CIMMYT®

INTERNATIONAL MAIZE AND WHEAT IMPROVEMENT CENTER

An Agro-Climatological Characterization of Bread Wheat Production Areas in Ethiopia

Jeffrey W. White,[1] Douglas G. Tanner,[2] and John D. Corbett[3]

Published jointly by the
Wheat Program
and the
NRG
Natural Resources Group

Geographic Information Systems Series 01-01

[1] GIS and Modeling Lab, Natural Resources Group, CIMMYT
[2] Agronomist, CIMMYT Wheat Program, Addis Ababa, Ethiopia
[3] Blackland Research and Extension Center, the Texas A&M University Research System

CIMMYT® (www.cimmyt.org) is an internationally funded, nonprofit, scientific research and training organization. Headquartered in Mexico, CIMMYT works with agricultural research institutions worldwide to improve the productivity, profitability, and sustainability of maize and wheat systems for poor farmers in developing countries. It is one of 16 food and environmental organizations known as the Future Harvest Centers. Located around the world, the Future Harvest Centers conduct research in partnership with farmers, scientists, and policymakers to help alleviate poverty and increase food security while protecting natural resources. The centers are supported by the Consultative Group on International Agricultural Research (CGIAR) (www.cgiar.org), whose members include nearly 60 countries, private foundations, and regional and international organizations. Financial support for CIMMYT's research agenda also comes from many other sources, including foundations, development banks, and public and private agencies.

Future Harvest® builds awareness and support for food and environmental research for a world with less poverty, a healthier human family, well-nourished children, and a better environment. It supports research, promotes partnerships, and sponsors projects that bring the results of research to rural communities, farmers, and families in Africa, Asia, and Latin America (www.futureharvest.org).

Correct citation: White, J.W., D.G. Tanner, and J.D. Corbett. 2001. *An Agro-Climatological Characterization of Bread Wheat Production Areas in Ethiopia.* NRG-GIS Series 01-01. Mexico, D.F.: CIMMYT.

Abstract: This report describes a GIS-based assessment of the distribution of wheat production in Ethiopia, with emphasis on climate factors limiting the potential wheat area and using mainly agro-climatological characteristics obtained from interpolated climate data contained in the Ethiopian Country Almanac. Results suggest that the greatest opportunity for expanding wheat production in Ethiopia would involve increasing the tolerance of wheat to warmer growing conditions but that other factors, including the adaptation of current and/or alternate crops, overall land-use suitability, and market constraints must be considered before moving wheat into new areas. Site similarity analyses further suggest that the current distribution of wheat research sites in Ethiopia provides a reasonable coverage of the traditional wheat production area in terms of climatic conditions, and support the relevance of the Kulumsa station for wheat research throughout much of Eastern and Southern Africa.

ISSN: 1405-7484
AGROVOC descriptors: Soft wheat; Wheats; Food production; Temperature resistance; Climatic factors; Precipitation; Climatic zones; Climatology; Ethiopia.
AGRIS category codes: P40 Meteorology and Climatology; E14 Development Economics and Policies
Dewey decimal classification: 633.1

Printed in Mexico.

Contents

Page

Page	
v	Summary
1	Introduction
2	Materials and Methods
3	Overview of Wheat Production in Ethiopia
4	Results and Discussion
8	Conclusions
8	Acknowledgments
9	References

Tables

1	Table 1.	Comparison of human population, per capita income, wheat area, wheat production and other parameters for Ethiopia and other countries in sub-Saharan Africa (from Aquino et al. 1996).
2	Table 2.	Sites referred to in the text or indicated in Maps 1 or 7.
5	Table 3.	Comparison of elevations and climate for four sites in Ethiopia using data from the Ethiopian Country Almanac (ECA) and actual meteorological station data (courtesy of EARO). Climate data are for the wettest quarter.

Figures

3	Figure 1.	Annual variation in climate at Kulumsa, Ethiopia.
4	Figure 2.	Relationships between total precipitation (A) and elevation (B) and mean minimum temperature during the wettest quarter for 180 wheat germplasm accessions collected in Ethiopia.
7	Figure 3.	Variation in wheat grain yield at Kulumsa, Ethiopia, as simulated for changes in growing season total precipitation (A) and mean temperature (B).

Maps

Page

Page		
10	Map 1.	Approximate distribution of traditional wheat production areas of Ethiopia and the location of sites mentioned in this paper (re-drawn from Belay et al. 1999)
10	Map 2.	Approximate distribution of traditional wheat production areas of Ethiopia superimposed on climatic zones of Ethiopia where precipitation is over 350 mm and the mean minimum temperature is between 6° and 11°C during the wettest quarter of the year. The darkest areas in the southwest have a growing season greater than 9 months, based on P/PE greater than 0.5.
11	Map 3.	Areas of Ethiopia where precipitation is over 350 mm, the mean minimum temperature is between 6° and 11°C during the wettest quarter of the year, and the growing season is 9 months or less. The vertically hatched zones represent elevations above 2000 m.
11	Map 4.	Approximate distribution of traditional wheat production areas of Ethiopia re-drawn from Belay et al. (1999), the proposed climate-based wheat zone, and 180 wheat germplasm collection sites.
12	Map 5.	Areas of Ethiopia where precipitation is over 350 mm, the mean minimum temperature is between 6° and 11°C during the wettest quarter of the year, and the growing season is 9 months or less. The additional dark areas receive between 300 and 350 mm of precipitation during the wettest quarter of the year.
12	Map 6.	Areas of Ethiopia where precipitation is over 350 mm, the mean minimum temperature is between 6° and 11°C during the wettest quarter of the year, and the growing season is 9 months or less. The additional dark areas have mean minimum temperatures between 11° to 13°C during the wettest quarter of the year.
13	Map 7.	Areas within Ethiopia having climatic conditions during the wettest quarter that are similar to those of one of eight wheat research sites in the country.
14	Map 8.	Areas in sub-Saharan Africa having climatic conditions during the optimal five-month growing season that are similar to those at Kulumsa, Ethiopia.

Summary

This report describes a GIS-based assessment of the distribution of wheat production in Ethiopia, with emphasis on climatic factors limiting the potential wheat area. Analyses relied primarily on agro-climatological characteristics obtained from interpolated climate data contained within the Ethiopian Country Almanac; the same GIS-based tool was used to analyze climatic data related to current and potential wheat production areas in Ethiopia.

Based on consultations with Ethiopian wheat scientists and examination of a published map approximating the geographic distribution of current wheat production, traditional rainfed wheat production areas were best described in a zone with 350 mm or more precipitation and mean minimum temperatures of 6°C to 11°C during the wettest quarter (i.e., three consecutive months). The lower altitude limit for this zone is roughly 2,000 m. The wettest quarter was used to restrict planting to the onset of the "meher" (long-season) rains; planting at the onset of the "belg" (short-season) rains would expose the maturing wheat crop to high rainfall during the succeeding meher.

Precipitation and temperature limits were tested further by comparing them to climatic conditions at 180 wheat germplasm collection sites in Ethiopia. Results suggested a similar lower limit for precipitation and minimum temperature range, but a higher upper limit for minimum temperature range, although many collections were made at lower sites (for example, along major roads and in markets) that are warmer than actual wheat growing areas.

Examining the potential for wheat cropping in drier or warmer environments, it was found that allowing production in areas with as little as 300 mm of precipitation during the wettest quarter resulted in the addition of a small area, primarily in the southeast near the Sinana research station. In contrast, raising the upper limit of the minimum temperature range by 2°C would perhaps double the potential wheat area on the periphery of the highlands, due to a mean rainfall of over 500 mm during the wettest quarter in such areas. Thus, the present agro-climatological constraint on wheat area is not lack of rainfall but warm temperatures. This suggests that attempts to identify new productive areas should focus on strategies for overcoming heat stress and on resistance to wheat diseases associated with warmer environments, subject of course to soil suitability, the presence of other crops, labor availability, and other socioeconomic factors in the areas identified for expansion.

On examining the distribution of eight wheat research stations, we found that the present set of stations covered most Ethiopian wheat zones and exhibited little overlap. In a broader similarity analysis for the Kulumsa station (a key center for wheat research in Eastern Africa), the climate at that location was similar to those of major wheat-producing areas of Kenya and Ethiopia, as well as in the Great Lakes Region (Rwanda, southwestern Uganda, and the North Kivu district of the Democratic Republic of the Congo), northern Tanzania, and Lesotho.

An Agro-Climatological Characterization of Bread Wheat Production Areas in Ethiopia

Introduction

Ethiopia is the second largest producer of wheat in sub-Saharan Africa, following South Africa (Table 1). About 900,000 ha of bread (*Triticum aestivum*) and durum (*T. turgidum* var. *durum*) wheats are grown in Ethiopia, primarily as highland rainfed crops. Mean wheat yields are around 1.4 t/ha, well below experimental yields of over 5 t/ha (Hailu 1991). Ethiopia's current annual wheat production of approximately 1.3 million tons is insufficient to meet domestic needs, forcing the country to import 30 to 50% of the annual wheat grain required. The yield gap of over 3 t/ha suggests the potential for increasing production through improved crop management, particularly increased use of fertilizers. However, there is also justification for examining whether wheat production can be introduced to non-traditional areas. Geographic information systems (GIS) provide a way to do this, allowing researchers to examine crop distribution in relation to climate and other factors.

This paper first examines the current distribution of wheat production in relation to climate. It then uses the described climatic limits as the basis for evaluating the potential for increasing wheat production area in Ethiopia. To understand the possible contribution that different research centers might make to improving wheat production in current or potential wheat areas, climate similarity analyses were conducted for research stations used by the cooperative National Wheat Research Program coordinated under the auspices of the Ethiopian Agricultural Research Organization (EARO).

Emphasis is given to the use of quantitative characterizations based on climate data that have been interpolated over all of Africa (Corbett and O'Brien 1997). This ensures that mapped distributions are more fully testable and reproducible, thus contributing to a more precise understanding of the adaptation of wheat in Ethiopia as well as in other countries.

Table 1. Comparison of human population, per capita income, wheat area, wheat production, and other parameters for Ethiopia and other countries in sub-Saharan Africa (from Aquino et al. 1996).

	Ethiopia	Kenya	South Africa	Sudan	Zambia	Zimbabwe
Estimated population, 1995 (million)	58.6	28.3	41.5	28.1	9.5	11.3
Estimated growth rate of population, 1993-2000 (% per year)	3.0	2.5	2.2	2.7	2.6	2.2
Per capita income, 1994 (US $)	100	250	3,040	…	350	500
Average wheat area harvested, 1993-1995 (000 ha)	884	155	1,166	325	18	41
Average wheat yield, 1993-1995 (t/ha)	1.4	1.6	1.7	1.5	3.1	4.9
Average wheat production, 1993-1995 (000 t)	1,270	252	1,983	483	55	199
Average net imports of wheat, 1992-94 (000 t)	391	215	557	460	28	90
Nitrogen applied, 1993-1994 (kg N/ha)	5	23	60	87	62	160

Materials and Methods

The primary data source for the climatic analyses were the climate surfaces for Africa developed by Corbett (1994) using thin plate smoothing splines (Hutchinson 1995). In this technique, monthly mean data for precipitation and temperature are interpolated from point data corresponding to long-term records of meteorological stations. This variant of spline techniques allows use of data from a digital elevation model (DEM, essentially a topographic map converted to grid-based format) to improve the estimation of variation in climate with elevation. The DEM had a 2.5 arc-minute grid size, which is roughly equivalent to a 5 km x 5 km grid size for regions near the equator. In addition to the basic climate variables, the set of surfaces includes data for potential evapotranspiration (PET) and ratios of precipitation to PET (P/PET). These variables are provided both on an annual basis and for various season models, including an optimal season defined as the five-month period with the highest value of P/PET and the wettest quarter defined as the three consecutive months with the greatest precipitation.

Climate data for long-term monthly means at specific sites were obtained from the FAO climate database for Africa (FAO 1984). A list of the locations considered in the current study is given in Table 2; the locations are also shown in Map 1.

Zones for climate and site similarity within Ethiopia were defined using the Ethiopia Country Almanac (ECA), a component of the Country Almanac Series of CD-ROM-based data sets and tools for manipulating spatial data (Corbett et al. 1999).

Table 2. Sites referred to in the text or indicated in Maps 1 or 7.

Site	Latitude (°N)	Longitude (°E)	Elevation (m)	Comments
Addis Ababa	9.03	38.75	2,354	Capital city of Ethiopia, wheat production area, waterlogging on Vertisols.
Adet†	11.27	37.48	2,240	Wheat research site, waterlogging on Vertisols, low soil fertility on Nitisols.
Alemaya	9.50	41.02	1,950	Maize and wheat research site, moisture stress zone.
Ambo	9.05	37.82	2,225	Key highland maize research site, waterlogging on Vertisols.
Asasa	7.13	39.21	2,360	Wheat research site, relatively short growing season with terminal moisture stress.
Awassa	7.05	38.47	1,750	Maize research site.
Bekoji†	7.53	39.25	2,780	Wheat research site, high rainfall, long growing season.
Debre Markos	10.35	37.73	2,440	Wheat production area, waterlogging on Vertisols.
Debre Zeit†	8.73	38.97	1,900	Durum research coordinating center, waterlogging on Vertisols.
Ginchi	9.03	38.15	2,250	Wheat research site, waterlogged Vertisol.
Goba	7.02	39.98	2,710	Wheat production area, bimodal rainfall.
Gondar	12.60	37.47	1,967	Wheat production area, high rainfall.
Holetta†	9.05	38.50	2,400	Wheat research site, *Septoria* hotspot, waterlogging on Vertisols.
Kulumsa†	8.00	39.15	2,200	National bread wheat research coordinating center.
Mekelle†	13.30	39.29	2,050	Capital city of Tigray Region, frequent droughts.
Sinana†	7.13	40.02	2,400	Wheat research site, bimodal rainfall.
Weldiya†,‡	11.75	39.60	2,320	Wheat production area.

† Sites characterized by climatic similarity analyses in Map 7.

‡ Actual coordinates refer to a point approximately 20 km west of Weldiya town that corresponds to a wheat and barley region (barley being grown at higher elevations).

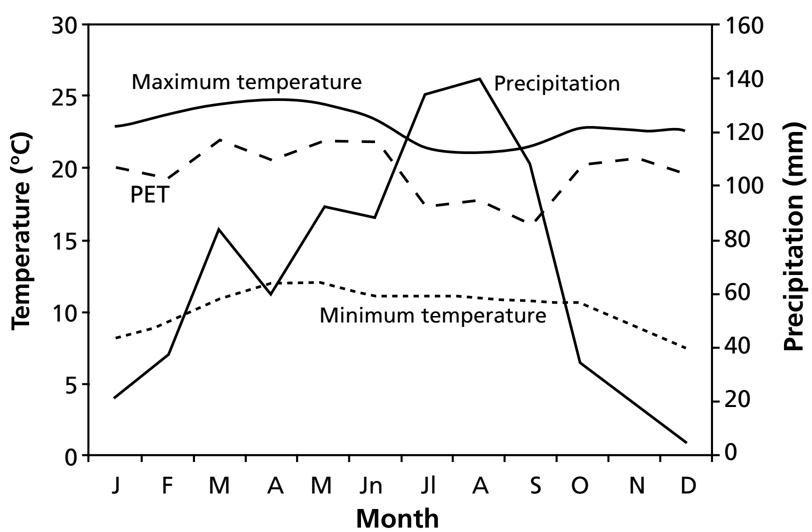
Climate zones are defined through map overlay and selection procedures. Zones of similar climate are specified by characterizing the climate at the latitude and longitude of the reference site and then selecting criteria for similarity. For this study, the similarity zones were usually based on the wettest quarter (three-month period) and considered ranges of +/- 50 mm for precipitation and PET and of +/- 1°C for mean maximum and minimum temperatures, unless otherwise specified. For similarity analyses over all of Africa, the Spatial Characterization Tool (Corbett and O'Brien 1997) was used, assuming +/- 10% ranges for the five most favorable months based on the ratio P/PET. All maps are presented unprojected, by latitude and longitude. To verify the limit of zones based on climatic limits, conditions at specific locations were also assessed. Presumed wheat production locations were obtained based on collection sites of bread wheats as listed in the USDA GRIN database (USDA-ARS-NGRP 2000).

Simulations of wheat crop growth and development were conducted using CERES Wheat V3.50[98.0] (Hoogenboom et al. 1994; P. Wilkens, personal communication, 1999). A 10-year set of weather data from Kulumsa, Ethiopia, was used in conjunction with a generic soil profile for a sandy loam assumed to allow root growth to a depth of 0.9 m. Seed was broadcast at a density of 180 plants/m^2 and fertilized each year with 10 kg of nitrogen. A window for sowing date from 1 July to 1 August was allowed.

Overview of Wheat Production in Ethiopia

In Ethiopia, wheat is grown primarily as a rainfed crop by smallholders in the highlands (Map 1). In most of the country, only a single wheat crop is grown during the second, longer rainy season (meher) which usually starts in June (Fig. 1). The short rains (belg), starting in March, are less reliable in most parts of Ethiopia; however, in the southeast of the country (e.g., Bale zone of Oromiyia Region), rainfall distribution is bimodal. Growing wheat in belg season implies harvesting during meher, which often results in high grain moisture levels and sprouting. Thus, wheat crops are typically sown by broadcasting in June or July and harvested in November or December (Hailu 1991). A very small area has also been grown as a winter crop under irrigation on state farms at lower elevations (Jamal 1994).

Figure 1. Annual variation in climate, Kulumsa, Ethiopia.



Bread wheat accounts for roughly 60% of total wheat production and nearly all cultivars are derived from modern, semi-dwarf wheats. Durum wheat accounts for most of the remaining 40%, although emmer wheat (*T. dicoccum* L.) is also grown. Bread wheat is produced at slightly higher elevations and on better drained soils than durum wheat, which is primarily found on poorly drained Vertisols (Hailu 1991).

Wheat production constraints include low soil fertility, grass weed infestations, waterlogging in Vertisol areas, and water deficits in short season areas (Tanner et al. 1991). Stripe rust (*Puccinia striiformis*) is common at higher elevations (> 2,400 m); stem rust (*P. graminis* f. sp. *tritici*) is more problematic at mid-elevations (2,000-2,400 m) (Bekele and Tanner 1995).

Double-cropping has recently been demonstrated as a promising option for southeastern Ethiopia (Tanner et al. 1994). In the Bale zone of Oromiya Region, the belg rains are sufficiently long and reliable for wheat or other crops. Double cropping could reduce the negative effects of the current practice of alternate season fallows: a continuous crop cover would reduce erosion; alternating crops would help control weeds; and human and animal power could be used more efficiently.

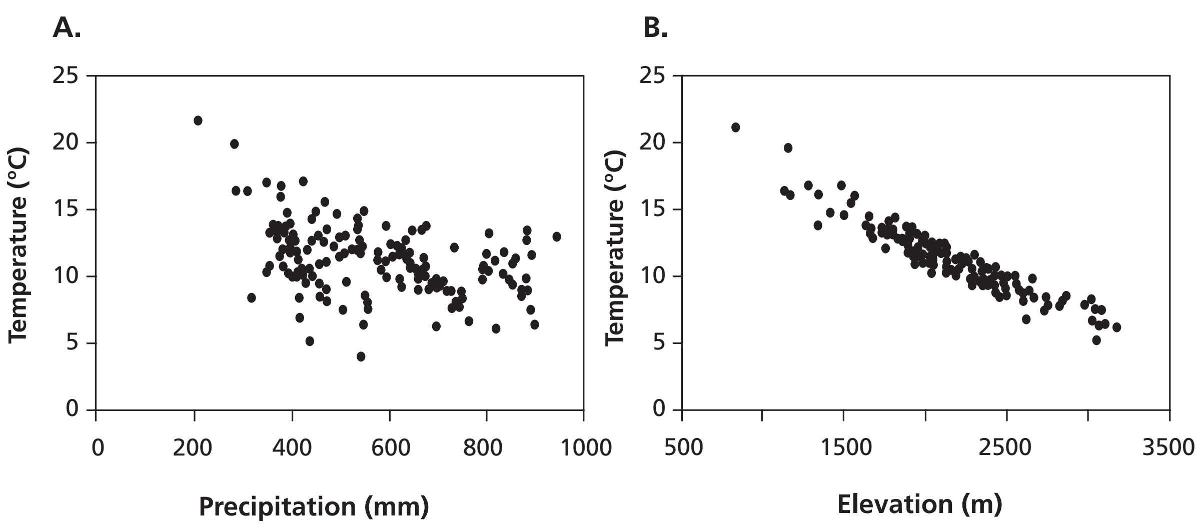
Results and Discussion

Present wheat production areas

A review of growing season conditions for various highland research sites suggested that precipitation and minimum temperature were key determinants of potential wheat areas. Setting requirements of at least 350 mm rainfall and a minimum temperature between 6° to 11°C during the wettest quarter (three months) produced a distribution map similar to the approximation of traditional wheat production areas reproduced from Belay et al. (1999; Map 2).

These limits, however, resulted in the inclusion of a high rainfall area of southwestern Ethiopia that is too wet for wheat production (annual precipitation > 1,800 mm). Subsequent consultations indicated that this area grows highland maize (*Zea mays* L.) and enset (*Musa abyssinica*), which are better suited to long, wet growing seasons. This zone was thus excluded from the potential wheat area by tightening the selection criteria to exclude areas having a growing season greater than 9 months (Map 2). The revised wheat zone closely corresponds to sites exceeding 2,000 m in altitude (Map 3).

Figure 2. Relationships between total precipitation (A) and elevation (B) and mean minimum temperature during the wettest quarter for 180 wheat germplasm accessions collected in Ethiopia.



To provide an independent estimate of appropriate temperature and rainfall ranges for wheat production zones, values for precipitation and mean minimum temperature during the wettest quarter were obtained for 180 bread wheat germplasm collection sites in Ethiopia (Map 4). It is notable that most collection points fell within the derived wheat production zone. These data also support the lower limits of 350 mm for precipitation and 6°C for minimum temperature (Fig. 2A) used to develop our wheat distribution map. However, the upper limit for minimum temperature proved more problematic, with about half the collection sites exhibiting minimum temperatures over 11°C and nine sites having values over 15°C. Comparing minimum temperature with elevation (as estimated from the 5 km digital elevation model, not as reported with the germplasm collection data) showed that some collections came from locations well below the suggested 2,000 m limit (Fig. 2B). Further inspection of passport data for bread wheat accessions suggested several possible explanations for these discrepancies. Most accession data did not include information on the type of collection, but in cases where this information was recorded, the seeds often came from markets. Thus, in many cases, samples may have come from locations lower than where their source crops were actually grown. It is also possible that some locations were erroneously recorded. Hijmans et al. (1999) noted that geographic coordinates reported for collection sites exhibit high error rates.

The described results must also be qualified in relation to possible sources of error in the climate data and the difficulty in attributing objective limits to ranges of adaptation or climatic similarity. Although a formal error analysis is not possible, indirect approaches can give some idea about the reliability of characterizations.

The climate surfaces have errors attributable to the source point data, the distribution of the points, the 5 km grid size of the DEM, and the interpolation procedure itself. One indicator of the cumulative effects of these errors is to compare interpolated values with actual observed data. Table 3 compares interpolated values from the ECA with actual, measured values for Debre Zeit, Kulumsa, Holetta, and Bekoji. Elevation figures were within 200 m of each other. Given the approximate relation between elevation and temperature, whereby temperature drops by roughly 0.6ºC per 100 m increase in elevation (see Fig. 2B), this discrepancy should result in an error of roughly 1ºC in temperature. In effect, temperature discrepancies were generally of this order and in the expected direction. Minimum temperature at Holetta was the notable exception, where a 95 m elevation difference corresponded to a 0.4ºC temperature difference opposite to the direction expected based on the elevation effect. This suggests that temperature errors in the current study were generally less than 1ºC. The magnitude of the

Table 3. Comparison of elevations and climate for four sites in Ethiopia using data from the Ethiopian Country Almanac (ECA) and actual meteorological station data (courtesy of EARO). Climate data are for the wettest quarter.

	Debre Zeit		Kulumsa		Holetta		Bekoji	
Data source:	**ECA**	**Station**	**ECA**	**Station**	**ECA**	**Station**	**ECA**	**Station**
Elevation (m)	2,046	1,900	2,130	2,200	2,495	2,400	2,996	2,780
Mean daily maximum temperature (°C)	23.3	24.2	21.9	21.1	20.0	19.8	16.2	17.2
Mean daily minimum temperature (°C)	11.7	12.4	11.0	10.9	9.1	8.7	5.9	7.7
Total precipitation (mm)	576	555	467	376	704	653	525	499
PET (mm)	300	--	297	--	257	--	242	--

discrepancies were lower than those reported for a similar study in highland Bolivia where a DEM with a 10 km grid cell size was used (Hodson et al. 1998).

Differences between interpolated and observed precipitation values varied from 21 mm at Debre Zeit to 91 mm at Kulumsa. Since there is often no consistent relationship between elevation and precipitation over large areas, these differences are not readily attributable to differences between actual elevation and DEM values. Unfortunately, current methods for interpolating precipitation data are extremely dependent on the number, distribution, and quality of the point data. Models such as PRISM attempt to improve the interpolations by accounting for effects of prevailing winds, slope and aspect, and weather systems (Natural Resources Conservation Service Water and Climate Center 1998) and offer hope for future improvements. Similarly, data on cloud cover and temperature can be used to improve estimates of rainfall in an area (Climate Prediction Center 2000; Arkin and Ardanury 1989), although values are typically reported on a 10 km grid.

Potential wheat production areas

Because water deficits and warm night temperatures seemed to be key factors delimiting bread wheat production areas in Ethiopia, potential new areas for bread wheat production were identified by assuming that technologies could be developed to allow wheat to be grown in drier or warmer environments. For drier conditions, such technologies might include more drought tolerant cultivars, supplemental irrigation from small catchments, or agronomic practices—such as reduced tillage and residue retention—that reduce runoff. Growing wheat under warmer conditions might require cultivars with greater heat tolerance as well as resistance to pathogens that prevail under warmer conditions (e.g., *Helminthosporium sativum*).

Applying the assumption that wheat will grow in areas receiving as little as 300 mm during the wettest quarter resulted in a surprisingly small addition (4%) to the potential wheat production area (Map 5). In contrast, a shift in adaptation to include areas with 2°C warmer minimum temperatures (e.g., up to 13°C) substantially increase potential wheat area (Map 6). The actual impact on total wheat area is impossible to estimate: zones that meet climate criteria may have unsuitable soils or topography or already be used for other, more profitable agricultural pursuits. However, as a rough indicator, increasing the minimum temperature limit by 2°C expanded the potential area suitable for wheat production by 108%.

These results seem counter-intuitive, given the popular conception of Ethiopia as an arid, drought-prone country. The principal explanation is that, in terms of wheat cropping and ignoring year-to-year variation, the Ethiopian highlands (to which the wheat crop is so well-adapted) represent a relatively humid environment. Precipitation during the wettest three months is usually well in excess of PET (Table 3; Fig. 1).

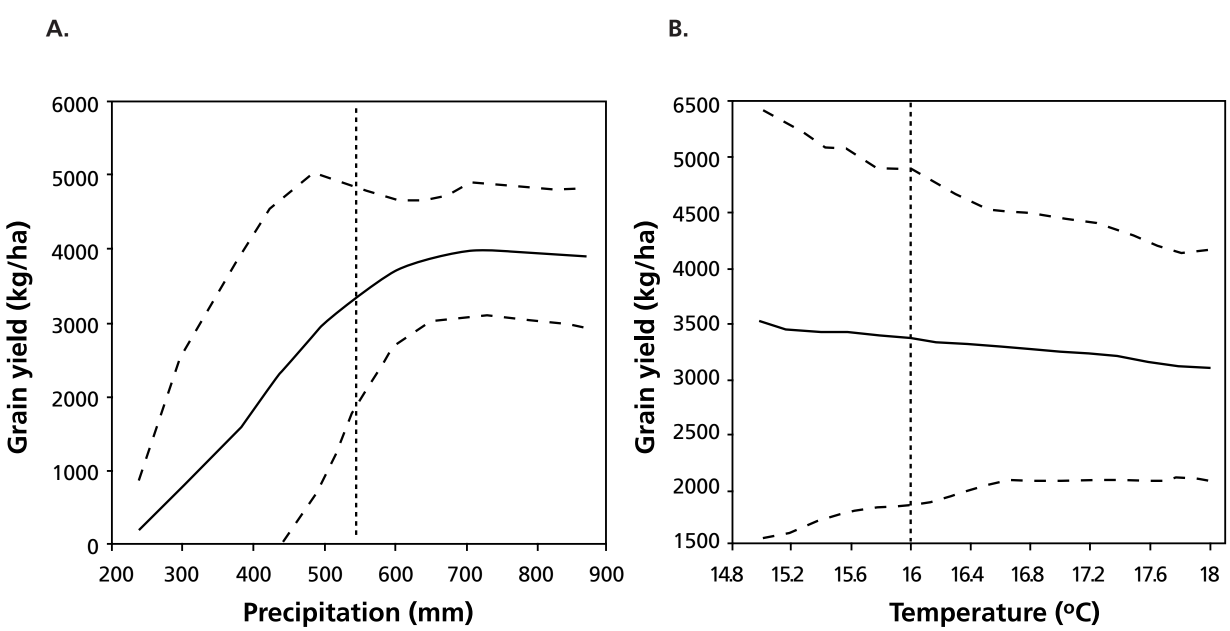
Representativeness of current wheat research sites

To examine whether the key wheat research sites used by the National Wheat Research Program of Ethiopia are representative of wheat production areas in Ethiopia, site similarity analyses were conducted for eight locations (Table 2). The sites were found to cover a wide range of environments (Map 7). Almost as important, the zones showed little or no overlap, suggesting that the set of research sites efficiently samples the current wheat production area.

The area of wheat production identified as "20 km west of Weldiya" (Map 7) in Welo zone of the Amhara Region is currently not served by a wheat research station. Consultation with agronomists familiar with the region confirmed that a limited amount of wheat research is conducted on behalf of the National Wheat Research Program by crop scientists based at Sirinka, a sorghum research station situated in a valley bottom at an altitude too low for wheat (ca. 1,850 m). It was also reported that, to address this deficiency, the Sirinka development plan includes the establishment of substations in the neighboring wheat production areas.

The ranges of precipitation, PET, and temperature limits used in these similarity analyses (+/- 50 mm and +/- 1°C) merit examination. The intention was to use a range corresponding to yield differences that are detectable in field trials. For potential grain yield levels of 3,000 to 4,000 kg/ha, this might represent a yield difference of 300 kg/ha. Using 10 years of weather data at Kulumsa, simulations were run to evaluate wheat yield response to precipitation and temperature (Fig. 3). Reducing precipitation from the mean of 540 mm to 490 mm over the growing season decreased yields 430 kg/ha, whereas an increase of 50 mm raised yields 345 kg/ha (Fig. 3A). Reducing the maximum and minimum temperatures during the growing season 1°C (for a growing season mean at Kulumsa of 16° C) increased wheat yields about 140 kg/ha (Fig. 3B). This was attributable mainly to a slight delay in maturity (120 days vs. 115 days for the actual weather). Increasing temperatures 1°C decreased wheat yields 130 kg/ha, whereas an increase of 2°C reduced wheat yields 270 kg/ha. These simulated results suggest that the limits used to define site similarity zones are probably conservative.

Figure 3. Variation in wheat grain yield at Kulumsa, Ethiopia, as simulated for changes in growing season total precipitation (A) and mean temperature (B).†



† Broken lines indicate +/- 2 standard deviations for simulations based on 10 years of weather data. The vertical lines indicate mean values over the growing season.

Because the Kulumsa research station is a center of excellence for bread wheat research in Eastern Africa and collaborates with other national wheat research programs in the Eastern and Central Africa Maize and Wheat Research Network (ECAMAW), the similarity of its climate to other sites in Eastern Africa was also considered. A less restrictive set of criteria were used for this exercise (i.e., +/- 20% of rainfall and potential evapotranspiration and +/- 10% of mean maximum and minimum temperatures), given that the goals for transnational collaborative research should be broader than those for a sub-national research program. Furthermore, to better compare Kulumsa conditions with those of wheat production zones elsewhere in sub-Saharan Africa, the five optimal months where P/PE is greater than 0.5 were considered. The results suggest that the climate at Kulumsa is similar to conditions in major wheat-producing areas of Kenya and Ethiopia, and significantly congruent with those of wheat-producing areas in the Great Lakes Region (Rwanda, southwestern Uganda, and the North Kivu district of the Democratic Republic of the Congo), northern Tanzania, Lesotho, and South Africa (Map 8). Of these areas, the only one not recognized as significant for wheat production is the area in South Africa and east of Lesotho. Wheat is apparently not grown in this area due to several factors, including the difficult terrain, competition from traditional smallholder crops, and the comparative advantage for the production of wheat as a winter crop in the Mediterranean climate of southwestern South Africa.

Conclusions

Our climate-based analyses suggest that the greatest opportunity for expanding wheat production area in Ethiopia would involve increasing the tolerance of wheat to warmer growing conditions; this means both heat tolerance and resistance to pathogens and pests of warmer climates. However, any plans for expanding wheat production must also consider other factors, including the adaptation of current and/or alternate crops, overall land-use suitability, and market constraints. The similarity analyses further suggest that the current distribution of wheat research sites in Ethiopia provides a reasonable coverage of the traditional wheat production area in terms of climate conditions, and support the relevance of the Kulumsa station for wheat research throughout much of Eastern and Southern Africa. Overall, these results demonstrate the utility of analyzing regional variation in climate using tools such as those provided in the Ethiopia Country Almanac.

Acknowledgments

Drs. Bedada Girma, Amanuel Gorfu, and Kidane Georgis of EARO and Doug Clements of CIDA/PSU-Ethiopia provided valuable information on the relative importance of wheat in various regions of Ethiopia. Adriana Rodriguez and Dave Hodson helped significantly in processing the spatial data. CIMMYT science writer Mike Listman and designer Wenceslao Almazán collaborated to edit and produce the publication. The authors express their gratitude to the Environmental Systems Research Institute, Inc., for providing the ArcInfo and ArcView software. The authors also appreciate the financial support provided by the CIMMYT/CIDA Eastern Africa Cereals Program to cover the cost of publishing this document.

References

Aquino, P., V. Hernández, and R.M. Rejesus. 1996. Selected wheat statistics. In: *CIMMYT 1995/1996 World Wheat Facts and Trends: Understanding Global Trends in the Use of Wheat Diversity and International Flows of Wheat Genetic Resources*, pp. 39-62. Mexico, D.F.: CIMMYT.

Arkin, P.A., and E. Ardanury. 1989. Estimating climatic-scale precipitation from space: A review. *Journal of Climate* 2:1229-1238.

Bekele Geleta and D.G. Tanner. 1995. Status of cereal production and pathology research in Ethiopia. In: D.L. Danial (ed.). *Breeding for Disease Resistance with Emphasis on Durability,* pp. 42-50. Wageningen, The Netherlands: Wageningen Agricultural University.

Belay Simane, D.G. Tanner, Amsal Tarekegene and Asefa Taa. 1999. Agro-ecological decision support systems for wheat improvement in Ethiopia: Climatic characteristics and clustering of wheat growing regions. *African Crop Science Journal* 7:9-19.

Climate Prediction Center. 2000. Famine Early Warning System (FEWS). www.cpc.ncep.noaa.gov/products/fews/ (10 June 2000).

Corbett, J.D. 1994. Climate Surfaces for Latin America v. 1.1. Five Arc-Minute Resolution. Climate Coefficients Created Using ANUSPLIN. Nairobi, Kenya: ICRAF.

Corbett, J.D., and R.F. O'Brien. 1997. The Spatial Characterization Tool – Africa v. 1.0. Texas Agricultural Experiment Station, Texas A&M University System, Blackland Research Center Report No. 97-03 (CD-ROM).

Corbett, J.D., S. Collis, B. Bush, E. Muchugu, R.F. O'Brien, R. Jeske, P. Burton, R. Martinez, C. Stone, J.W. White, and D.P. Hodson. 1999. USAID's African Country Almanac. Version 2.0.1. Texas A&M University System, Blackland Research Center Report No. 99-06. CD-ROM.

FAO. 1984. Agroclimatological Data for Africa. Rome: FAO.

Hailu Gebre-Mariam. 1991. Wheat production and research in Ethiopia. In: Hailu Gebre-Mariam, D.G. Tanner, and M. Hulluka (eds.). *Wheat Research in Ethiopia: A Historical Perspective.* Addis Ababa: IAR/CIMMYT.

Hijmans, R., M. Screuder, J. de la Cruz, and L. Guarini. 1999. Using GIS to check co-ordinates of genebank accessions. *Genetic Resources and Crop Evolution* 46:291-296.

Hodson, D., J.D. Corbett, P.C. Wall and J.W. White. 1998. An Agro-climatological Overview of Wheat Production Regions of Bolivia. NRG-GIS Paper 98-01. CIMMYT, Mexico, D.F.

Hoogenboom, G., J.W. Jones, P.W. Wilkens, W.D. Batchelor, W.T. Bowen, L.A. Hunt, N.B. Pickering, U. Singh, D.C. Godwin, B. Baer, K.J. Boote, J.T. Ritchie, and J.W. White. 1994. Crop models. In: G.Y. Tsujo, G. Uehara, and S. Balas (eds.). *DSSAT v3,* pp. 95-244. Honolulu: University of Hawaii.

Hutchinson, M.F. 1995. Interpolating mean rainfall using thin plate smoothing splines. *International Journal of GIS* 106:211-232.

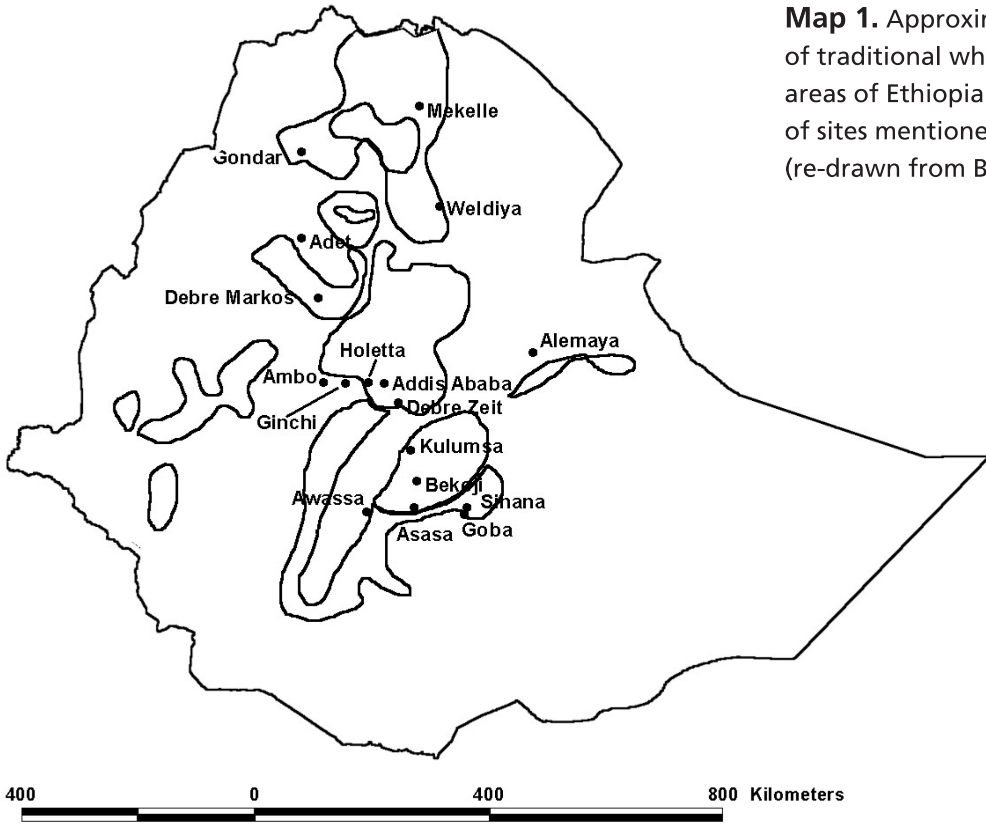
Jamal Mohammed. 1994. Performance of wheat genotypes under irrigation in Awash Valley, Ethiopia. *African Crop Science Journal* 2:145-152.

Natural Resources Conservation Service Water and Climate Center. 1998. PRISM Briefing Book and Questionnaire: A Description of the PRISM Model for Spatially Distributing Observed Precipitation. http://ocs.orst.edu/prism/nrcs_brief.html (9 June 2000).

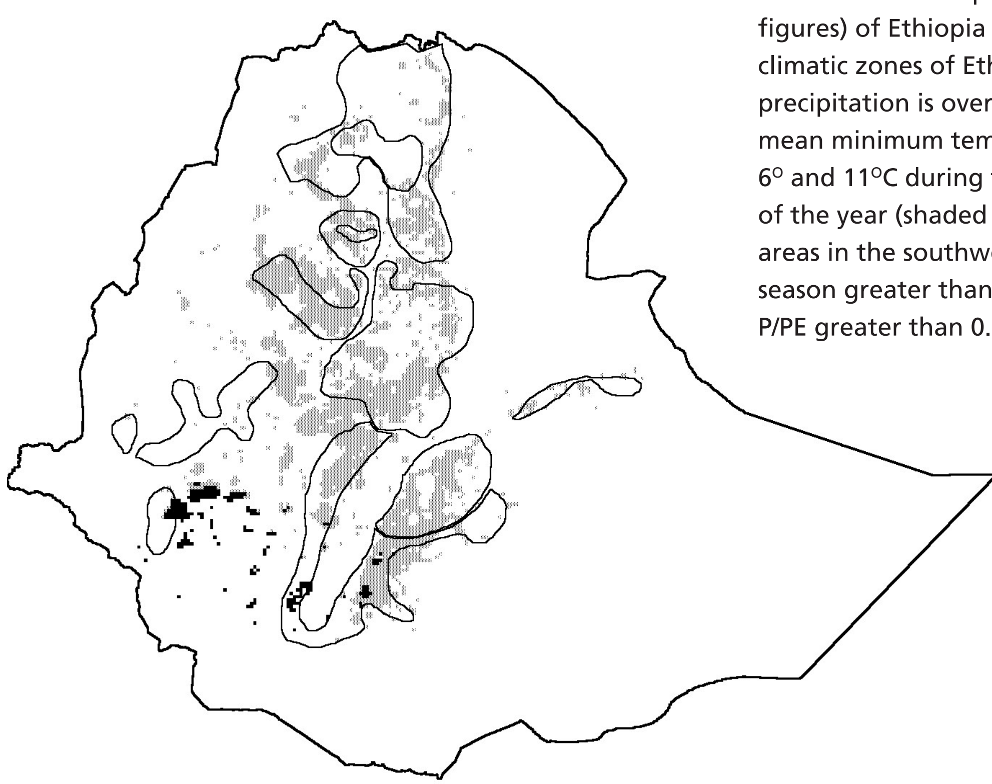
Tanner, D.G., Amanuel Gorfu, and Kassahun Zewde. 1991. Wheat agronomy research in Ethiopia. In: Hailu Gebre-Mariam, D.G. Tanner, and Mengistu Hulluka (eds.). *Wheat Research in Ethiopia: A Historical Perspective*, pp. 95-135. Addis Ababa: IAR/CIMMYT.

Tanner, D.G., Zewdu Yilma, Lemma Zewdie, and Girmay Gebru. 1994. Potential for cereal-based double cropping in Bale Region of southeastern Ethiopia. *African Crop Science Journal* 2:135-143.

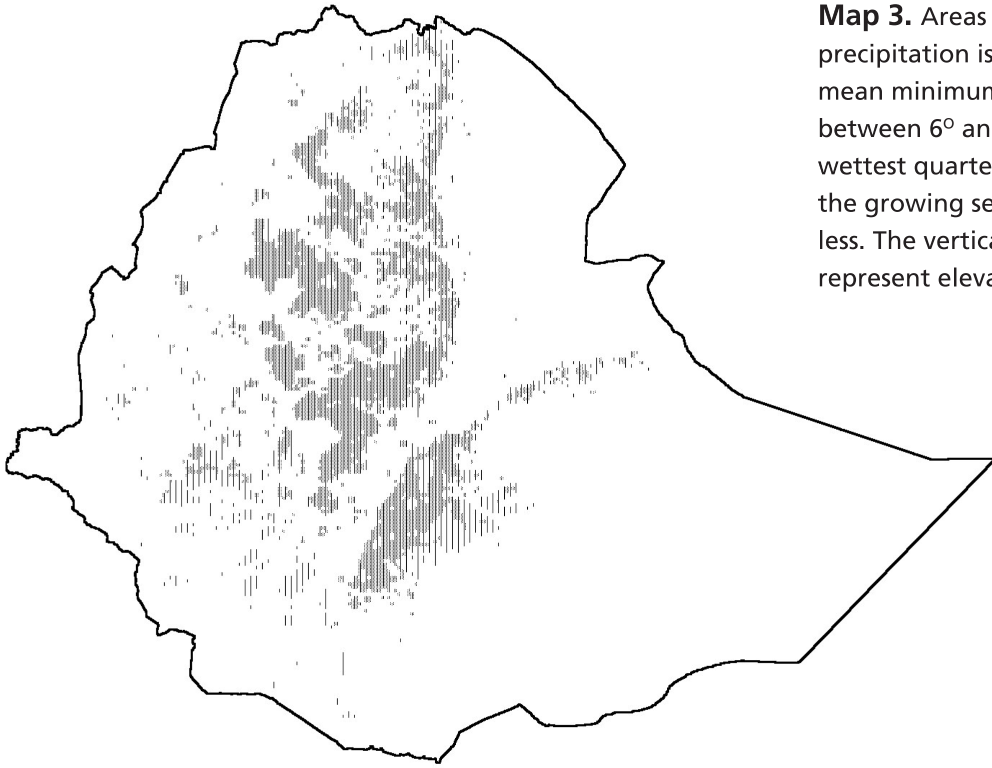
USDA-ARS-NGRP. 2000. USDA, ARS, National Genetic Resources Program. Germplasm Resources Information Network (GRIN) [Online Database]. National Germplasm Resources Laboratory, Beltsville, Maryland. www.ars-grin.gov/usr/local/apache/cgi-bin/npgs/html/obs.pl?1164702 (07 June 2000).



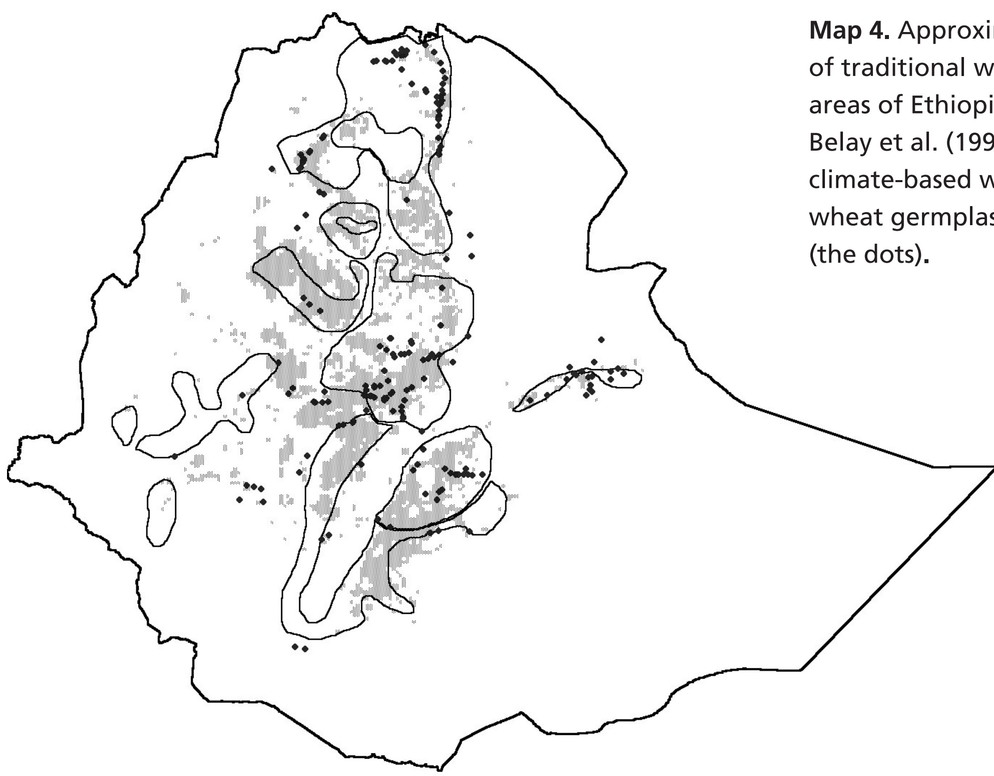
Map 1. Approximate distribution of traditional wheat production areas of Ethiopia and the location of sites mentioned in this paper (re-drawn from Belay et al., 1999).



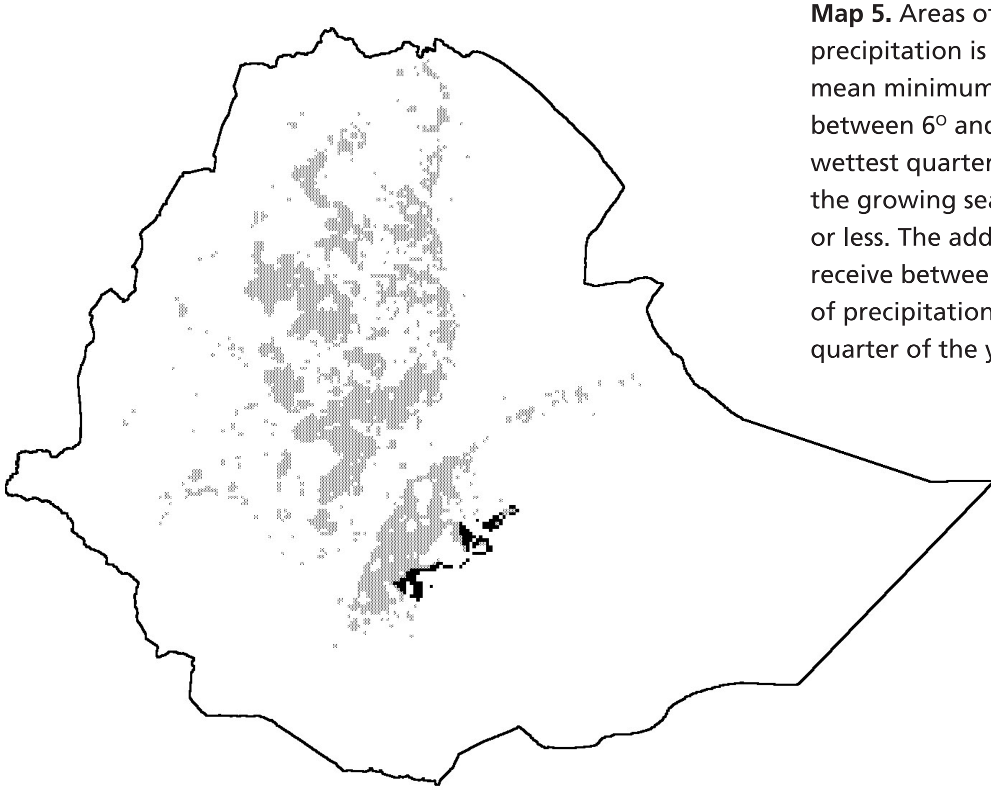
Map 2. Approximate distribution of traditional wheat production areas (line figures) of Ethiopia superimposed on climatic zones of Ethiopia where precipitation is over 350 mm and the mean minimum temperature is between 6° and 11°C during the wettest quarter of the year (shaded areas). The darkest areas in the southwest have a growing season greater than 9 months, based on P/PE greater than 0.5.



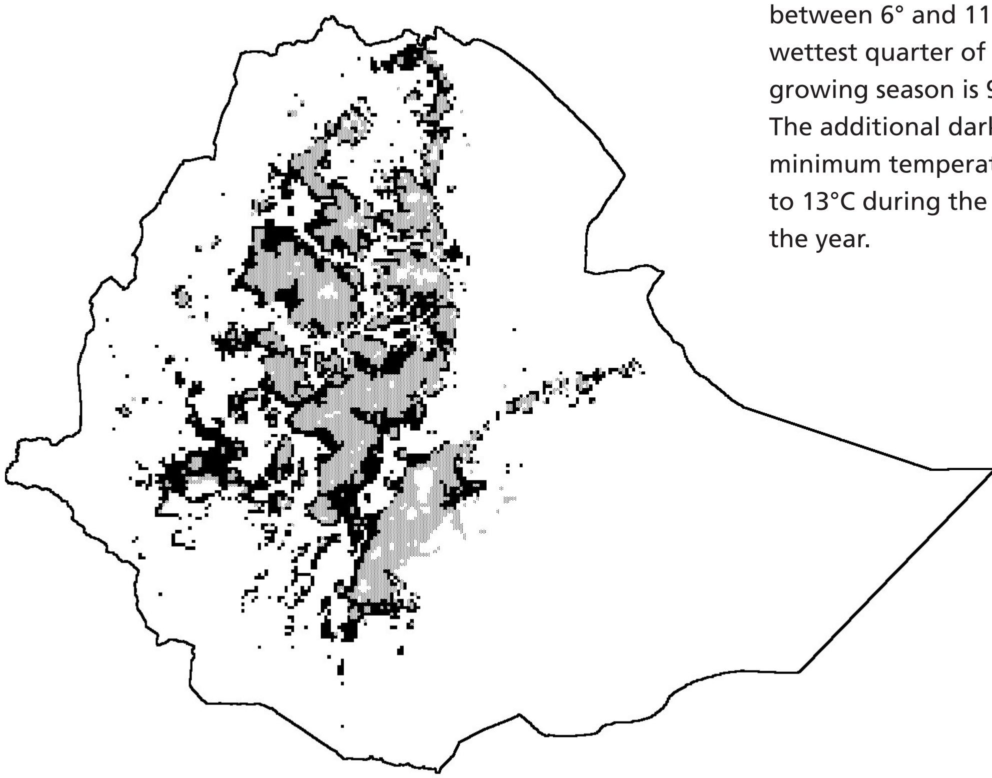
Map 3. Areas of Ethiopia where precipitation is over 350 mm, the mean minimum temperature is between 6° and 11°C during the wettest quarter of the year, and the growing season is 9 months or less. The vertically hatched zones represent elevations above 2000 m.



Map 4. Approximate distribution of traditional wheat production areas of Ethiopia re-drawn from Belay et al. (1999), the proposed climate-based wheat zone, and 180 wheat germplasm collection sites (the dots).

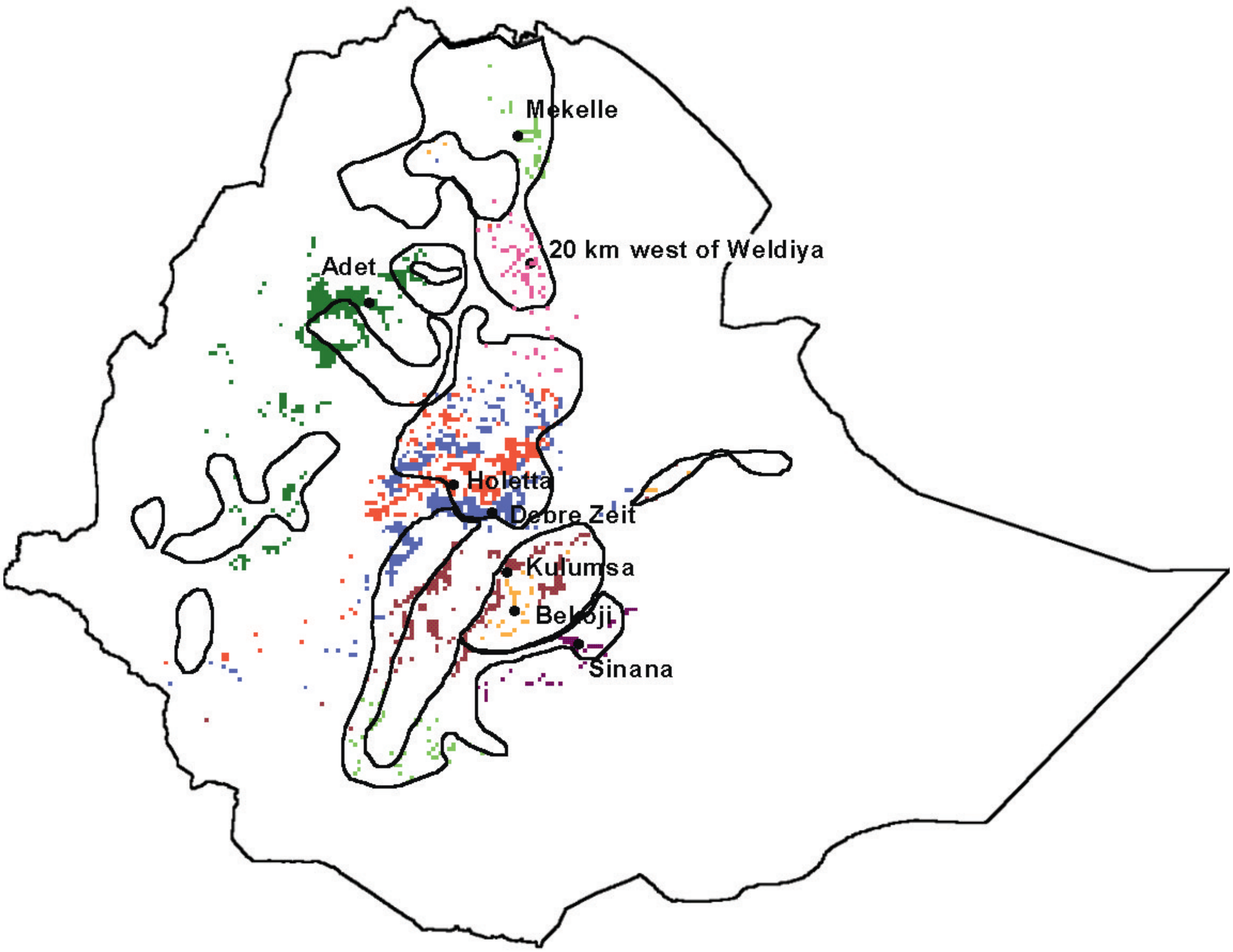


Map 5. Areas of Ethiopia where precipitation is over 350 mm, the mean minimum temperature is between 6° and 11°C during the wettest quarter of the year, and the growing season is 9 months or less. The additional dark areas receive between 300 and 350 mm of precipitation during the wettest quarter of the year.



Map 6. Areas of Ethiopia where precipitation is over 350 mm, the mean minimum temperature is between 6° and 11°C during the wettest quarter of the year, and the growing season is 9 months or less. The additional dark areas have mean minimum temperatures between 11° to 13°C during the wettest quarter of the year.

Map 7. Areas within Ethiopia having climatic conditions during the wettest quarter that are similar to those of one of eight wheat research sites in the country.



Map 8. Areas in sub-Saharan Africa having climatic conditions during the optimal five-month growing season that are similar to those at Kulumsa, Ethiopia.