stagnogleyic subgroups (ARg, ANg, CMg, SNg, SNj, SCg, CHg, PHg. PHj, GRg, LVg, LVj, PDg, PDj, PZg, LXg, LXj, ACg, ALg, ALj)
No constraints	Excessively and well drained soils: all other soils	Excessively and well drained soils: all other soils

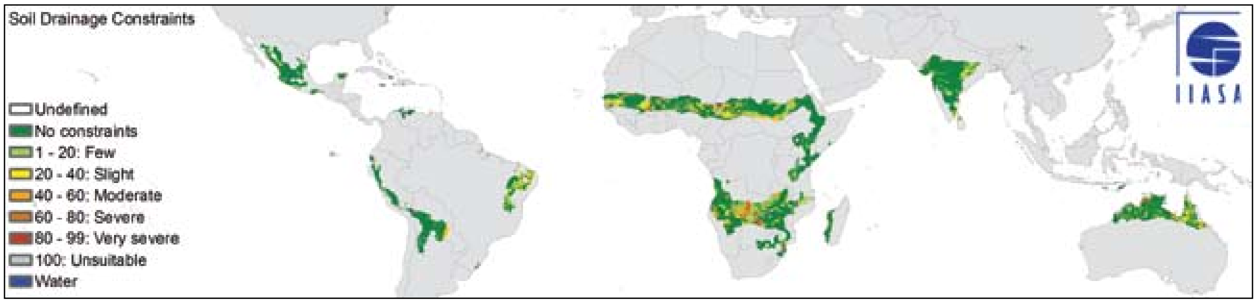

Figure 105. Soil drainage constraints in the SAT.

Soil Texture Constraints

Table 11. Soil texture constraint classifications for soil units according to FAO '74 and FAO '90

	FAO '74	FAO '90
Severe constraints	Coarse textured soils. Soils with less than 18% clay, more than 65% sand, or which have stones, boulders or rock outcrops in the surface layer or at the surface: All Arenosols (Q, Qc, Ql, Qf, Qa), all Regosols (R, Re, Rc, Rd, Rx) and Vitric Andosols (Tv) with coarse texture, and all soils with petric and stony phase.	Coarse textured soils, soils with less than 18% clay, more than 65% sand, or have stones, boulders or rock outcrops in the surface layer or at the surface: All Arenosols (AR, ARh, ARb, ARl, ARo, ARa, ARc, ARg), all Regosols (RG, RGe, RGc, RGy, RGd, RGu, RGi), all Podzols (PZ, PZh, PZb, PZf, PZc, PZg, PZi) and Vitric Andosols (ANz) with texture "1", and soils with skeletic, yermic, rudic, desert and Gobi phases.
Constraints	Soils with heavy cracking clays: Soils with 30% or more clay to at least 50 cm deep, with cracks at least 1 cm wide and 50 cm deep at some period in most years (unless irrigated), and high bulk density between the cracks: All Vertisols (V, Vp, Vc) and vertic sub-groups (Bv and Lv).	Soils with heavy cracking clays: Soils with 30% or more clay to at least 50 cm deep, with cracks at least 1 cm wide and 50 cm deep at some period in most years (unless irrigated), and high bulk density between the cracks: All Vertisols (VR, VRe, VRd, VRk, VRy) and vertic sub-groups (CMv, LVv).
No constraints	Soils with medium and fine textures: all other soils.	Soils with medium and fine textures: all other soils.

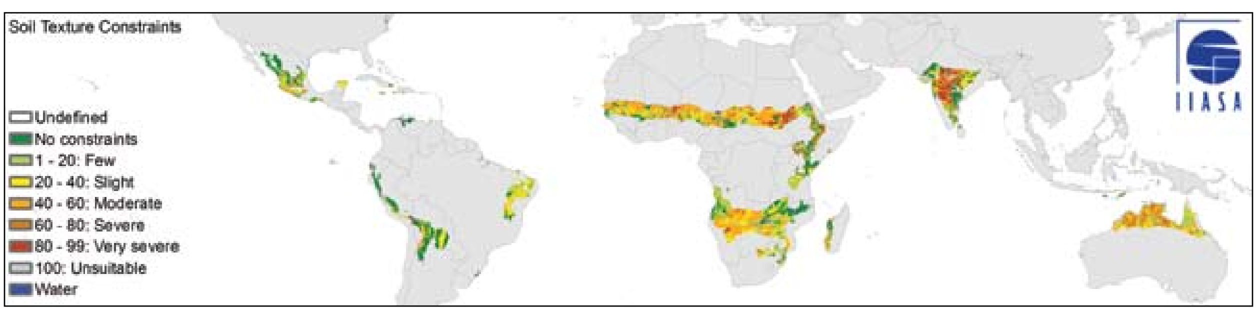

Figure 106. Soil texture constraints in the SAT.

Soil Chemical Constraints

Table 12. Soil chemical constraint classifications for soil units according to FAO '74 and FAO '90

	FAO '74	FAO '90
Severe constraints	Soils with severe salinity, sodicity, or gypsum limitations.· Soils with a high salt content or exchangeable sodium saturation within 100 cm of the surface: All Solonchaks (Z, Zo, Zm, Zt, Zg), all Solonetz (S, So, Sm, Sg) and Solodic Planosols (Ws); Soils with gypsic horizons: Gypsic Xerosols (Xy), Gypsic. Yermosols (Yy); Soils with saline and sodic phases	Soils with severe salinity, sodicity, or gypsum limitations: Soils with a high salt content or exchangeable sodium saturation within 100 cm of the surface: All Solonchaks (SC, SCh, SCm, SCk, SCy, SCn, SCg, SCi), all Solonetz (SN, SNh, SNm, SNk, SNy, SNj, SNg) and Salic Fluvisols (FLs);· All Gypsisols (GY, GYh, GYk, GYl, GYp) and soils with gypsic horizons: (RGy, VRy, SNy, SCy, Ksy);· Soils with salic and sodic phases
No constraints	All other soils	All other soils

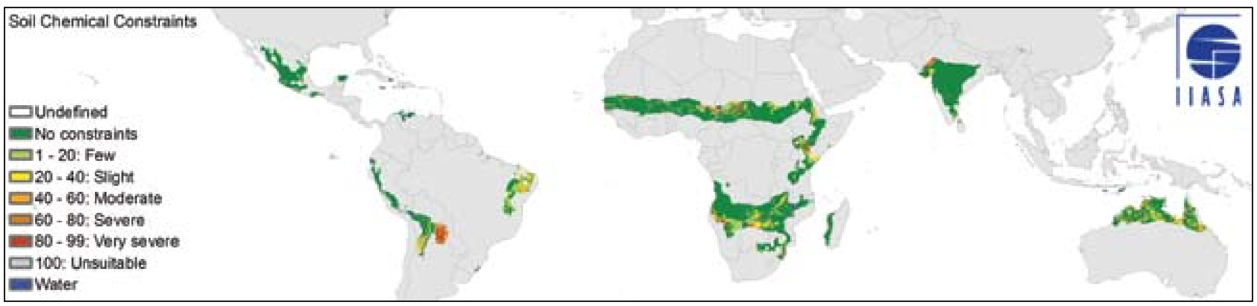

Figure 107. Soil chemical constraints in the SAT.

Micellaneous Land Units

The miscellaneous land units of the DSMW are considered as severe constraints. They include: dunes, shifting sands, salt flats, rock debris, desert detritus, glaciers and snow caps

Combined Soil Constraints

Figure 108. combines the individual soil constraints into a single map to show the extent of soil constraints to agriculture throughout the SAT.

Figure 109 combines all constraints, soil, terrain, and climate into a single map.

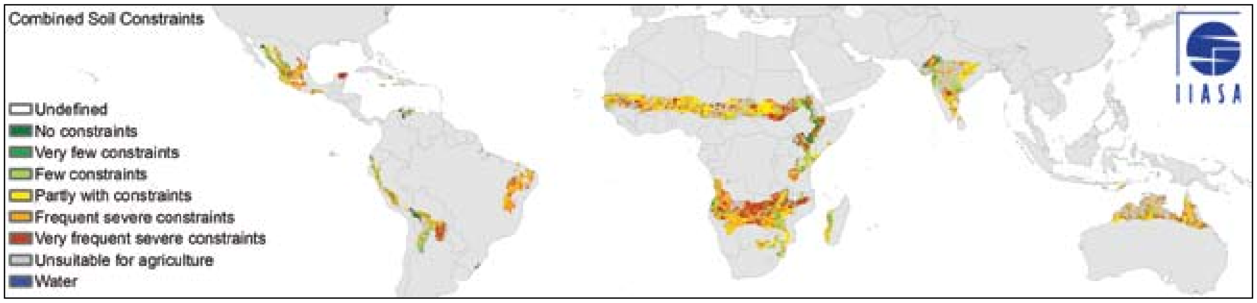

Figure 108. Combined soil constraints in the SAT.

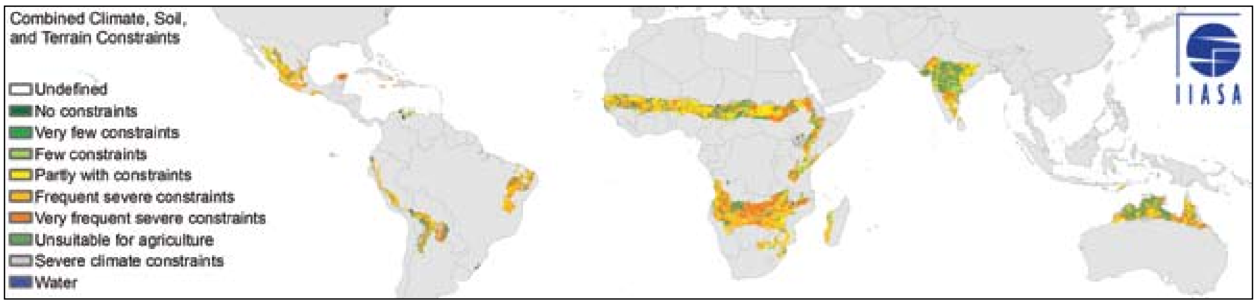

Figure 109. Combined soil, terrain, and climate constraints in the SAT.

Appendix III: Select Spatial Climate Change Impact Results

Human activities are changing the Earth's climate, and this is having an impact on all ecosystems. The expected changes in climate will alter regional agricultural systems, with consequences for food production. Maps of possible impacts of climate change in the 2020s on yields of maize, pearl millet, and sorghum in the semi-arid tropics are shown in this appendix. Potentially attainable rain-fed yields under high inputs were simulated using AEZ. The example scenario for the 2020s here is based on climate modeling results from the Hadley Centre's HadCM3 model (Gordon et al., 2000; Pope et al., 2000) and the IPCC SRES A2 scenario (Nakicenovic and Swart, 2000) were used. As was done in the main report, individual crop cultivars were grouped together to obtain yields and yield differences for the crop. By doing so, the calculations fully account for optimal adaptations of crop calendars and switching of crop cultivars.

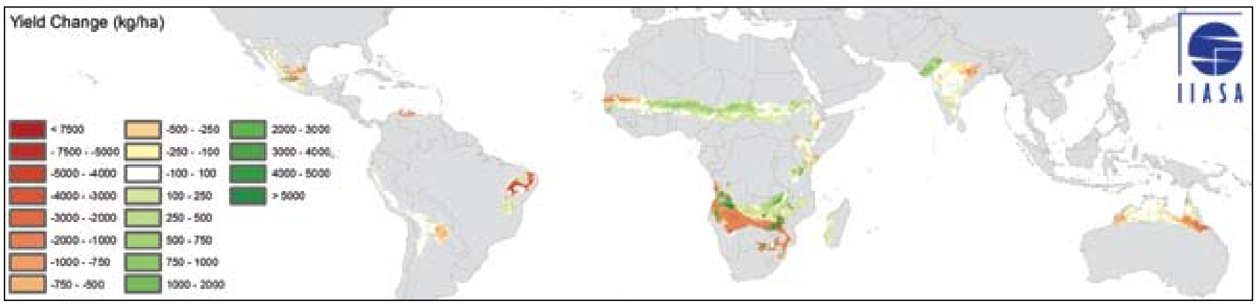

Figure 110. Maize yield changes in the 2020s simulated with AEZ using HadCM3 and SRES A2.

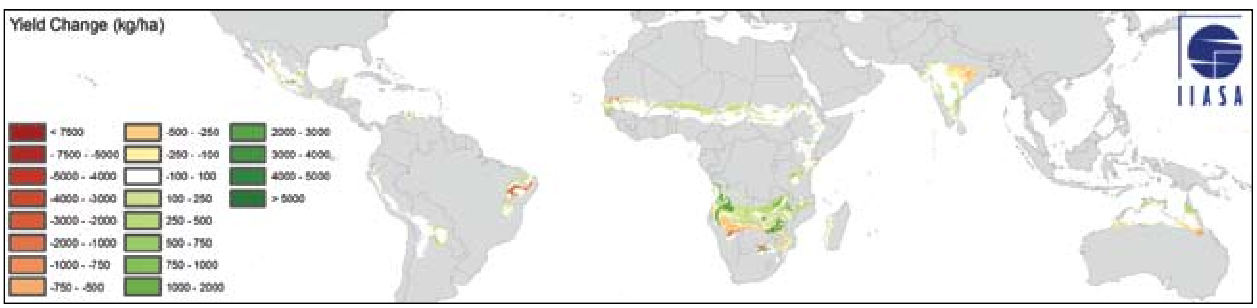

Figure 111. Pearl millet yield changes in the 2020s simulated with AEZ using HadCM3 and SRES A2.

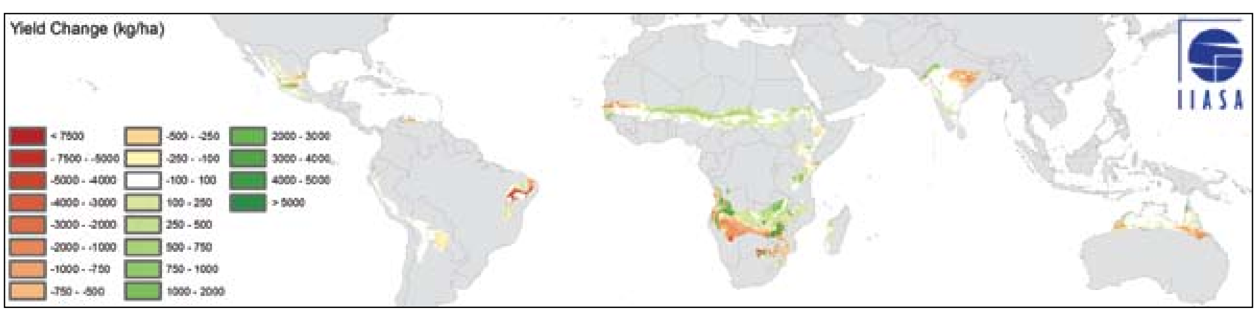

Figure 112. Sorghum yield changes in the 2020s simulated with AEZ using HadCM3 and SRES A2.

The results show that the impact on yield of the climatic and socio-economic scenario of the future selected is mixed in the SAT. For the SAT as a whole, there is practically no change in the average attainable yield. The mean and median changes are below 100 kg ha^{-1} in all cases and are almost all positive. Spatially, though, the picture is different. Modest improvements are shown in many areas such as just below the Sahara in Africa, and also in Tanzania, Zambia and parts of Zimbabwe and Angola, Western and Southen India, but declining yield is shown for Northeastern India, Brazil, Mexico, and the southern parts of Africa, Namibia, Botswana, Mozambique, South Africa, and parts of Zimbabwe and Angola. The largest negative impacts in terms of average maize yield occur in the SAT zones of Botswana, Brazil, Columbia, and Namibia, and Venezuela, where average potentially obtainable maize yields drop by more than 1 t ha^{-1}. Countries that benefit the most include the Congo, Zimbabwe, Guinea-Bissau, and Malawi with yield increases greater than 0.5 t ha^{-1}. In most of the case study countries, average yields in the SAT regions change very little overall, but vary within the countries. Maize yield in South Africa, though, does drop by about 0.5 kg ha^{-1}. Regions of yield gains and losses are similar for the other crops. Although the full impacts of climate change will not be felt by the 2020s, but this scenario suggests that climate change will already be affecting agriculture yields in some areas.

Appendix IV: Soil Moisture Storage Capacity for the Soil Units of the FAO/UNESCO Soil Map of the World

The amount of soil moisture stored in the soil profile, and available to a crop, varies, e.g., with depth of the soil profile, the soil physical characteristics, and the rooting pattern of the crop. Depletion of soil moisture reserves causes the actual evapotranspiration to fall short of the potential rate. Soil moisture storage capacity of soils (S_{max}) depends on soil physical and chemical characteristics, but above all on effective soil depth or volume. For the soil units of the Legend of the Soil Map of the World (FAO, 1974), FAO has developed procedures for the estimation of S_{max} (FAO, 1995).

The table below has been adjusted from the original table (see Fischer et al., 2002) for rooting patterns applicable for crop growth on residual soil moisture.

Soil moisture storage capacity (S_{max}) classes derived for FAO soil units (based on rooting depths up to 150 cm)

FAO Legend '74 Soil Unit	SLU	Coarse		Medium		Fine		FAO Legend '74 Soil Unit	SLU	Coarse		Medium		Fine	
		mm	CL	mm	CL	mm	CL			mm	CL	mm	CL	mm	CL
Eutric Gleysols	Ge	n.a.	1	n.a.	1	n.a.	1	Eutric Cambisols	Be	160	3	270	1	250	1
Calcaric Gleysols	Gc	n.a.	1	n.a.	1	n.a.	1	Dystric Cambisols	Bd	160	3	270	1	250	1
Dystric Gleysols	Gd	n.a.	1	n.a.	1	n.a.	1	Humic Cambisols	Bh	160	3	270	1	250	1
Mollic Gleysols	Gm	n.a.	1	n.a.	1	n.a.	1	Gleyic Cambisols	Bg	160	3	270	1	250	1
Humic Gleysols	Gh	n.a.	1	n.a.	1	n.a.	1	Gelic Cambisols	Bx	160	3	270	1	250	1
Plinthic Gleysols	Gp	n.a.	1	n.a.	1	n.a.	1	Calcic Cambisols	Bk	160	3	270	1	250	1
Gelic Gleysols	Gx	n.a.	1	n.a.	1	n.a.	1	Chromic Cambisols	Bc	160	3	270	1	250	1
Eutric Regosols	Re	160	3	270	1	250	1	Vertic Cambisols	Bv	160	3	270	1	250	1
Calcaric Regosols	Rc	160	3	270	1	250	1	Ferralic Cambisols	Bf	140	3	245	1	215	1
Dystric Regosols	Rd	160	3	270	1	250	1	Orthic Luvisols	Lo	245	1	270	1	260	1
Gelic Regosols	Rx	160	3	270	1	250	1	Chromic Luvisols	Lc	245	1	270	1	260	1
Lithosols	I	13	6	19	6	18	6	Calcic Luvisols	Lk	245	1	270	1	260	1
Cambic Arenosols	Qc	160	3	270	1	250	1	Vertic Luvisols	Lv	245	1	270	1	260	1
Luvic Arenosols	Ql	160	3	270	1	250	1	Ferric Luvisols	Lf	220	1	245	1	230	1
Ferralic Arenosols	Qf	160	3	270	1	250	1	Albic Luvisols	La	245	1	270	1	260	1
Albic Arenosols	Qa	160	3	270	1	250	1	Plinthic Luvisols	Lp	245	1	270	1	260	1
Rendzinas	E	39	5	57	5	53	5	Gleyic Luvisols	Lg	245	1	270	1	260	1
Rankers	U	39	5	57	5	53	5	Eutric Podzoluvisols	De	245	1	270	1	260	1
Ochric Andosols	To	300	1	300	1	300	1	Dystric Podzoluvisol	Dd	245	1	270	1	260	1
Mollic Andosols	Tm	300	1	300	1	300	1	Gleyic Podzoluvisols	Dg	245	1	270	1	260	1
Humic Andosols	Th	300	1	300	1	300	1	Orthic Podzols	Po	160	3	270	1	250	1
Vitric Andosols	Tv	300	1	300	1	300	1	Leptic Podzols	Pl	160	3	270	1	250	1
Pellic Vertisols	Vp	200	2	200	2	200	2	Ferric Podzols	Pf	140	3	245	1	215	1
Chromic Vertisols	Vc	200	2	200	2	200	2	Humic Podzols	Ph	160	3	270	1	250	1
Orthic Solonchaks	Zo	160	3	270	1	250	1	Placic Podzols	Pp	160	3	270	1	250	1

FAO Legend '74 Soil Unit	SLU	Coarse		Medium		Fine		FAO Legend '74 Soil Unit	SLU	Coarse		Medium		Fine	
		mm	CL	mm	CL	mm	CL			mm	CL	mm	CL	mm	CL
Mollic Solonchaks	Zm	160	3	270	1	250	1	Gleyic Podzols	Pg	160	3	270	1	250	1
Takyric Solonchaks	Zt	160	3	270	1	250	1	Eutric Planosols	We	230	1	255	1	250	1
Gleyic Solonchaks	Zg	160	3	270	1	250	1	Dystric Planosols	Wd	230	1	255	1	250	1
Orthic Solonetz	So	160	3	270	1	250	1	Mollic Planosols	Wm	230	1	255	1	250	1
Mollic Solonetz	Sm	160	3	270	1	250	1	Humic Planosols	Wh	230	1	255	1	250	1
Gleyic Solonetz	Sg	160	3	270	1	250	1	Sodic Planosols	Ws	230	1	255	1	250	1
Haplic Yermosols	Yh	160	3	270	1	250	1	Gelic Planosols	Wx	230	1	255	1	250	1
Calcic Yermosols	Yk	160	3	270	1	250	1	Orthic Acrisols	Ao	220	1	245	1	230	1
Gypsic Yermosols	Yy	160	3	270	1	250	1	Ferric Acrisols	Af	220	1	245	1	230	1
Luvic Yermosols	Yl	245	1	270	1	260	1	Humic Acrisols	Ah	220	1	245	1	230	1
Takyric Yermosols	Yt	160	3	270	1	250	1	Plinthic Acrisols	Ap	220	1	245	1	230	1
Haplic Xerosols	Xh	160	3	270	1	250	1	Gleyic Acrisols	Ag	220	1	245	1	230	1
Calcic Xerosols	Xk	160	3	270	1	250	1	Eutric Nitosols	Ne	220	1	245	1	230	1
Gypsic Xerosols	Xy	160	3	270	1	250	1	Dystric Nitosols	Nd	220	1	245	1	230	1
Luvic Xerosols	Xl	245	1	270	1	260	1	Humic Nitosols	Nh	220	1	245	1	230	1
Haplic Kastanozems	Kh	160	3	270	1	250	1	Orthic Ferralsols	Fo	220	1	245	1	230	1
Calcic Kastanozems	Kk	160	3	270	1	250	1	Xanthic Ferralsols	Fx	220	1	245	1	230	1
Luvic Kastanozems	Kl	245	1	270	1	260	1	Rhodic Ferralsols	Fr	220	1	245	1	230	1
Haplic Chernozems	Ch	160	3	270	1	250	1	Humic Ferralsols	Fh	220	1	245	1	230	1
Calcic Chernozems	Ck	160	3	270	1	250	1	Acric Ferralsols	Fa	220	1	245	1	230	1
Luvic Chernozems	Cl	245	1	270	1	260	1	Plinthic Ferralsols	Fp	220	1	245	1	230	1
Glossic Chernozems	Cg	160	3	270	1	250	1	Eutric Histosols	Oe	n.a.	1	n.a.	1	n.a.	1
Haplic Phaeozems	Hh	160	3	270	1	250	1	Dystric Histosols	Od	n.a.	1	n.a.	1	n.a.	1
Calcaric Phaeozems	Hc	160	3	270	1	250	1	Gelic Histosols	Ox	n.a.	1	n.a.	1	n.a.	1
Luvic Phaeozems	Hl	245	1	270	1	260	1	Eutric Fluvisols	Je	n.a.	1	n.a.	1	n.a.	1
Gleyic Phaeozems	Hg	160	3	270	1	250	1	Calcaric Fluvisols	Jc	n.a.	1	n.a.	1	n.a.	1
Orthic Greyzems	Mo	160	3	270	1	250	1	Dystric Fluvisols	Jd	n.a.	1	n.a.	1	n.a.	1
Gleyic Greyzems	Mg	160	3	270	1	250	1	Thionic Fluvisols	Jt	n.a.	1	n.a.	1	n.a.	1

Appendix V: AEZ Database

This appendix lists and describes the sources of data applied by AEZ to assess the agricultural potential in the semi-arid tropics.

Climate Data

Time series climatic data are used for this study from the Climate Research Unit's 0.5 x 0.5 degree latitude/longitude gridded monthly data for the period 1901-2002 (CRU TS 2.1; Mitchell & Jones, 2005).

Soil Data

Digital soil information for GAEZ was obtained from FAO. The Digital Soil Map of the World (DSMW, version 3.5) provides classification at 5-minute latitude/longitude grid-cells and global coverage of soils according to the FAO Legend '74 (FAO, 1995). The composition of the soil associations in terms of percentage occurrence of soil units, soil phases, textures, and terrain-slope classes is stored in the soil association composition database. For the characterization of the soil units in terms of physical and chemical properties, use has been made of (i) the soil unit characteristics database from the FAO DSMW CD-ROM (FAO, 1995), and (ii) the soil profile database of the World Inventory of Soil Emissions Potential (WISE) (Batjes, 1995). The latter database provides information on physical and chemical soil attributes for soil units of both the FAO '74 and the FAO '90 classifications (Batjes et. al., 1997).

Terrain Data

Under an agreement with the National Aeronautics and Space Administration (NASA) and the Department of Defense's National Geospatial-Intelligence Agency (NGA), the U.S. Geological Survey (USGS) is now distributing elevation data from the Shuttle Radar Topography Mission (SRTM). The SRTM is a joint project between NASA and NGA to map the Earth's land surface in three dimensions at a level of detail which is unprecedented. The SRTM 90m DEM's have a resolution of 90m at the equator, and are provided in mosaiced 5 deg x 5 deg tiles for easy download and use. Processed SRTM data, with a resolution of 3 arc seconds (approximately 90m at the equator), i.e. 6000 rows by 6000 columns for each 5˚ x 5˚ tile, have been used for calculating: (i) terrain slope gradients for each 3 arc-sec grid cell; (ii) aspect of terrain slopes for each 3 arc-sec grid cell; (iii) terrain slope class for each 3 arc-sec grid cell; and (iv) aspect class of terrain slope by 3 arc-sec grid cell. Products (iii) and (iv) were then aggregated to provide distributions of slope gradient and slope aspect classes by 30 arc-sec grid cell and for 5'x5' grid cells used in this analysis.

Distributions of slope gradients were calculated grouping values into 9 classes:

C1: 0 % ≤ slope ≤ 0.5 %

C2: 0.5 % ≤ slope ≤ 2 %

C3: 2 % ≤ slope ≤ 5 %

C4: 5 % ≤ slope ≤ 10 %

C5: 10 % ≤ slope ≤ 15 %

C6: 15 % ≤ slope ≤ 30 %

C7: 30 % ≤ slope ≤ 45 %

C8: Slope > 45 %

C9: Slope gradient undefined (i.e. outside land mask)

Slope aspects were grouped in 5 classes:

North: 0˚ < aspect ≤ 45˚ or 315˚ < aspect ≤ 360˚

East: 45˚ < aspect ≤ 135˚

South: 135˚ < aspect ≤ 225˚

West: 225˚ < aspect ≤ 315˚

Undefined: Slope aspect undefined; this value is used for grids where slope gradient is undefined or slope gradient is less than 2 percent.

Figure 1 presents an extract of the global slope gradient inventory based on the nine classes described above, and Figure 2 presents an extract of the global aspect inventory for a 1800 rows by 2100 columns sub-grid of a 5° by 5° tile (tile 40_03; 15° -20° longitude and 45° – 50° latitude) covering the area of 15.5° – 17.25° longitude and 47.5° – 49° latitude centered on the city of Vienna.

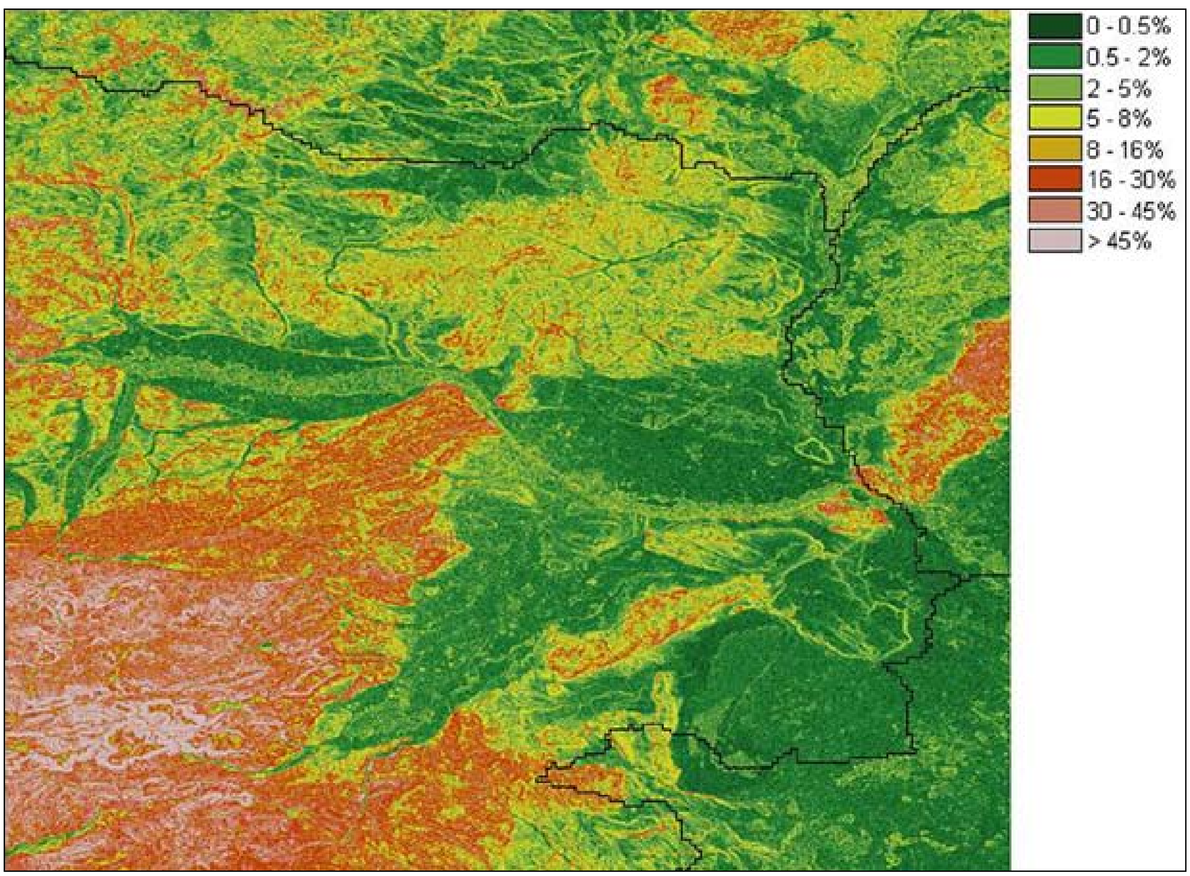

Figure 113. Extract of slope gradient class by 3 arc-sec grid cell.

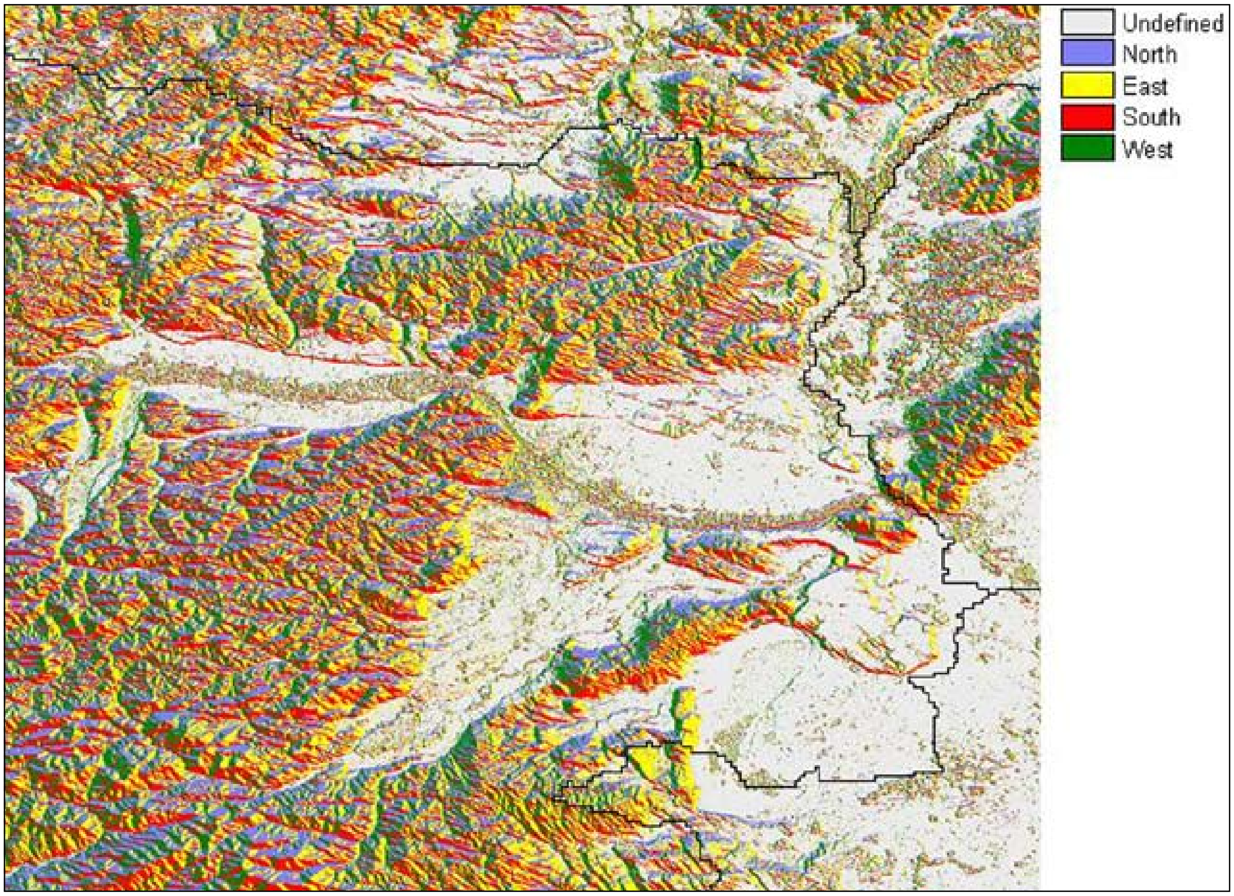

Figure 114. Extract of slope aspect class by 3 arc-sec grid cell.

Land Cover and Land Use Data

Four datasets are used for the compilation of a global land cover and land use inventory of six major land cover/land use categories at 5' resolution . These datasets are:

1. GLC2000 land cover classifications (http://www-gvm.jrc.it/glc2000), using regional and global legends;
2. an IFPRI interpretation of the global land cover categorization providing 17 land cover classes at 30 arc-sec. resolution (IFPRI, 2002), based on a reinterpretation of the Global Land Cover Characteristics Database (GLCC ver. 2.0), EROS Data Centre (EDC, 2000);
3. FAO's Global Forest Resources Assessment 2000 (FAO, 2001) at 30 arc-sec. resolution, and
4. a digital Global Map of Irrigated Areas (GMIA) version 3.0 of (FAO-AGLW/University of Frankfurt) at 30 arc-sec. resolution. This inventory provides by grid-cell the percentage land area equipped with irrigation infrastructure.

Protected Areas

Two main categories of protected areas are used in the analysis: (i) protected areas where restricted agricultural use is permitted, and (ii) strictly protected areas where agricultural use is not permitted. The categories are derived from international and national conventions. These include legally protected areas from World Heritage Convention, Ramsar Wetland Convention, Biogenetic Reserves, European Diploma Type A, Bird Directive and the IUCN Classes I-VI. The spatial dimension of these areas has been compiled by FAO-SRDN. Table 1 below presents an overview of various convention types, which in turn are grouped in broad categories namely one class where some agricultural use is permitted and another class where no agricultural use is allowed.

Land Areas Required for Infrastructure and Settlement

Urban areas and land required for settlement and infrastructure were compiled using:

- Land indicated as urban land in the 30 arc sec land cover dataset, and
- Estimates based on cross-section regressions relating per capita residential and infrastructure land to population density. These were then applied in conjunction with a global population data set at 30 arc-sec. The latter was compiled by FAO-SDRN using LANDSCAN 2003 (http:// www.ornl.gov/landscan) and scaled to match national UN population estimates of year 2000.

2. The main categories are: cultivated land, subdivided into (i) rain-fed and (ii) irrigated land, (iii) forest, (iv) pastures and other vegetated land, (v) barren and very sparsely vegetated land, (vi) water and (vii) urban land and land required for housing and infrastructure.

Table 13. Convention types of legally protected areas, whether or not permitting agricultural use

Convention Types: International

Codes		Name	Description	Agricultural use
1	INR1	Ramsar (Wetlands) Convention	Convention on Wetlands of International Importance Especially as Waterfowl Habitat	no
2	INH1	World Heritage Convention	Convention Concerning the Protection of the World Cultural and Natural Heritage	no
3	INF1	UNESCO-MAB Biosphere Reserves	UNESCO-MAB Biosphere Reserves Programme	no
23		Helsinki Convention	Convention on the Protection of the Marine Environment of the Baltic Sea Area	n.a.
24	INB1	Barcelona Convention	Convention for the Protection of the Mediterranean Sea against Pollution	n.a.
25	ING1	Biogenetic Reserves	European Network of Biogenetic Reserves	no
26	INEA	European Diploma Type 'A'	European Diploma (Council of Europe)	no
27	IND1	Bird Directive	The European Communities Directive on the Conservation of Wild Birds (79/409/EEC)	no
34	INEB	European Diploma Type 'B'	The European Communities Directive on the Conservation of Wild Birds (79/409/EEC)	restricted
35	INEC	European Diploma Type 'C'	The European Communities Directive on the Conservation of Wild Birds (79/409/EEC)	restricted
UNESCO-MAB		www.unesco.org/mab		
Ramsar		www.ramsar.org		
div. Europe		http://www.nature.coe.int/english/main/econets/peen/summary.htm		

Convention Types: National

IUCN categories		Protected area managed for	Agricultural use
Ia	Strict Nature Reserve	science	no
Ib	Wilderness Area	wilderness protection	no
II	National Park	ecosystem conservation & recreation	no
III	Natural Monument	conservation of specific natural features	no
IV	Habitat/ Species Management Area	conservation through management intervention	no
V	Protected Landscape/ Seascape	landscape/seascape conservation and recreation	restricted
VI	Managed Resource Protected Area	the sustainable use of natural ecosystems	restricted
IUCN categories		http://www.unep-wcmc.org/protected_areas/categories/eng	

About ICRISAT

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is a non-profit, non-political organization that does innovative agricultural research and capacity building for sustainable development with a wide array of partners across the globe. ICRISAT's mission is to help empower 600 million poor people to overcome hunger, poverty and a degraded environment in the dry tropics through better agriculture. ICRISAT belongs to the Alliance of Centers of the Consultative Group on International Agricultural Research (CGIAR).

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