Maize Production Environments Revisited: *A GIS-based Approach*

Introduction

In agricultural research and development, priorities are often set and promising technologies targeted within particular crop production settings, taking into account spatial variation in biophysical and socioeconomic factors. Agricultural production environments vary by climate (a function of latitude, altitude, and other factors), soil and related aspects, consumer and producer preferences, accessibility, and input use, among other things. The effectiveness of agricultural interventions – improved cultivars, agronomic management practices, decision support systems – depends on these factors. Thus, researchers often define the limits of an environment within which a given technology is applicable.

When the CIMMYT Maize Program began developing germplasm for maize production environments in the developing world 35 years ago, it adopted a strategy for efficiently applying resources to a range of needs and problems. That strategy involved grouping the world's maize production regions into major ecologies: the lowland tropics, the subtropics, midaltitude regions, and the highlands. By the late 1980s, the Program had subdivided these ecologies into 30 areas called mega-environments (MEs) in 70 countries. MEs were defined as the largest subunits of a crop's growing or target environment within which a particular variety or related practice was useful (Pham and Edmeades 1987; CIMMYT 1989b; Delacy et al. 1994). For the Maize Program at that time, it involved such factors as maturity, preferred grain color and texture, and production constraints (e.g., drought, low N conditions, diseases, insect pests) to which the germplasm must be resistant or tolerant. The typical ME encompassed large (in excess of 1 million ha), not necessarily contiguous areas in several countries (CIMMYT 1989a).

Use of the ME concept at CIMMYT

Mega-environments were originally intended to help crop breeders manage genotype-by-environment interaction and extrapolate successful varieties and results from one site or region to other locations where they might have potential use. The relative size of each ME — together with considerations such as impact on the poor, likeliness of success, and the presence of alternative suppliers — was a key criterion in strategic planning and the subsequent allocation of resources during the late 1980s and early 1990s (CIMMYT 1989a). Since then, the concept has also been applied in designing and testing new crop management practices (Sayre and Moreno Ramos 1997; CIMMYT Annual Report 1999) and other products of research by CIMMYT and its partners. The ME concept has proven useful for setting priorities, planning strategy, and collaborating with researchers worldwide (CIMMYT 1990).

Refining ME definitions

CIMMYT initially characterized maize and wheat production environments through consultation with regional staff and scientists in national programs (CIMMYT Maize Program 1988;

CIMMYT 1989b). The criteria used were semi-quantitative, and there was frequent discussion about whether the classification of environments could be revised using more objective and easily reproducible measures. The development of geographic information systems (GIS), as well as improved coverage and reliability in data for factors such as climate, soils, and topography, offered a way to achieve this, as demonstrated in preliminary work by Pollak and Corbett (1993).

This paper describes a GIS-based approach for refining the definition of maize MEs. It reviews the origin of the ME concept in more detail, summarizes various iterations of maize MEs, and concludes with a version that uses daylength, temperature, and season rainfall as classification criteria.

Previous ME Classification Methods

The first global ME study: 1985-1988

The first initiatives at CIMMYT to assemble ME information started in 1977 for wheat. Regional and national program staff were asked to identify major production regions by country, setting a lower limit of harvested area of 100,000 ha annually. These regions were described in terms of area; crop type; moisture conditions; incidence of heat, cold, and drought; maturity requirements; and the average annual loss to specific diseases and insects. By 1985, after several iterations of data collection and analysis, rough maps of national production regions were available and a computerized database was produced (CIMMYT 1989b).

Tropical maize is grown over a wider range of environments than wheat and interacts more closely with its environment, making the ME approach potentially more useful for maize. When CIMMYT began to define global maize MEs in 1985, it used the same approach as for wheat, except that losses from pests and diseases were considered and greater attention paid to preferences for grain texture and color. The main criteria were elevation and climate zones (Appendix A). The information was computerized and rough maps of 30 MEs, as drawn by the numerous contributors, were published in 1988. This reference, often referred to as “The Yellow Book” (CIMMYT Maize Program 1988), has since been an important tool for CIMMYT and its partners. A summary table was developed (CIMMYT 1989c) in which not only area but yield level and grain production were estimated (Appendix A). Production data could be weighted by factors such as utilization (food vs feed), per capita income, relative strength of a national program, or emphasis on a particular region (e.g., sub-Saharan Africa).

Updating the global ME 1985-88 survey results

The construction of a database from expert knowledge was very expensive, making it impracticable to update the ME definitions comprehensively on a regular basis. Because biannual updates of maize area, production, and yield were needed, the 1985-88 estimates were increased with correction factors derived from FAO country level statistics. The areas of all MEs in a given country were automatically increased at the same ratio as the increase for the country’s entire maize area.

Table 2. Agroclimatic criteria used for the maize environment classification by Dowswell et al. (1996).

Environment	Mean growing season temperature (°C) Min.	Max.	Mean	Altitude (masl)	Latitude
Tropical	22	32	28	<1,000	33° or lower
Subtropical	17	32	25	<1,600	23-33°
"	17	32	25	1,000-1,800	23° or lower
Temperate	14	24	20	<500	34° or higher
Highland	7	24	16	>1,800	23° or lower
"	9	25	18	>1,600	23-34°

In publications on the impact of international maize breeding (Lopez-Pereira and Morris 1994; Morris 1998), the 1985-1988 ME classification was updated with information from the FAO AGROSTAT (FAO 1990) database (see Appendix B; Tables B.1 and B.2). Dowswell et al. (1996) suggested a more expanded table with agroclimatic criteria (Table 2). Using information from the 1985-1988 study, they produced an area table by region (Appendix B; Table B.3).

Classification of testing sites with point based meteorological data

In 1989, an attempt was made to classify maize testing sites in sub-Saharan Africa (Pollak and Pham 1989). Forty-two sites from sub-Saharan Africa were used to create seven clusters. Fifty-two monthly agroclimatic variables from ten years of meteorological data from those sites were used. The classification used Ward's method of cluster analysis and canonical discriminant analysis. They identified four lowland regions, two midaltitude regions, and one highland region. Lowland regions were separated into 1) high rainfall, 2) warm temperatures and high rainfall, 3) low minimum temperature, and 4) very high temperature.

The 1991 classification attempt

In 1991, an interdisciplinary group was formed at CIMMYT to redefine maize MEs using more objective criteria. An initial effort resulted in the criteria shown in Table 3. These classification criteria were to be sent to CIMMYT outreach staff and collaborating national programs, as was done in 1985, but with the hope of obtaining more objective and reproducible area estimates. The effort never went further, due to funding constraints.

Limitations to previous classification approaches

The 1985-88 study is still widely used in international maize research, including the private sector (McCarter 1998, personal communication). This testifies to the overall utility of the ME concept and the robustness of the maize MEs defined largely on expert knowledge. However, several limitations of this approach are apparent.

The definition of environments is subjective. For example, terms such as "midaltitude" and "subtropical" are sometimes used interchangeably where germplasm requirements are similar, so

Table 3. Maize Mega-Environment Update Committee classification, 1991.

Ecology	Mean growing season temperature (°C)	Elevation (masl)	Latitude
Lowland tropics	>24	0-1,000	30°N-30°S
Midaltitude tropical	20-24	800-1,800	30°N-30°S
Subtropical	20-24	-	>20°N & >20°S
Tropical highland transition	17-20	1,500-1,800	30°N-30°S
Tropical highland	12.5-17	>2,000	30°N-30°S
Temperate	20-22	-	>30°N & >30°S
Highland temperate	15-20	-	>30°N & >30°S

results are not easily reproducible, and the two types of ME are not separated well enough. (The 1985-88 classification created many overlapping subdivisions in certain regions.) Crop losses due to diseases, pests and abiotic stress factors are estimated, rather than being based on trial results. The timing and severity of common stresses are not defined, even though they may strongly affect the extent of crop losses. As a result, an assessment of one stress factor in a given region may not really be comparable to the same level of stress identified in another region. This makes the aggregation of areas with similar ratings for various stress factors imprecise. The same applies for the use of elevation: perceptions of "lowland," "midaltitude," and "highland" can vary among maize researches, especially across regions and where countries have established their own classifications. Moreover, the ME definitions described above focus on regions where CIMMYT has strong contacts, leaving certain areas in Asia, for example, poorly characterized. Finally, maize cropping locations, circumstances, and systems have changed considerably since the original ME study, but updating of the definitions has been sketchy for lack of resources to do a more complete, methodical revision.

GIS-based Approaches

To avoid confusion in terminology, update area and production data, identify non-overlapping MEs, and introduce more useful, diagnostic variables, CIMMYT proposed in 1996 to redefine global maize MEs using geographic information systems (GIS). Use of a GIS can ensure that criteria are applied consistently across regions. Furthermore, a GIS can combine or link many types of data (climate and soils, pests and diseases, socioeconomic factors) by overlaying and merging them.

The availability of environmental data has improved greatly with the development of GIS. Elevation data on a 1-km grid are available for the entire globe (USGS 1997). Climate data, including long-term monthly means for maximum and minimum temperature and totals for precipitation and potential evapotranspiration, are available as interpolated surfaces with a grid cell size typically of 5 to 10 km^2 (Corbett and O'Brien 1997). The interpolation procedures used can allow for elevation effects and normally offer more accurate results than simple estimations of climate based on reference to the nearest station (Hartkamp et al. 1999). Obtaining detailed and reliable soil and crop distribution data is still problematic. The best global soil database is the FAO digital soil map of the world (FAO 1996) at a 1:5,000,000 scale. Crop distribution data are available for Latin America (Hyman et al. 1998) and efforts to obtain similar data for Africa are under way (P. Thornton, personal communication). [2]

A first attempt to define maize ecologies using GIS-based approaches was made by Pollak and Corbett (1993) for Central America and Mexico. They clustered grid cells based on elevation and mean monthly precipitation and temperature data during the growing season (April through October). Ten ecologies were identified: three lowland, three highland, two subtropical, and two transitional from subtropical to highland.

Gebrekidan et al. (1992) and Corbett (1998) proposed a geographic approach to define maize production environments for Kenya. The ecologies (lowland, midaltitude, transitional, and highland) are based on altitude and a cutoff between moist (> 550 mm) and dry (< 550 mm) for the growing

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[2] Crop distribution data are critical sources of information on area and production, essential to the definition of maize production environments.

season (March to August). The moist transitional zone (1,200 to 2,000 masl, > 550 mm) accounts for the largest portion (41%) of the total maize area.

Criteria from the aborted 1991 study were later used at CIMMYT to create global maps representing maize production zones. An example is given for South America in Appendix C. The growing season was determined using the Spatial Characterization Tool (SCT) "optimal season" climate model (Corbett and O'Brien 1997). The optimal season is defined as the five-month period with the largest ratio of precipitation over potential evapotranspiration. Mean growing season temperatures were replaced by minimum and maximum temperature ranges (-6ºC and +6ºC from the mean temperature). This approach is only approximate, because diurnal temperature ranges in lowland tropical areas are typically smaller than in the highlands. Data on the start and length of the onset of the growing season were estimated by assuming that the ratio of precipitation to potential evapotranspiration exceeds 0.5 during the season ("trigger season" climate model). This approach has proven useful in targeting different maturity classes of maize in sub-Saharan Africa, although the 0.5 limit appears to be too high for most drier areas where maize is sown at low densities (Hodson et al. 1999).

In a regional refinement to this global classification, maize areas were assigned to ME climatology zones in Latin America, based on maize production data. A crop distribution database for Latin America was developed by the GIS group at the Centro Internacional de Agricultura Tropical (CIAT; Hyman et al. 1998). Disaggregated, municipality-level maize production information was reclassified to identify municipalities where at least 10,000 ha of maize was grown, applying a probability model that included infrastructure, transportation access, and location of populated areas. The crop distribution information for maize was then overlaid on the ME zonal maps for Latin America by country (Appendix D).

Methodology for this Study

About 150 representative sites were selected from records for international maize trials, and approximately 70 sites were added to cover regions where trials had not been conducted (Appendix E).[3] Information on planting dates was compiled from international trial reports and in consultation with maize researchers. A separate set of planting dates was obtained using the climate models for the trigger and optimal seasons, as defined in the SCT environmental database (Corbett and O'Brien 1997). Monthly climate data for the selected sites were obtained using the climate surfaces. For Africa and Latin America, gridded climate surfaces were derived from Corbett and O'Brien (1997). For Asia, gridded climate surfaces were derived from Jones (1998). Starting with the reported month of planting, variables from the first four consecutive months were taken. This interval was chosen to represent a 120-day maize crop cycle.

Daylength (d) was estimated using the algorithm of Goudriaan and Van Laar, (1994):

$$d=12 * [1+ (2/pi) * asin(a/b)]$$

$$a = sin(lat)*sin(om) \quad b = cos(lat)*cos(om)$$

$$sin(om) = - sin (pi * 23.45/180) * cos (2 * pi * (td + 10)/365),$$

where :

lat = latitude

td = day of year.

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[3] The geographical coordinates of these sites were carefully checked.

To represent the daylength that affects floral initiation, three values for *td* were used: 15 days, 30 days, and 45 days after planting date.[4]

For the hierarchical cluster analysis, Ward's clustering procedure (Ward 1963) within SAS 6.12 (SAS Institute 1998) was used. All variables (daylength, temperature difference, mean temperature, precipitation and evapotranspiration) were standardized by subtracting the mean and dividing by the standard deviation. Cluster distance was not stable enough to determine an optimal number of clusters, so a maximum of 15 clusters was allowed, since this was considered to provide a manageable number of MEs. Clusters were estimated based on daylength and the first four monthly mean climate variables derived from:

- Planting dates as reported in the CIMMYT Maize International Testing Unit database or compiled through consultation with maize scientists.
- Planting dates as estimated based on start of the trigger season.
- Planting dates as estimated based on the start of the optimal season.

Criteria were derived from evaluating the values of the environmental variables of members within each cluster. Maize production environments were mapped and feedback from experts was sought. After several iterations this resulted in a revised set of criteria for defining maize MEs.

Results and Discussion

Planting date and clusters

Each approach to define planting date and growing season (reported, trigger season model, optimum season model) resulted in different cluster compositions. Site clusters using planting date from trigger season resembled site clusters from reported planting date more than site clusters from optimal season (data not shown). A set of "best bet" planting dates was compiled from the reported planting dates, trigger planting dates, and expert knowledge. These climate data were clustered again, giving the clusters shown in Appendix F. Mean cluster values are shown in Table 4.

Determining criteria

Classification criteria were determined from the range of values for environmental variables of the individual sites within the clusters. This was done iteratively; e.g., assuming a daylength of 13.5 h for high latitude to temperate areas and checking the sites that segregate at this criterion. This proved to segregate better at a daylength of 13.4 h. This process resulted in the use of three classification criteria: daylength, mean temperature, and seasonal rainfall over the four-month growing season (Table 5). After this process of determining the criteria based on membership of the selected sites to specific clusters, another application of the criteria involving maize scientists took place. For instance, analysis of the clusters suggested a different temperature criterion for distinguishing non-equatorial subtropical lowlands from non-equatorial subtropical midaltitude environments (22ºC) than for distinguishing equatorial tropical lowlands from equatorial tropical midaltitude environments (24ºC). Upon mapping, however (see next paragraph), this did not provide a

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[4] The 15th day of the planting month was considered the planting date.

Table 4. Cluster mean values for variables: daylength, temperature difference, mean temperature, precipitation and evapotranspiration. M1, M2...refers to month of growing season.

	Fre-	Daylength (h)			Tdifference (ºC)				Tmean (ºC)				Precipitation (mm)				Evapotranspiration (mm)			
Cluster	quency	M1	M2	M3	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4
1	5	12.2	12.0	11.8	7.3	7.7	8.2	8.7	27.4	27.0	25.6	23.9	243	125	66	41	170	172	166	156
2	28	12.5	12.6	12.7	10.0	9.1	8.3	8.1	28.0	27.7	27.4	27.1	116	161	196	233	190	181	169	165
3	7	10.7	10.5	10.5	14.5	15.4	15.8	16.4	21.1	18.1	17.7	20.0	16	10	12	13	142	126	126	152
4	19	12.1	12.2	12.1	7.8	7.6	7.7	8.2	25.7	25.7	25.8	26.0	182	196	177	166	109	105	107	114
5	25	12.0	12.0	12.0	11.8	10.8	10.6	11.0	21.8	21.2	20.9	20.9	95	135	119	89	117	108	104	107
6	15	12.6	12.6	12.6	9.9	9.3	9.4	9.5	26.8	26.3	26.1	26.3	279	352	364	322	131	122	120	119
7	9	12.1	12.1	12.1	9.4	8.8	8.9	9.5	15.3	15.2	15.2	15.1	172	233	190	124	89	86	82	86
8	23	12.7	12.8	12.9	11.2	9.6	9.5	9.7	22.7	22.0	21.9	21.9	145	251	244	210	137	121	117	112
9	39	13.0	13.0	13.0	12.5	11.6	11.4	11.6	24.1	23.9	24.0	24.3	129	171	163	138	144	140	135	130
10	12	13.3	13.1	12.9	14.3	13.6	14.0	14.8	21.3	20.6	20.4	20.6	97	113	97	73	149	139	125	108
11	17	12.7	12.9	13.1	14.0	13.0	12.8	13.0	14.3	14.9	15.5	16.0	81	110	119	115	112	114	118	120
12	11	13.7	13.7	13.5	9.1	7.2	7.3	7.7	26.8	26.4	26.2	25.2	218	359	348	240	228	209	210	197
13	2	13.5	13.7	13.8	9.1	6.9	5.8	6.1	23.1	24.0	24.0	23.9	327	735	1133	1061	215	200	195	200
14	5	13.5	13.5	13.4	14.1	13.3	13.2	12.8	25.4	26.8	27.2	25.8	1	3	10	22	196	204	195	171
15	4	14.1	13.9	13.7	13.9	10.4	10.5	13.7	32.5	31.0	29.8	27.8	74	139	144	53	355	295	280	280

satisfactory distinction between lowland and midaltitude environments, so we reverted to a uniform temperature criterion of 24ºC to distinguish between lowland and midaltitude environments in both the equatorial tropics and non-equatorial subtropics.

Finally, locations were classified according to the new criteria. To compare classification methods, the sites were also classified using the previous classification criteria. This is depicted in the first columns of Appendix G.

Mapping maize MEs

Because the actual planting date for each map cell was not available, we used the planting date surface as defined by the trigger season model of the SCT (Corbett and O'Brien 1997) for mapping maize MEs. Moreover, planting dates as reported by collaborators conducting international maize trials may not necessarily follow the actual growing season, because they may plant late due to late arrival of seed shipments or use irrigation (which allows them to plant outside the normal season). Farmers in contrast are more dependent on the actual start of the growing season.[5] Daylength maps were calculated from latitude grids and the trigger season planting date (averaging values for +15, +30 and +45 days after trigger season planting date). Zonal maps were made using criteria from Table 5 (Appendix H). A simplified map (centerfold) was created by eliminating the precipitation criteria.

Use of maize mega-environment maps and information

The maize MEs provide a global characterization of the target environments for tropical maize germplasm. Potential users and applications include:

- For research managers to set priorities and allocate resources.
- For scientists to focus efforts on relevant products; i.e., those most urgently needed for the most important MEs. (Thus, if early-maturing, drought

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[5] The start of the trigger growing season commonly coincides with the main (summer-autumn) growing season. The secondary season is thus not represented here.

Table 5. Cluster criteria for revised maize mega-environments, including subdivisions based on precipitation, for a 4-month growing season.

No.	Name	Daylength (h)	Mean temperature (°C)	Precipitation (mm)
1a	Too dry lowland tropical	11 to 12.5	≥ 24	< 200
1b	Lowland tropical mesic	11 to 12.5	≥ 24	≥ 200 and <600
1c	Lowland tropical wet	11 to 12.5	≥ 24	≥ 600 and <2,000
1d	Lowland tropical excess	11 to 12.5	≥ 24	≥ 2,000
2a	Too dry tropical midaltitude	11 to 12.5	> 18 and < 24	< 200
2b	Tropical midaltitude mesic	11 to 12.5	> 18 and < 24	≥ 200 and < 600
2c	Tropical midaltitude wet	11 to 12.5	> 18 and < 24	≥ 600 and < 2,000
2d	Tropical midaltitude excess	11 to 12.5	> 18 and < 24	≥ 2,000
3a	Too dry tropical highland	11 to 12.5	≤ 18	< 200
3b	Tropical highland mesic	11 to 12.5	≤ 18	≥ 200 and < 600
3c	Tropical highland wet	11 to 12.5	≤ 18	≥ 600 and < 2,000
3d	Tropical highland excess	11 to 12.5	≤ 18	≥ 2,000
4a	Too dry non-equatorial tropical/subtropical lowland	12.5 to 13.4	≥ 24	< 200
4b	Non-equatorial tropical/subtropical lowland mesic	12.5 to 13.4	≥ 24	≥ 200 and < 600
4c	Non-equatorial tropical/subtropical lowland wet	12.5 to 13.4	≥ 24	≥ 600 and < 2,000
4d	Non-equatorial tropical/subtropical lowland excess	12.5 to 13.4	≥ 24	≥ 2000
5a	Too dry non-equatorial tropical/subtropical midaltitude	12.5 to 13.4	> 18 and < 24	< 200
5b	Non-equatorial tropical/subtropical midaltitude mesic	12.5 to 13.4	> 18 and < 24	≥ 200 and < 600
5c	Non-equatorial tropical/subtropical midaltitude wet	12.5 to 13.4	> 18 and < 24	≥ 600 and < 2000
5d	Non-equatorial tropical/subtropical midaltitude excess	12.5 to 13.4	> 18 and < 24	≥ 2,000
6a	Too dry non-equatorial tropical/subtropical highland	12.5 to 13.4	≤ 18	< 200
6b	Non-equatorial tropical/subtropical highland mesic	12.5 to 13.4	≤ 18	≥ 200 and < 600
6c	Non-equatorial tropical/subtropical highland wet	12.5 to 13.4	≤ 18	≥ 600 and < 2,000
6d	Non-equatorial tropical/subtropical highland excess	12.5 to 13.4	≤ 18	≥ 2,000
7a	Subtropical winter hot dry	≤ 11	≥ 24	< 200
7b	Subtropical winter hot mesic	≤ 11	≥ 24	≥ 200 and < 600
7c	Subtropical winter hot wet	≤ 11	≥ 24	≥ 600 and < 2,000
7d	Subtropical winter hot excess	≤ 11	≥ 24	≥ 2,000
8a	Too dry subtropical winter warm	≤11	> 18 and < 24	< 200
8b	Subtropical winter warm mesic	≤11	> 18 and < 24	≥ 200 and < 600
8c	Subtropical winter warm wet	≤11	> 18 and < 24	≥ 600 and < 2,000
8d	Subtropical winter warm excess	≤11	> 18 and < 24	≥ 2,000
9a	Too dry subtropical winter cold	≤ 11	≤ 18	< 200
9b	Subtropical winter cold mesic	≤ 11	≤ 18	≥ 200 and < 600
9c	Subtropical winter cold wet	≤ 11	≤ 18	≥ 600 and < 2,000
9d	Subtropical winter cold excess	≤ 11	≤ 18	≥ 2,000
10a	Too dry temperate/subtropical lowland dry	≥ 13.4	≥ 24	< 200
10b	Temperate/subtropical hot mesic	≥ 13.4	≥ 24	≥ 200 and < 600
10c	Temperate/subtropical hot wet	≥ 13.4	≥ 24	≥ 600 and < 2,000
10d	Temperate/subtropical hot excess	≥ 13.4	≥ 24	≥ 2,000
11a	Too dry temperate/subtropical warm dry	≥ 13.4	> 18 and < 24	< 200
11b	Temperate/subtropical warm mesic	≥ 13.4	> 18 and < 24	≥ 200 and < 600
11c	Temperate/subtropical warm wet	≥ 13.4	> 18 and < 24	≥ 600 and < 2,000
11d	Temperate/subtropical warm excess	≥ 13.4	> 18 and < 24	≥ 2,000
12a	Too dry temperate/subtropical cold dry	≥ 13.4	≤ 18	< 200
12b	Temperate/subtropical cold mesic	≥ 13.4	≤ 18	≥ 200 and < 600
12c	Temperate/subtropical cold wet	≥ 13.4	≤ 18	≥ 600 and < 2,000
12d	Temperate/subtropical cold excess	≥ 13.4	≤ 18	≥ 2,000

stressed maize turns out to occupy substantially more area than currently estimated, it may deserve increased attention.)
- For scientists to test the right type of germplasm in the appropriate environments. This should also allow a reduction in the number of testing sites.
- For national program researchers and other partners to decide which type of germplasm and trials most suit their needs.

Challenges

The ME definitions provided here need to be refined through one or several of the following:

- Development of a global database of actual maize planting dates for main and secondary seasons.
- Identification of irrigated maize production areas.
- Integration of improved data on soils.
- Integration of data on consumer preferences.
- Integration of data on the incidence and severity of diseases and insect pests.
- Linkage to crop distribution data to obtain maize production information.

For validation purposes there is a need to link the proposed maize environment definitions to data on genotype-by-environment interactions from trials across MEs; this could also improve the efficiency of international testing. The work of Crossa et al. (1993) exemplifies an effective study of genotype-by-environment interaction. They analyzed eight years of historical maize data from multi-environment trials using pattern analysis on performance data. In this way, they were able to 1) tease out long-term relationships among international maize testing environments for which breeding strategies ought to be defined and 2) assess the long-term precision of trials at the specific testing locations.

Conclusions

The ME concept has proven a useful tool for setting priorities, allocating resources, and fostering international collaboration in agricultural research and development. Use of a GIS can allow scientists to 1) define environments according to more quantitative criteria and 2) visualize how these criteria affect the location of the environments. To be fully useful, the ME definitions provided here need to be refined using actual maize distribution and production data, as well as information on major production constraints, by country. A GIS-based approach can help researchers establish a framework within which other spatial data can be consulted. The ultimate goal is for researchers and other users to be able to formulate task-specific versions of the MEs or “query” a ME definition for information of interest.