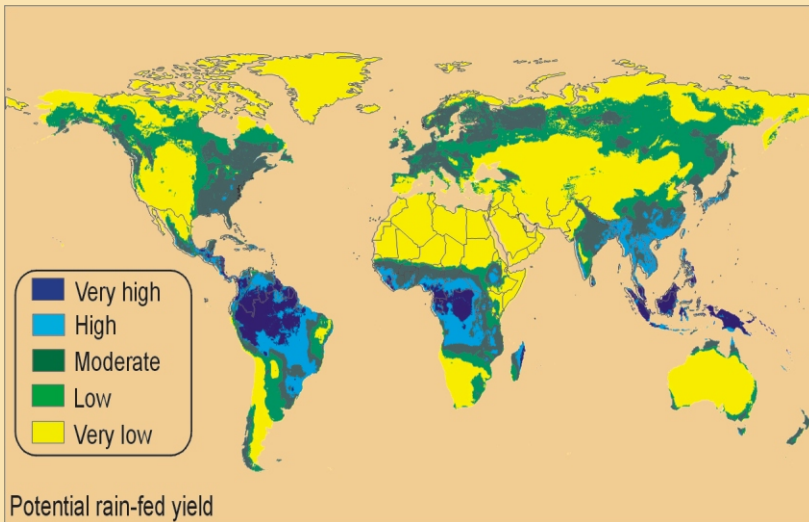


WORKING PAPER 20

Estimating the Potential of Rain-fed Agriculture

Peter Droogers, David Seckler and Ian Makin



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International Water Management Institute

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Summary

The ability of countries to achieve sufficient food production is closely related to water management. Worldwide, some 17 percent of agricultural lands are irrigated, producing 40 percent of total cereal production. Irrigation is also associated with negative economic, environmental, social and political consequences as well as positive ones. For this reason, there is a great deal of interest in meeting future food needs through rain-fed agriculture, as a partial substitute for irrigation. A global estimate of the potential for rain-fed agriculture could provide an answer to the question “How much irrigation is required?” Global studies done to date have relied on coarse resolution climate data (0.5–1 degree arc). In this study a high-resolution climate dataset (10-minute arc) was combined with a soil water storage capacity map and a dynamic water and crop model to estimate the potential for rain-fed agriculture. The methodology applied here, based on a high-resolution climate dataset, allows analyses on a global scale without losing the smaller regional-scale issues.

Introduction

Sufficient food production is one of the main challenges for mankind. Currently, 800 million people suffer from hunger, among them 200 million children below 5 years of age. Trends for the near future are negative for developing countries, especially for sub-Saharan Africa, as world population will increase and degradation of lands will continue. Food production is directly related to water availability. However, water is expected to be one of the most critical natural resources in the next century. For example, only 17 percent of the world's agricultural land is irrigated but it produces 40 percent of the total cereal crop. The International Water Management Institute (IWMI) estimates that, by 2025, cereal production will have to increase by 38 percent to meet world food demands (Seckler et al. 1999). One of the most important issues in world food policy debates is whether additional demand will require large investments in additional irrigation systems or whether increased area and yields from rain-fed agriculture can satisfy at least a substantial part of the demand. This issue has become increasingly important, as water in developing countries is becoming increasingly scarce, water development increasingly expensive and, in some cases, environmentally destructive. Seckler et al. (1999) estimate, for example, that by 2025 one-third of the world's population will experience severe water scarcity.

Recently, the Food and Agriculture Organization of the United Nations (FAO), in collaboration with the International Institute for Applied Systems Analysis (IIASA), developed a comprehensive system that enables rational land-use planning on the basis of an inventory of land resources and evaluation of biophysical limitations and potentials (FAO/IIASA 2000). Some of their key findings are: i) the earth's natural resources are sufficient to meet the food demand for future generations, ii) in several regions, the rain-fed cultivation potential has already been exhausted, iii) 27 percent of the global land surface is too dry for rain-fed crop cultivation and 13 percent is too cold, and iv) some 3 billion hectares of land are suitable for rain-fed production.

One of the major problems in attempting to determine the relative future roles of irrigated and rain-fed agriculture is the lack of sufficiently accurate and specific agroclimatic data on a global basis. Research by IWMI and the University of East Anglia (UEA) that created the World Water and Climate Atlas for Agriculture has alleviated this problem (IWMI 2000). Global studies done so far have relied on coarse resolution climate data (0.5–1 degree arc). In this study, the IWMI/UEA Atlas, with a high resolution (10-minute arc), is combined with the FAO soil map and a dynamic water and crop model to identify areas with good potential for rain-fed agriculture.

Many of the areas identified are already productive in rain-fed agriculture. Many more are in forests, grasslands and environmentally important areas that should not be developed for crops. Some of the areas are saline or alkaline, or too subject to diseases and pests to be agriculturally useful. Also, for economic reasons, farmers are reluctant to invest in inputs for all but the best rain-fed agriculture. This practice results in much lower yields or lower physically potential yields than in irrigated agriculture. For these reasons, no attempt is made here to estimate the amount of food that can be produced from rain-fed agriculture. Instead, this study should be regarded as a first, strictly agro-climatic, step *toward* producing such an estimate in the near future.

In summary, the objectives of this study are to identify potential areas and production from rain-fed agriculture on both global and small regional scales.

Methodology

Global Datasets

Two global datasets were used to estimate the potential for rain-fed agriculture: the IWMI/UEA Climate Atlas (New et al. 2000) and the FAO/UNESCO Digital Soil Map of the World (FAO/UNESCO 1995). The IWMI/UEA Climate Atlas has been developed by using data from 30,000 weather stations around the world in the period 1961–1990. These data were quality-controlled and gridded to monthly average values to a resolution of 10-minute arc (about 18 km at equator), by applying the spline surface fitting technique (Hutchinson 1999). Currently, the following datasets are included: precipitation, temperature, temperature range, relative humidity, sunshine, wind speed, number of rain days and number of frost days. This dataset was used to calculate reference crop evapotranspiration (ET_0) using the modified Penman-Monteith equation (Allen et al. 1998).

The FAO/UNESCO Digital Soil Map of the World was used to derive soil physical parameters, required for estimating the Soil-Water Storage Capacity (SWSC). Soil texture data, organic matter content and bulk density were used to derive soil physical functions (retention curve and hydraulic conductivity) by applying pedo-transfer functions as developed by Wosten et al. (1998). The SWSC was calculated as the difference between field capacity and wilting point multiplied by the soil depth as derived from the Digital Soil Map of the World. A more detailed description of this procedure is given by Droogers (2000).

Soil Water and Crop Production Model

There is a wide range of detailed crop production models where carbon production functions are coupled to partitioning models of this produced carbon among different plant organs (e.g., Van Diepen et al. 1989). Data requirements of these models are high and tend to be plant-specific, crop-variety-specific and location-specific. In many cases, a simpler parametric model approach is taken, treating production as a function of potential yield and the ratio of actual to potential evapotranspiration (e.g., Doorenbos and Kassam 1979). A limitation of this approach is that potential yield is poorly defined and it is difficult to obtain reliable global estimates. In general, physically based models are used in small spatial resolutions, while the parametric based models can be applied at coarser resolutions.

The majority of these models, both simplified and detailed, require estimates of vegetation cover for each model period. Obviously, in this study, where the potential of rain-fed agriculture is explored, these data are lacking. Therefore, an innovative procedure is proposed, based on a simplified soil water and crop production model, where the model itself determines the existence of vegetation.

The soil-water model uses a simplified bucket approach, where rainwater either runs off or enters the soil from precipitation as triggered by the soil water storage capacity, and leaves the soil by either soil evaporation or crop transpiration. Potential soil evaporation is set at 25 percent of ET_0 , corresponding to the average crop factor for crops in their initial stage (Allen et al. 1998), while potential crop transpiration is considered to be equal to ET_0 . Actual soil evaporation and crop transpiration are limited to the simulated actual soil-water storage.

In this model, it is unknown whether the soil is bare or covered by a crop. Vegetation cover is assumed as i) the ratio of actual over potential crop transpiration that exceeds a value of 0.35, ii) ET_0 is greater than 2 mm d^{-1} (60 mm month^{-1}) and iii) conditions i) and ii) exist for a minimum of three sequential months.

The first assumption, actual over potential transpiration (ET_a/ET_0) is greater than 0.35, represents that a crop will wither if water stress is severe, regardless of the water availability before or after such a dry period. The 35-percent value represents an average for different crops and different growing stages of the crop (Hargreaves 1975).

The assumption that ET_0 must exceed a value of 60 mm month^{-1} is used here as an integrated parameter to describe the overall weather conditions. This value of 60 mm corresponds roughly to conditions with temperatures of about $10 \text{ }^\circ\text{C}$ and low radiation inputs, which is a way of controlling for periods where the crop will not grow.

The minimum period of suitable conditions for crop growth is about 100 days. Obviously, this period depends on the kind of crop and the climatic conditions during this period. For the main food crops (rice, wheat, sorghum, maize) this 100-day period is the lower limit to obtain at least some yield (Doorenbos and Kassam 1979).

The whole procedure can be expressed in the following equations:

$$T_{act} = \min(ET_0, SWS_{t-1} + P) \quad [\text{if crop}] \quad (1)$$

$$E_{act} = \min(0.25ET_0, SWS_{t-1} + P) \quad [\text{if no crop}] \quad (2)$$

$$SWS_t = SWS_{t-1} + P - E_{act} - T_{act} \quad (3)$$

where, T_{act} is actual transpiration (mm), ET_0 is reference evapotranspiration (mm), SWS is soil-water storage (mm), t is the period, P is precipitation (mm), and E_{act} is actual soil evaporation (mm). We assume that as long as SWS -actual is lower than SWS -capacity all the precipitation will infiltrate, as areas of $18 \times 18 \text{ km}^2$ are used.

The model is run iteratively, with a time step of one month, to identify months with suitable conditions for vegetation growth, assuming rainfall at 75 percent probability of exceedence. At each time step, the availability of water from rainfall or soil storage is computed and compared to the criteria for successful crop growth. Each month is considered suitable for crop production if soil moisture is suitable in a sequence of three or more months.

It should be noted that some areas receive too much water, resulting in crop loss from waterlogging and flood damage, and many of these areas are suitable only for rice crops. On the other hand, agricultural management practices such as summer fallowing for wheat can make areas productive that would otherwise appear to be too dry for crops. These and other refinements are not included here, but will be taken up in later studies.

The simplified crop growth model proposed here is based on the Productivity of Water (PW) concept (Molden and Sakthivadivel 1999), and the yield reduction function based on the ratio, actual over potential evapotranspiration (Doorenbos and Kassam 1979). PW expresses how much yield can be produced out of 1 m^3 water, defined as kg m^{-3} . Values of the PW index range from 0.5 to 1.5 kg m^{-3} for cereals, depending on variety, climate, soil and management.

As this study concentrates on the estimation of potential, and not actual, rain-fed agricultural production, we assume that only physical conditions affect PW. Climatic condition is the paramount physical factor affecting PW, where high ET_0 values induce a low PW (Stanhill 1985) due to physiological processes in the plant, such as stomatal closure, high maintenance respiration and temperature regulation. Based on this, we assumed a linear relationship between the ET_0 and the PW:

$$PW = PW_{\max} \left(1 - \frac{ET_0}{ET_{\max}}\right)$$

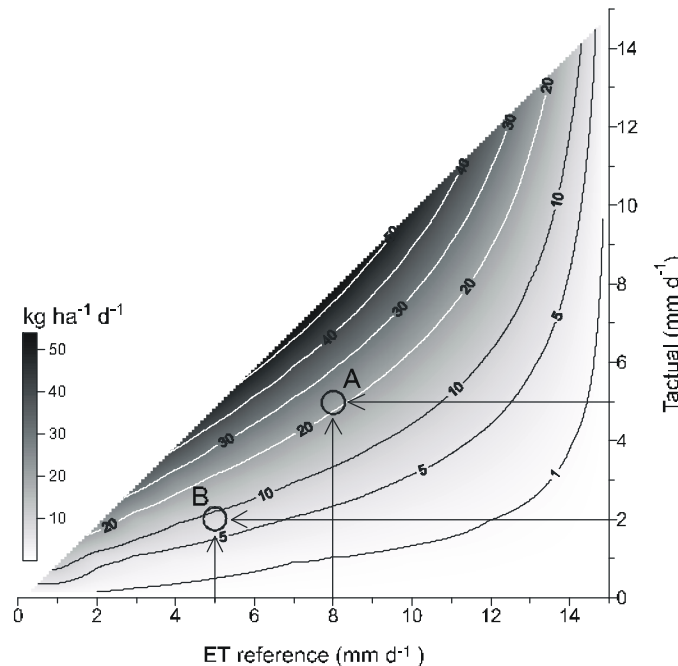
where, PW is the Productivity of Water for cereals in kg m^{-3} , PW_{\max} is the upper limit of PW defined as 1.5 kg m^{-3} , ET_{\max} is the upper limit for evapotranspiration to get any production defined as 15 mm d^{-1} , and ET_0 is reference evapotranspiration (mm d^{-1}). This relation corresponds to general values documented by Stanhill (1985) for temperate zones (1.25 kg m^{-3}) and arid zones (0.64 kg m^{-3}). It should be emphasized here that the PW values obtained with this method are the absolute maximum values, with perfect inputs and management, ignoring the fact whether this is feasible or economically attractive.

Finally, the yield is defined by the ratio, actual over potential evapotranspiration (Doorenbos and Kassam 1979):

$$Yield = PW \cdot T_{\text{act}} \cdot \frac{ET_{\text{act}}}{ET_0}$$

where, yield is expressed in $\text{kg ha}^{-1} \text{ d}^{-1}$ and ET_{act} is actual crop transpiration (mm d^{-1} or $\text{m}^3 \text{ ha}^{-1} \text{ d}^{-1}$). Figure 1 shows this crop growth function. As PW values used here are related to cereals, yields are also expressed in kg cereals. This is a well-known approach to express the total global production in cereal equivalents. By adding up the daily values, total annual potential yields are obtained. Take, for example, a location with a 3-month growing period as defined by the three conditions above, with an ET_0 of 8 mm d^{-1} and a T_{act} of 5 mm d^{-1} (point A in figure 1). This corresponds to a production of $22 \text{ kg ha}^{-1} \text{ d}^{-1}$ and an annual production of $2,000 \text{ kg ha}^{-1}$. The same yield will be obtained for areas with a growing season of 8 months and an ET_0 of 5 mm d^{-1} and a T_{act} of 2 mm d^{-1} (point B in figure 1).

Figure 1. Crop growth related to actual crop transpiration and reference evapotranspiration.



Applications

Soil-Water Storage Capacity (SWSC)

The soil moisture storage capacity varies from 0 to 800 mm (figure 2), with the majority of soils having values between 100 and 300 mm (figure 3). Higher values of SWSC are found for organic soils. A clear distinction can be seen in the distribution of SWSC between sub-Saharan Africa and Southeast Asia, the latter having a dual-normal distribution and the former a log-normal distribution. This dual-normal distribution originates not only from the mountainous areas of the Himalayas, but also from large areas in central India. For sub-Saharan Africa, most soils have an SWSC of at least 150 mm, and over 20 percent of them have an SWSC higher than 300 mm.

Figure 2. Soil moisture storage capacity (mm) as derived from the FAO digital map of the world.

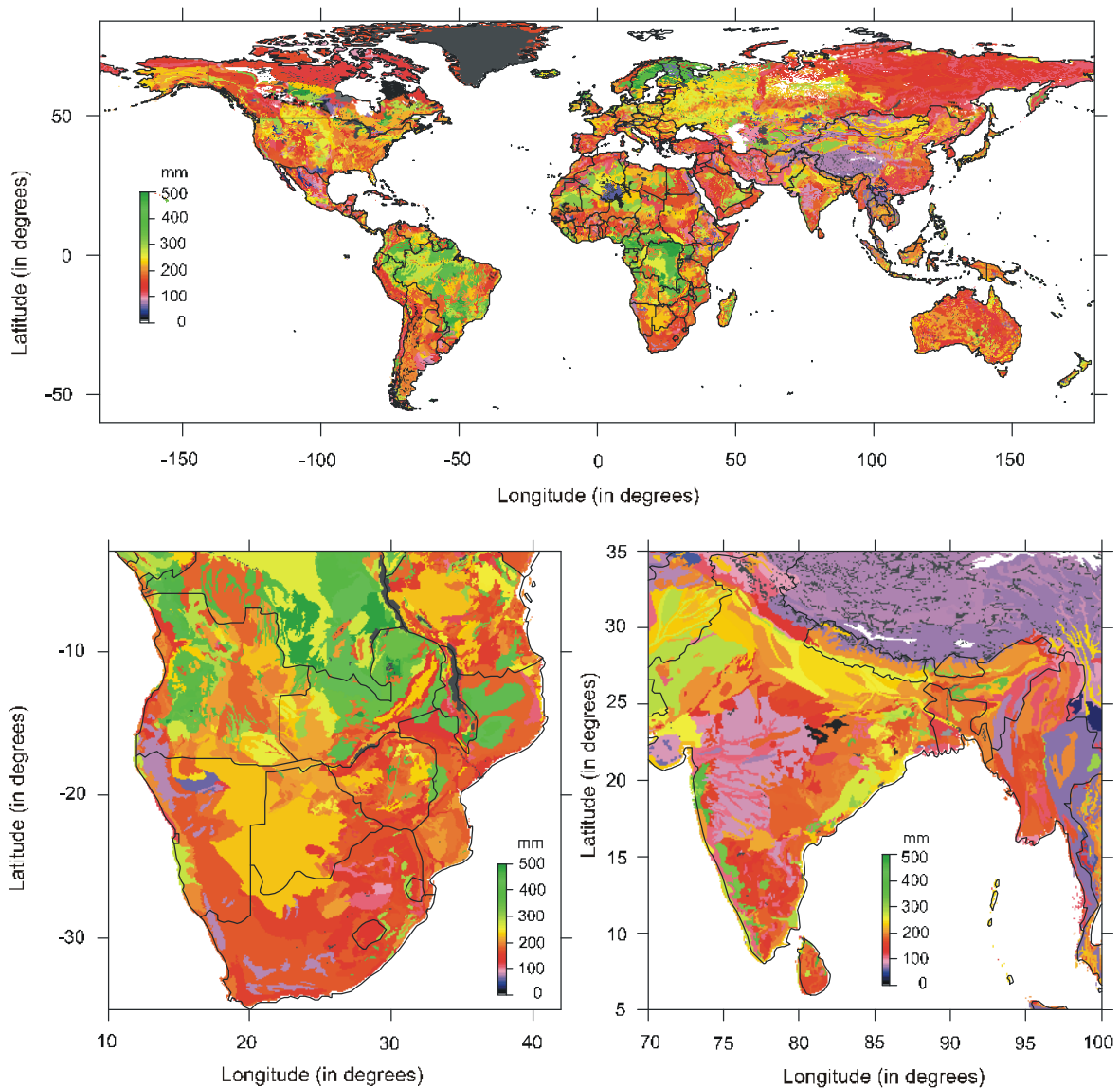
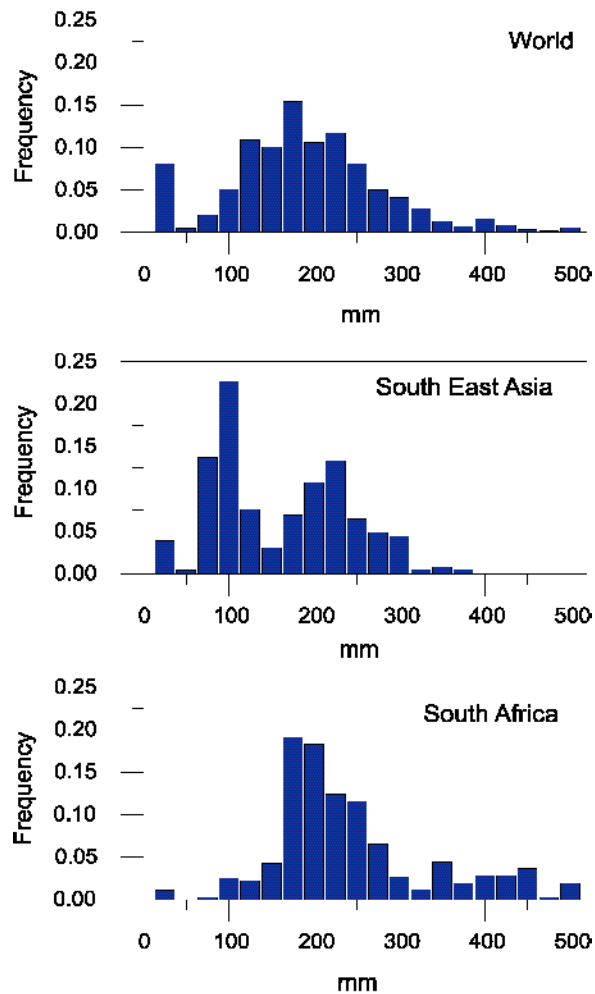


Figure 3. Distribution of soil moisture storage capacities (mm) on a global scale and for the two regions studied in detail.



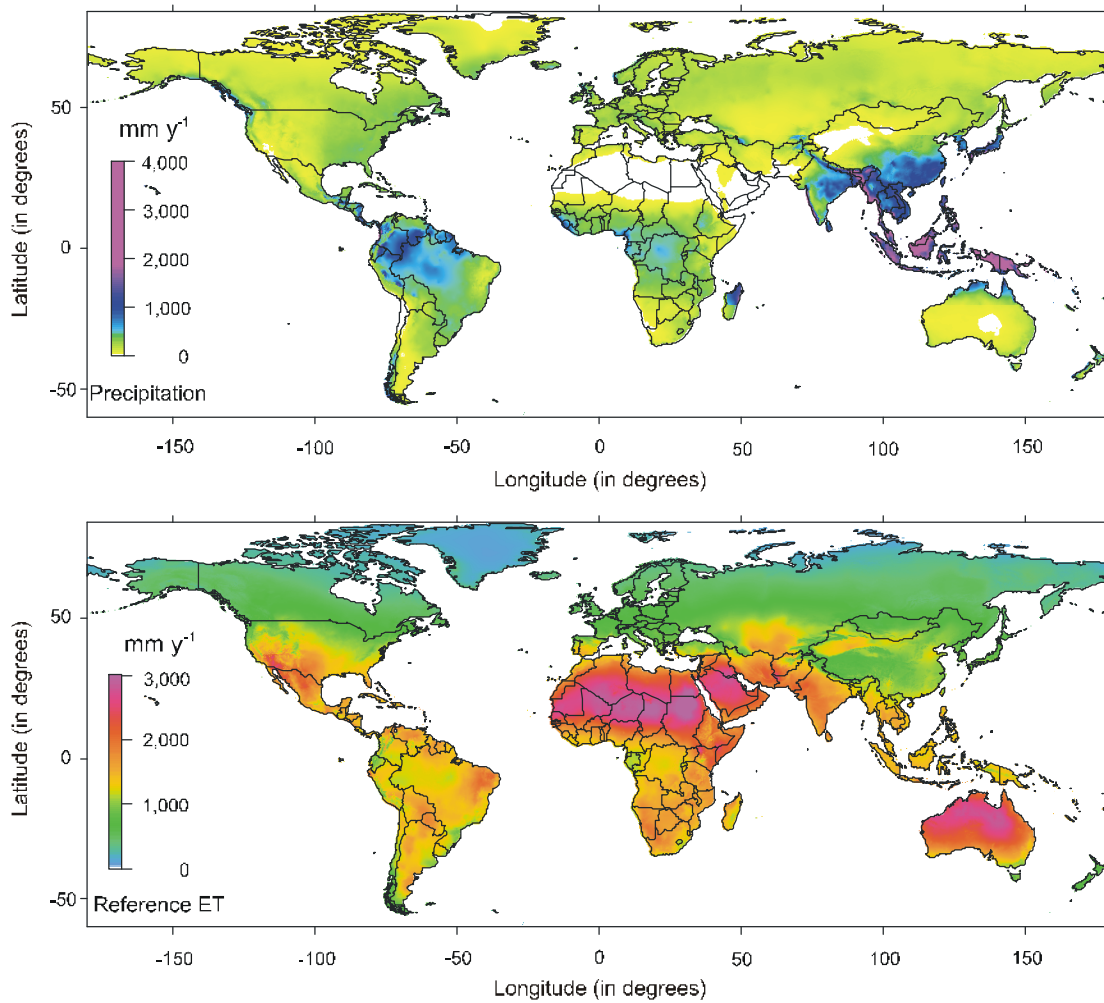
Climate Atlas

Global precipitation at 75 percent probability level of occurrence and the ET_0 are depicted in figure 4. The general trend of having wet areas around the equator and dry regions around the tropics of Cancer and Capricorn can be observed, with regions of almost zero precipitation at the Sahara, the Arabian Peninsula, the Gobi Desert and major areas in Australia. ET_0 for these areas ranges up to values of 3,000 mm y^{-1} . Values of 1,000 and lower can be found at latitudes greater than 40° N and 40° S.

Annual precipitation rates as well as potential evapotranspiration for sub-Saharan Africa are shown in figure 5. The general precipitation pattern shows the well-known decrease in rainfall from north to south. Also the increase from east towards west due to the prevailing wind direction is clear. ET_0 values do not show the same trend on an annual base, as the seasonal trends average out on such an annual base. During summer, ET_0 values for southern and eastern parts are higher while, during winter, the trend is reversed, resulting in a more homogenous pattern.

Precipitation in Southeast Asia is very high at the western coasts of India and Thailand, and at some regions in the Himalayas. Regions in the north of the Himalayas and Pakistan and the western part of India are extremely dry with precipitation rates lower than 100 mm y^{-1} .

Figure 4. Annual global precipitation and reference evapotranspiration rates from IWMI's Climate Atlas.



To illustrate the functioning of the soil-water and crop production model, three locations were selected and the input and output of the model are plotted (figure 6). The top graph shows a location **in Western India (10° 47' N, 76° 7' E)** where annual precipitation is high (1,761 mm). April precipitation is partly lost by bare soil evaporation, and partly stored in the soil profile. May is the first month of the growing season and the plant transpires the water stored in April, as well as the 120-mm rain. During the monsoon season, June–August, the soil profile is filled up, the crop transpires at the maximum rate, and the remainder of the water flows out of the system by runoff. Precipitation and crop transpiration are more or less in equilibrium in September and October, followed by a precipitation deficit in November, December, and January. During these months the soil-water storage is depleted to support crop growth. In February, the soil-water storage is completely depleted and no crop growth is possible. The total length of the growing season is 9 months. Ignoring soil-water storage, this would have been only 6 months, based on monthly rainfall.

Figure 5. Annual precipitation and reference evapotranspiration rates from IWMI's Climate Atlas for Southern Africa and Southeast Asia.

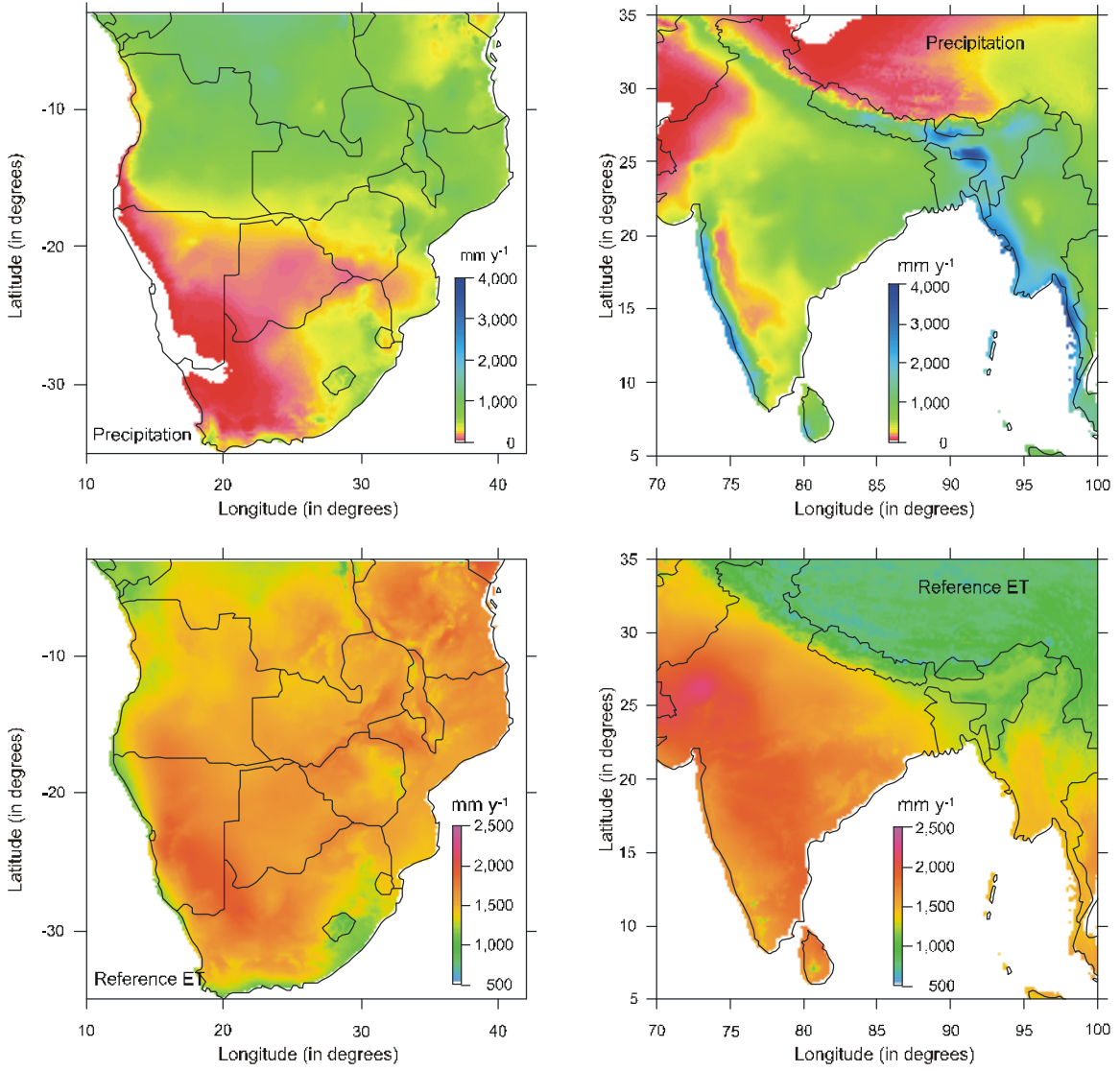
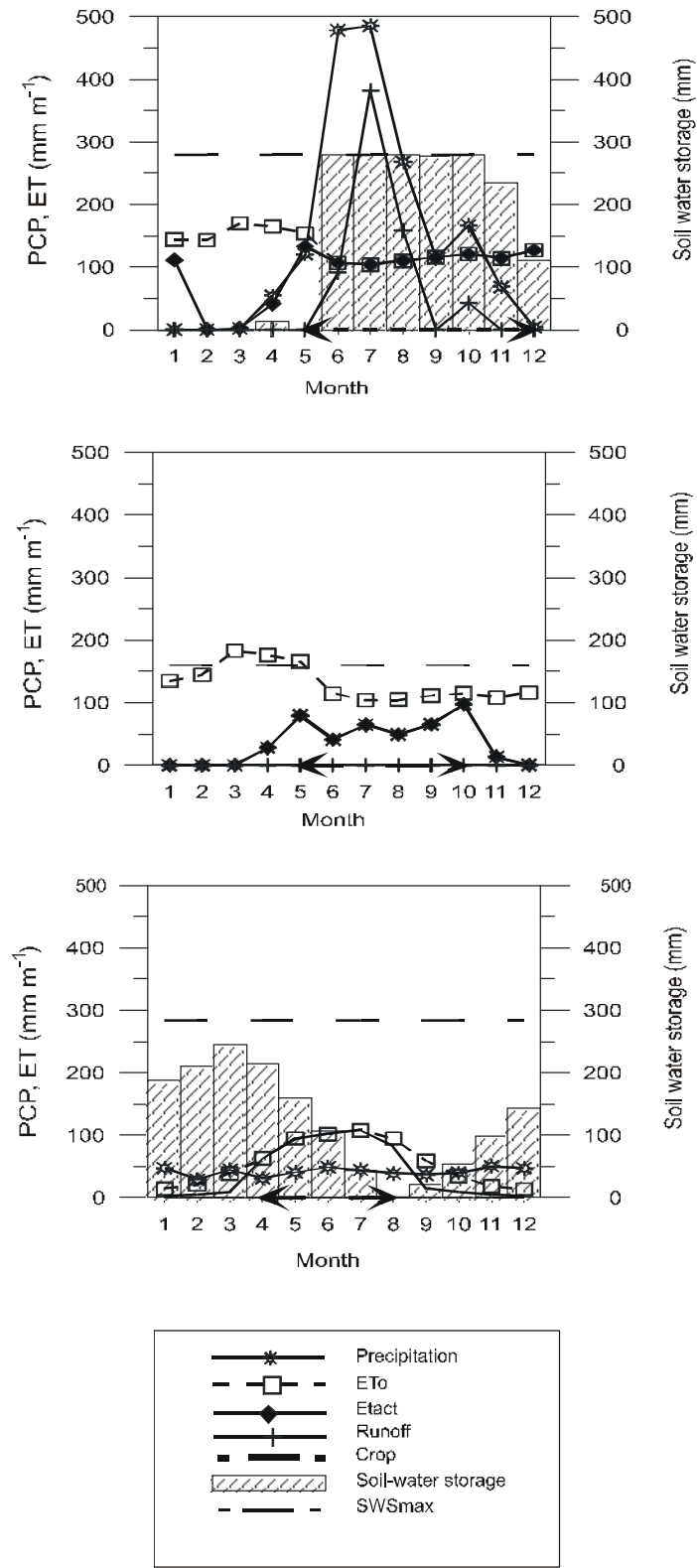


Figure 6. Example of the soil-water and crop production model for three different conditions.



Soil-Water and Crop Production Model

The second example is also from India ($12^{\circ}26'N$, $76^{\circ}32'E$), with a similar ET_0 but with much lower precipitation rates. Actual soil-water storage is zero during the whole year, and precipitation is directly used for evapotranspiration. Although some precipitation occurs in April and November, no crop has been considered and all the evapotranspiration originates from soil evaporation.

Finally, the last example is taken from the Netherlands ($51^{\circ}29'N$, $4^{\circ}55'E$) and it shows a pattern where precipitation occurs during the whole year, but at a rather low intensity. Soil-water storage is here of paramount importance as ET_0 is about double the precipitation during the growing season. A crop is considered for the months April to August. The climatic conditions before April are unsuitable for crop growth as defined by the three conditions above. Also no crop was considered in September, as ET_0 was just below the criterion of 2 mm d^{-1} .

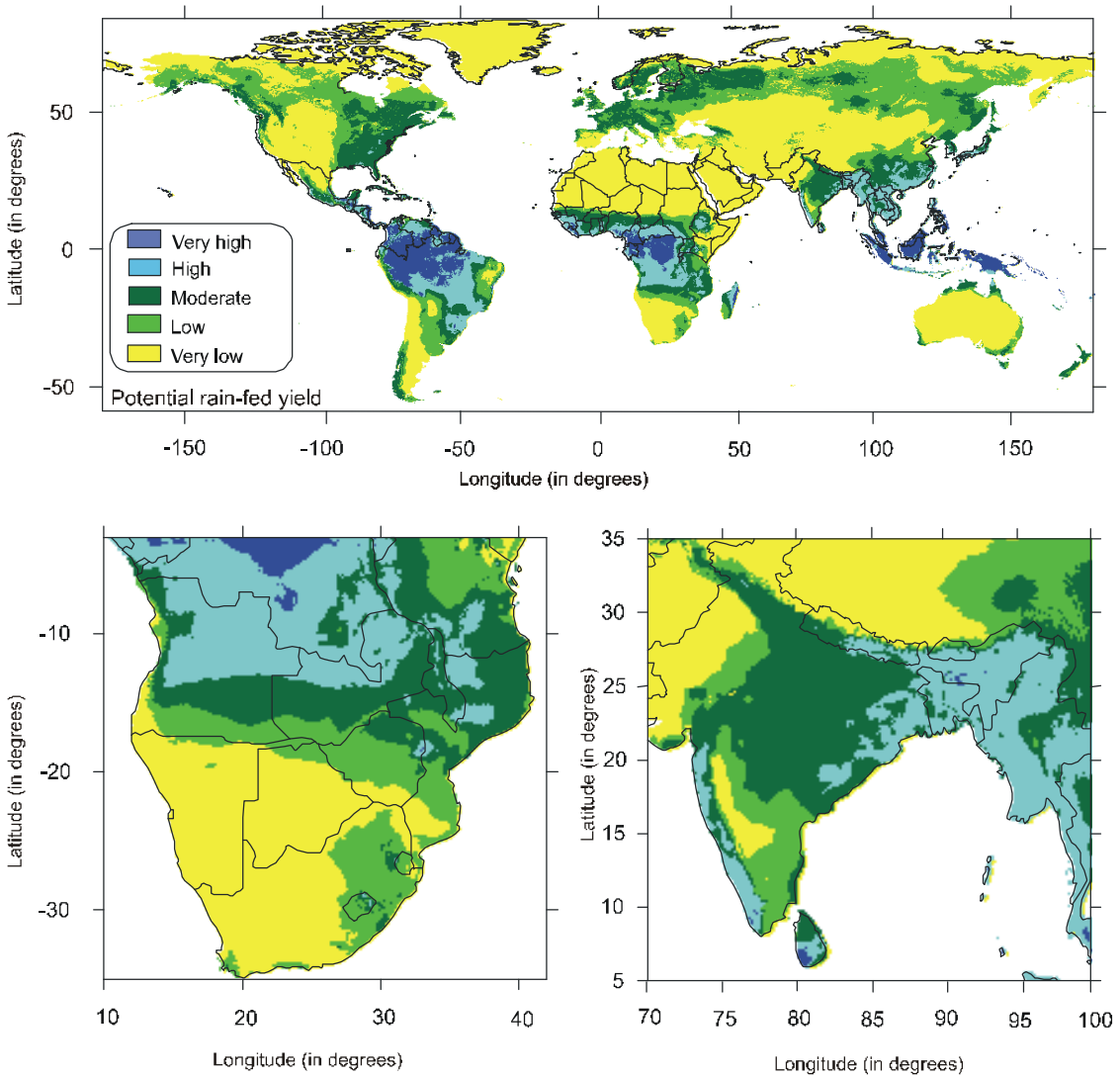
Total annual yields for the three examples were $11,000$, 2600 , and 5200 kg ha^{-1} , respectively. Although yields are high for the first example in India, the poor distribution of rain causes a substantial amount of runoff, which is not used to enhance crop growth. (Note, on a large-area basis, runoff can result in runoff irrigation to lower lands.) The second example shows water stress, and all the precipitation is directly used for crop growth. Finally, the case for the Netherlands shows some water shortage in August, and unfavorable climatic conditions for the beginning and the end of the year, while the crop benefits from water stored in the soil.

Rain-fed Potential

Figure 7 shows the potential for rain-fed agriculture as estimated using the IWMI/UEA Climate Atlas, the global soil-water-holding capacity map, and the soil-water and crop model. The four groups are defined somewhat arbitrarily at estimated production levels of 0 – $3,500$, $3,500$ – $7,500$, and $7,500$ – $12,500$, and higher than $12,500 \text{ kg ha}^{-1}$, for very low, moderate, high, and very high, suitability respectively. The extensive areas where potential yields of purely rain-fed agriculture are zero are striking. The distribution in area of these groups indicates that, on a global scale, 46 percent of the earth's surface is unsuitable for rain-fed agriculture due to limitations in climatic conditions. This leaves some 7 billion hectares with a potential for rain-fed crop production from which an area of 4.7 billion hectares is classified as moderate, high, or very high suitable. According to values from the World Resources Institute, 1.5 billion hectares are currently cropped—the remainder is presumably in forests, grasslands, wetlands and the like.

Detailed maps are shown again for sub-Saharan Africa and Southeast Asia. Obviously, the potential for rain-fed agriculture follows the ET_0 and, especially, the precipitation parameters. The potentials for rain-fed crop production are almost zero for the entire countries of Namibia and Botswana, for a substantial part of South Africa, and for some parts of Botswana and Mozambique. Only rainwater harvesting techniques, irrigated agriculture, or extensive livestock activities can support food supply. For much of Pakistan and India, rain-fed agriculture is impossible; for other areas of these countries the potential is low to moderate. Potentials for Eastern India, Bangladesh and Burma are high. A comparison between these two regions shows that Southeast Asia tends to have fewer areas with low or zero potentials, but it also lacks areas with high potentials (figures 7 and 8). In other words, extremes in potential for rain-fed agriculture are more profound in sub-Saharan Africa than in Southeast Asia.

Figure 7. Potentials for rain-fed agriculture on a global and regional scale.



The analysis has been done for some selected countries, shown in table 1. Considering only these areas classified as *moderate* to *very high*, as suitable areas for rain-fed agriculture, some countries do not fully utilize their potential area (USA, India), while other countries have larger actual cropped areas than potential ones (Spain, Pakistan, Morocco, South Africa). This is perhaps due to such factors as runoff and other kinds of irrigation, and fallowing. It should be emphasized again, that the values for potential areas are only defined using the climate and soil water as limiting factors, and ignoring the fact that other commitments are made to land. Countries where the actual cropped area is larger than the potential cropped area might have a fair amount of crops irrigated (Pakistan) or are using large areas with only limited suitability for rain-fed agriculture (South Africa). The values for Spain are somewhat peculiar, as the actual cropped area is much larger than the potential cropped area, while the percentage irrigated is quite low.

Figure 8. Cumulative distribution curve of yields from rain-fed agriculture.

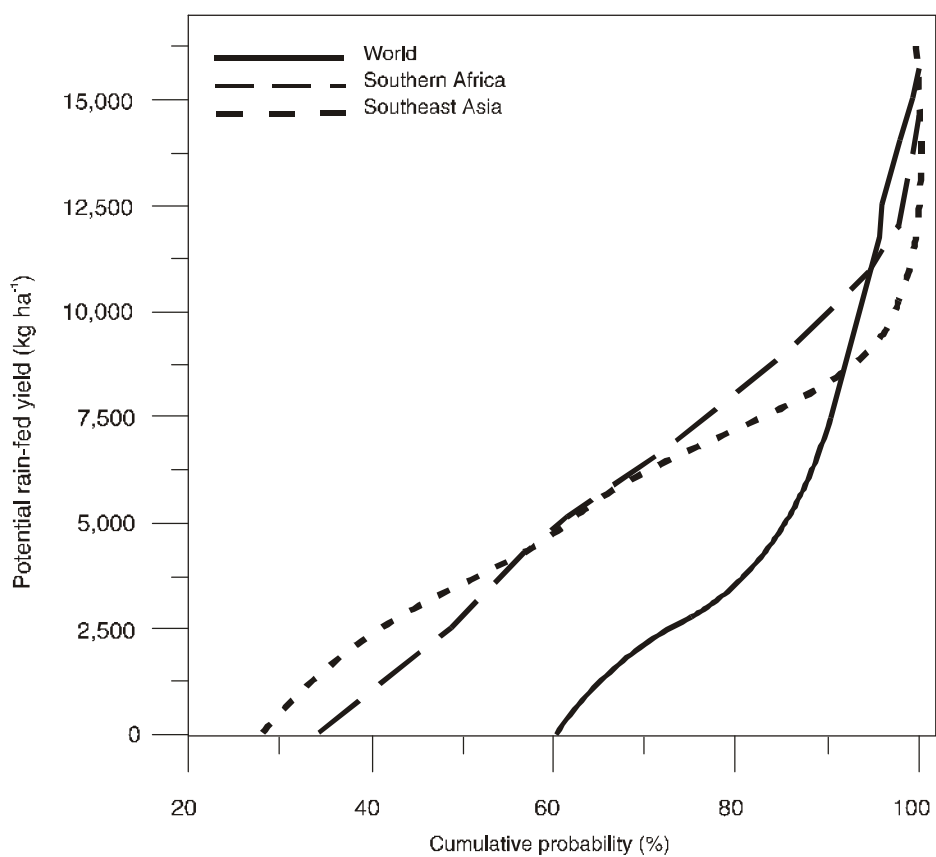


Table 1. Rain-fed potential for some selected countries.

	Land area	Rain-fed potential		Actual cropped WRI	Irrigated WRI %
		All	Suitable		
	'000 ha				
World	13,614,741	7,343,920	4,740,047	1,459,338	17
USA	794,270	392,021	272,374	189,799	11
Spain	48,240	12,362	2,615	20,512	18
Pakistan	87,310	4,951	2,009	20,330	80
India	317,649	252,456	195,107	169,078	29
Morocco	41,199	337	0	8,352	13
South Africa	122,125	39,940	2,841	13,169	8

Note: All are rain-fed potential areas classified as ranging from low to very high suitable; suitable are areas classified from moderate to very high. The actual cropped area and percentage of cropland irrigated are presented by the World Resources Institute (2000).

Future Research

One of the most interesting areas of future research and refinement of the model is in comparing the potential yields estimated here with the actual yields obtained by experiment stations, best farmers, regions and countries. For example, it is striking that areas considered as highly productive rain-fed areas, such as the USA corn belt and Western Europe, are not classified as having a high potential for rain-fed agriculture. Clearly, these areas benefit from high inputs in terms of fertilizer, pesticides, crop variety and appropriate management, rather than from optimum climate conditions. This leads to the well-known conclusion that, for other areas around the globe, production can increase substantially as socioeconomic and socio-technical conditions improve.

Overall, three main conclusions emerge from this study. First, that there is a large potential for rain-fed agriculture in many areas of the world, if the technical and socioeconomic constraints can be overcome. Second, however, many other areas of the world absolutely need more irrigation to meet the needs of their growing populations—and this is probably true of the world as a whole, even with increased international trade in food. Third, complementary to both of the preceding conclusions, there is a large potential for increasing food production through small-scale water-harvesting systems that provide partial irrigation when water is most needed by the crops. We will be using this model to evaluate this potential in the near future.

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