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An Agroclimatological Overview of Wheat Production Regions of Bolivia

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Abstract: This report describes use of the Spatial Characterization Tool (SCT) developed by Texas A&M University to analyze the similarity of the climates of research sites in the major wheat production areas in Bolivia — the highland intermountain valleys and the lowland plains — to those of other regions. For highland environments, zones of similarity were only found in scattered regions of Bolivia and Peru, and the complex topography of the Andean region and the relatively large SCT grid cells (9 km x 9 km) hampered climate characterization. For lowland sites, combined results of analyses of the favorable season plus the coolest or driest quarters of the year (when wheat is actually grown in lowland Bolivia) identified the environments of adjacent areas of Bolivia, two regions in Brazil, small regions in Venezuela, plus areas in Mexico, Central America, and Africa as similar to those of the target sites in Bolivia. Site similarity analysis appears to be a valuable method for understanding relations among crop production environments, allowing prediction of crop responses to agronomic practices, assessments of genetic diversity or sustainability, and other types of studies. Current applications, however, are limited by a lack of quality data.

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Summary

Within cropping system/natural resource management research, there is often the assumption that results are site-specific. This assumption may sometimes be incorrect, and simply reflect the frustration or limited knowledge of site-level researchers overwhelmed by the complexities of extrapolating technology. Traditionally, comparisons among agroecological regions have been based on definitions of broad zones, such as the "mega-environments" used by CIMMYT. Whereas their broadness makes them useful in setting global research priorities for crop breeding programs, it also means that they may not capture the level of ecological variation needed to predict the responses of crops to specific agronomic practices or allow assessments of genetic diversity or sustainability. Climate similarity analyses using geographic information systems (GIS) can permit more quantitative comparisons among regions and sites, adding value to research on cropping systems and natural resource management.

In Bolivia, research on wheat production systems is constrained by the country's broken topography, complex environments, and limited financial resources. An understanding of how production environments in Bolivia compare to those in nearby countries or in Central America, Mexico, or even Africa might generate major efficiencies in the form of shared research experiences, where regions are similar. This report describes use of the Spatial Characterization Tool (SCT; developed by Texas A&M University) to analyze the similarity of the climates of research sites in the major wheat production areas in Bolivia — the highland Andean valleys and the lowland plains — to those of other regions. The SCT uses interpolated surfaces of monthly data for precipitation, evapotranspiration, and maximum and minimum temperature. For both regions, initial comparisons classified an environment as similar to that of another site if their precipitation (P) and potential evapotranspiration (PET) fell within a $\pm$ 20% range of similarity and their maximum and minimum temperatures within a $\pm$ 10% range, for the most favorable (largest values of P/PET ratio) five months of the year.

For highland environments, zones of similarity were found only in scattered regions of Bolivia and Peru. In fact, comparison of Bolivian environments with those at highland sites of Peru and Colombia, plus one cool lowland site in Chile, confirmed the impression that similar highland environments may be numerous but are geographically scattered. In addition, the complex Andean topography coupled with the relatively large grid cells (9 km x 9 km) of the SCT hampered climate characterization. An alternative approach, which characterized the highland environments in terms of rainfall patterns during the favorable season, provided a workable solution to this problem. **For lowland sites**, combined results of analyses of the favorable season plus the coolest quarter and the dry season (when wheat is actually grown in lowland Bolivia) identified the environments of adjacent areas of Bolivia, two regions in Brazil, small regions in Venezuela, plus areas in Mexico, Central America, and Africa as similar to those of the target sites in Bolivia.

Site similarity analysis appears to be a valuable method for understanding relations among crop production environments. Many agricultural applications can be envisaged. Similar to the examples from agronomy that are discussed above, the approach can be used to identify probable areas of adaptation for new cultivars or in germplasm collection efforts, identifying regions where materials are most likely to be found, based on similarity to known colletions sites. The approach could also be adapted easily for studies of disease, pest, and weed distributions – for instance, to map potential areas of spread for organisms that have been introduced recently or that have become problematic due to changes in cropping practices.

In applying similarity analyses, however, scientists should be aware of possible limitations. The most problematic of these is data quality. Interpolated climate surfaces necessarily have limitations due to spatial scale. As seen in the case of the Bolivian highlands, analyses for a region where elevation varies dramatically over relatively short distances must be handled with caution. Similarly, where the density of source data (meteorological stations in the case of climate surfaces) is low, interpolations necessarily become less reliable. Finally, climate is only *one* determinant of agronomic performance; similarity analysis could easily be extended to, say, soil characteristics. Here again, though, the lack of good data on soils and other non-climate factors affecting cropping system performance limits the scope and usefulness of similarity studies, despite their representing an improvement over the mega-environment approach for agronomic and sustainability research.

Resumen

En la investigación del manejo de los sistemas de cultivo y de los recursos naturales existe con frecuencia la suposición de que los resultados son específicos a un sitio. Esta suposición es a veces incorrecta y simplemente manifiesta la frustración o falta de conocimientos de los investigadores a nivel local, abrumados por las complejidades de extrapolar la tecnología. Tradicionalmente, las comparaciones entre las regiones agroecológicas se han basado en la definición de áreas extensas, como los "mega-ambientes" empleados por el CIMMYT. Aunque debido a su extensión estos mega-ambientes son útiles al establecer las prioridades de investigación mundiales de los programas fitotécnicos, a veces no revelan el nivel de variación ecológica necesario para predecir la respuesta de los cultivos a prácticas agronómicas específicas ni permiten evaluar la diversidad genética y la sustentabilidad. Los análisis de similitud climática utilizando los sistemas de información geográfica (GIS) permiten efectuar comparaciones más cuantitativas entre regiones y sitios, lo cual hace más valiosa la investigación del manejo de los sistemas de cultivo y de los recursos naturales.

En Bolivia, la investigación de los sistemas de producción de trigo está restringida por la irregular topografía, los complejos ambientes y los limitados recursos financieros del país. Comprender la forma en que los ambientes de producción en Bolivia se comparan con los de sus países vecinos, de América Central, México, e incluso Africa, permite aprovechar mejor las experiencias de la investigación en regiones similares. Este informe describe el uso de la Herramienta de Caracterización Espacial (Spatial Characterization Tool; SCT), creada en la Universidad Texas A&M, en el análisis de la similitud climática de los sitios de investigación en las principales zonas productoras de trigo en Bolivia —los valles altos y las llanuras de tierras bajas— con la de otras regiones. La SCT emplea superficies interpoladas de datos mensuales de precipitación, evapotranspiración y temperaturas máxima y mínima. En ambas regiones, las comparaciones iniciales clasificaron un ambiente como similar al de otro sitio cuando su precipitación (P) y evapotranspiración potencial (PET) estaban dentro de un rango de $\pm$ 20% de similitud y sus temperaturas máxima y mínima dentro de un rango de $\pm$ 10%, durante los cinco meses más favorables del año (los mayores valores de la proporción P/PET).

En cuanto a los ambientes de tierras altas, se encontraron áreas similares sólo en regiones dispersas de Bolivia y Perú. De hecho, la comparación de los ambientes en Bolivia con los de los sitios altos de Perú y Colombia, más un sitio de tierras bajas y frescas en Chile, confirmaron la suposición de que los ambientes similares de tierras altas son numerosos pero dispersos geográficamente. Además, la compleja topografía andina, combinada con las grandes celdas reticuladas (9 km x 9 km) de la SCT, dificultó la caracterización climática. Se solucionó este problema mediante otro método que caracterizó los ambientes de tierras altas con base en los patrones pluviométricos durante el ciclo favorable de cultivo. Respecto a los sitios de tierras bajas, los resultados combinados de los análisis del ciclo favorable, más los del trimestre más frío y la temporada más seca del año (cuando se cultiva el trigo en las tierras bajas de Bolivia) identificaron los ambientes de algunas áreas adyacentes de Bolivia, dos regiones en Brasil, extensiones pequeñas en Venezuela, más áreas en México, Centroamérica y Africa como similares a los de los sitios en Bolivia.

El análisis de similitud de sitios parece ser un método valioso para entender las relaciones entre los ambientes de producción, que podría tener muchas aplicaciones en la agricultura. Al igual que en los ejemplos antes mencionados, este método se puede utilizar para identificar las probables zonas de adaptación de las nuevas variedades o también, para la recolección de germoplasma, las regiones donde es más probable encontrar materiales, con base en la similitud con sitios de recolección que ya hayan sido caracterizados. El método podría adaptarse fácilmente a estudios de distribución de enfermedades, plagas y malezas —por ejemplo, se podrían crear mapas de las probables zonas de dispersión de organismos de introducción reciente o que se hayan vuelto problemáticos debido a cambios en las prácticas de cultivo.

Sin embargo, los científicos deben estar conscientes de las posibles limitaciones de los análisis de similitud. La más problemática de éstas es la calidad de los datos. Las superficies climáticas interpoladas forzosamente tienen limitaciones, debido a la escala espacial. Como se ha visto en el caso de las tierras altas de Bolivia, los análisis de una región donde la elevación varía en forma impresionante en distancias muy cortas deben manejarse con cautela. De igual forma, las interpolaciones se vuelven menos confiables donde es baja la densidad de datos fuente, procedentes de las estaciones metereológicas en el caso de superficies climáticas. Finalmente, el clima es sólo uno de los factores determinantes del comportamiento agronómico; los análisis de similitud podrían extenderse fácilmente para abarcar, por ejemplo, las características edafológicas. Sin embargo, la falta de buenos datos edafológicos y de otros factores no climáticos que afectan el comportamiento de los sistemas de cultivo, limita el alcance y la utilidad de los estudios de similitud, a pesar de que éstos superan al sistema de los mega-ambientes en las investigaciones agronómica y de la sustentabilidad.

An Agroclimatological Overview of Wheat Production Regions of Bolivia

Introduction

Wheat research in Bolivia faces multiple challenges. Among these are the difficulties of using limited research resources to address problems in diverse production environments. The latter constraint reflects both the overall economic situation of Bolivia and, more specifically, the intermediate importance of wheat production in the national economy (Table 1). In this context, researchers in Bolivia can benefit from experiences in other wheat regions with similar production conditions, and may also want to participate in regional projects where partners from other countries will seek similar information about how Bolivian wheat environments relate to their own.

Within cropping system/natural resource management research, there is often the assumption that results are uniquely site specific. This assumption may sometimes be incorrect, and simply reflect premature acquiescence of site-level researchers overwhelmed by the complexities of extrapolating technology. Lacking suitable tools for identifying areas similar to their own home site in well defined ways, they may conclude that there are no such areas — one way of dealing with an awkward, seemingly intractable problem.

The analysis described here is part of a broader effort to add value to cropping system and natural resource management research by fostering more effective learning, extrapolation and synthesis. These three aims may be described in the following manner:

- *Learning* - Drawing on results from other (similar) research sites that may be of relevance for scientists at a home site.
- *Extrapolation* – Defining and identifying additional, similar areas for potential application of technologies developed at the home site.
- *Synthesis* - Pooling the experience gained at several (similar) home sites to better understand the conditions that govern the performance of specific technologies.

Table 1. Comparison of selected economic and wheat production parameters for Bolivia and other countries in South America (from Aquino et al. 1996).

	Bolivia	Peru	Ecuador	Colombia	Brazil	Paraguay	Uruguay	Argentina	Chile
Estimated population, 1995 (million)	7.4	23.8	11.5	35.1	161.8	5.0	3.2	34.6	14.3
Estimated growth rate of population, 1993-2000 (%/year)	2.4	1.9	2.0	1.4	1.6	2.5	0.6	1.2	1.5
Per capita income, 1994 (US $)	770	2,110	1,280	1,670	2,970	1,580	4,660	8,110	3,520
Average wheat area harvested, 1993-1995 (000 ha)	124	95	33	48	1,278	202	201	4,812	382
Average wheat yield, 1993-1995 (t/ha)	1.0	1.3	0.7	2.0	1.5	2.2	2.0	2.1	3.5
Average wheat production, 1993-1995 (000 t)	119*	120	22	94	1,922	442	400	9,874	1,326
Nitrogen applied per hectare of wheat harvested, 1993-1994 (kg N/ha)	1	39	50	27	15	16	40	10	62

Although the full characterization of a production environment should cover soils, diseases, pests, weeds, and socioeconomic conditions, climate is usually the primary determinant of crop adaptation. The first order characteristic of climate, in ecological terms, was the underlying reason why the Spatial Characterization Tool (SCT) technology has been focused around interpolated climate surfaces. This paper compares climate conditions of wheat producing regions in Bolivia with those of other countries in Latin America and Africa. The method is based on a comparison of climatic conditions at specific, representative sites with climate over a region. This permits greater flexibility than traditional methods for defining agroecological zones at the continental scale. The Bolivian sites used in this study were also being used in research to develop improved agronomic practices for wheat production in moisture stressed environments of Bolivia.

Wheat Production Environments in Bolivia and Nearby Countries

Wheat is produced in Bolivia in two contrasting regions: the Andean highlands and the eastern lowlands. The highlands present broken topography and wheat is grown in and around numerous valleys and small plateaus characterized by very diverse climates. The eastern lowlands are almost flat, with relatively uniform climatic parameters but with a rainfall gradient from 800 to 1,600 mm/yr in the agricultural area.

In the Andean highlands, wheat is grown predominantly in small-scale, subsistence farming systems. Production is rainfed, depending on the summer rains from October to March. In favorable (higher precipitation) areas, potato is the preferred crop, receiving most inputs and being planted prior to wheat or other crops. A legume crop generally follows potatoes, and after that wheat or other cereals, which receive little if any inputs. In the lower rainfall areas and areas with severely degraded soils, wheat and barley are usually the only crops produced. These marginal areas account for some 60% of wheat and barley production in the highlands. According to production surveys, most highland farmers have livestock, and crop residues are an important source of fodder during the dry season (Wall et al. 1997a, b).

Moisture stress is the major limitation to small-grain cereal productivity in the inter-Andean valleys (Wall et al. 1997a, b). Rainfall in the wheat producing areas ranges from approximately 300 to 600 mm per year. However, moisture stress is a function not only of low and/or poorly distributed rainfall, but also of run-off brought about by excessive cultivation of sloping lands. This results in another major problem: erosion. Other constraints coupled with moisture stress are declining soil chemical fertility and poor plant stands.

The Tarata site in the High Valley of Cochabamba is on a gently sloping valley bottom in a low rainfall area on degraded alluvial soils. Under rainfed conditions, the main crops are wheat or (with irrigation) maize. Average farm size in the valley is approximately three hectares. The headquarters of the Bolivian Institute of Agricultural Technology (IBTA) is located close to Tarata.

Tarabuco and Yamparaez are located in adjacent valleys some 60 km apart in gently rolling areas of the Department of Chuquisaca. Tarabuco is slightly wetter and has more fertile soils than Yamparaez. In the former area, potato is the major crop, followed by barley, while on the more degraded and less fertile soils of

Yamparaez, wheat is the major crop. As in the Tarata area, farm size is about three hectares, usually divided among several dispersed fields.

The lowland wheat production region corresponds to non-traditional areas that were originally covered with forest but are being developed as Bolivia's major agricultural frontier. These regions grow warm season crops such as soybean during the summer rainy season, and wheat is planted as temperatures drop going into the drier winter season, typically late April to early May. The largest lowland wheat areas are in the Department of Santa Cruz, where wheat production has increased ten-fold over the past decade in conjunction with an expansion in soybean production, free-market economic policies and a concerted research and extension program. Again the major limitation to wheat productivity is water; scarce winter rainfall (150-250 mm during the crop season) is exacerbated by the structural degradation of fragile alluvial soils as a result of disc-tillage, leading to low water infiltration rates and increased run-off and soil compaction, the latter hampering root exploration and further reducing available water.

The two sites in the eastern lowlands are the locations of a multi-institution research and extension effort called the Sustainable Agriculture Program, based on two large-scale mechanised commercial farms, Paraiso and San Rafael. These lie some 80 km apart northeast of the city of Santa Cruz. Both sites are flat with alluvial soils. The Paraiso site has been cultivated for over 30 years, whereas the forest was cleared at San Rafael some 10 years ago. The main crops in the region are summer soybeans alternated with winter wheat, sunflower or sorghum in a system with two crops per year.

Materials and Methods

The primary data source for the climate analyses were the climate surfaces of Latin America developed by Corbett (1994) using trivariate thin plate smoothing splines (Hutchinson 1995). With 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 estimation of variation in climate with elevation. The DEM used for Latin America was ETOPO5 (EROS Data Center, U.S. Geological Survey). It uses a 5 arc-minute grid size, which is roughly equivalent to a 9 km x 9 km grid size near the equator. In addition to the basic climate variables, the set of surfaces includes data for potential evapotranspiration (PET), ratios of precipitation to PET (P/PET) both on a monthly basis and for a favorable season defined as the five consecutive months with the greatest P/PET ratios. Climate surfaces for Africa were from Corbett and O'Brien (1997) and are based on a 2.5 arc-minute (roughly 5 km x 5 km) DEM. Climate data for long-term monthly means at specific sites were obtained from the FAO climate database for Latin America (FAO 1985).

Climatic and site similarity zones were defined using the Spatial Characterization Tool (Corbett and O'Brien 1997). This tool works within the ArcInfo GIS software (Environmental Systems Research Institute, Inc., Redlands, CA). Climatic zones are defined through conventional map overlay and selection procedures. The similarity zones are created by specifying the latitude and longitude of a reference site, and then selecting criteria for similarity. This includes climate variables plus the range of variation another location may show for a given variable and still be considered "similar" to the reference site. For this study, the similarity zones were based on the favorable five-month growing period and considered ranges of P, PET and mean maximum and minimum temperatures, unless specified otherwise. All maps are presented in a geographic reference system (unprojected, as latitude and longitude). A list of the locations considered in the study is given in Table 2. The same locations are shown in Figure 1.

Figure 1. Base sites used for comparisons.

Table 2. Base sites used for comparisons.

Location	Latitude	Longitude	Comments
Cochabamba, Bolivia	-17.38	-66.17	Inter-Andean valley. City surrounded by irrigated area and mountains.
Oruro, Bolivia	-17.97	-67.12	High plateau. City surrounded by hills.
Sucre, Bolivia	-19.05	-65.27	Inter-Andean valley.
Tarabuco, Bolivia	-19.18	-64.90	Large, favorable inter-Andean valley. Area of potato production and site of IBTA research center.
Tarata, Bolivia	-17.62	-66.00	Inter-Andean valley. Some irrigation. Wheat in marginal areas. Main IBTA wheat research center.
Yamparaez, Bolivia	-19.20	-65.15	Large inter-Andean valley. Mostly cereal production. IBTA research area.
Cañada Larga, Bolivia	-17.45	-62.22	Lowland Santa Cruz region. CIAT (Bolivian Inst.) experiment station.
Paraiso, Bolivia	-17.43	-62.77	Lowland Santa Cruz region. Wheat production area. Close to Okinawa 2 colonization area.
San Rafael, Bolivia	-17.23	-62.27	Lowland Santa Cruz region. Wheat production area. Recent expansion on east bank of Rio Grande.
Abancay, Peru	-13.73	-72.77	Highland, inter-Andean valley of southern Peru.
Huancayo, Peru	-12.15	-75.07	Favorable, highland inter-Andean valley of Peru.
Ipiales, Colombia	0.80	-77.75	High rainfall, highland region of southern Colombia, similar to northern Ecuador.
Tunja, Colombia	5.53	-73.32	Intermediate rainfall highland region of central Colombia.
Cauquennes, Chile	-35.90	-72.23	Lowland, winter rainfall region of west-central Chile.

Results and Discussion

Highland regions

Figure 2 shows similarity zones for Tarata, Tarabuco, and Yamparaez. For all locations, the most striking result is that only small regions elsewhere in the Andes are identified as having similar environments, even allowing for a ±20% range in variation of P and PET. This was confirmed by similarity maps for other Andean highland sites such as Tunja, Ipiales, and Huancayo, which again showed relatively small regions of similarity (Fig. 3a-c). Similarly, Cauquennes, which represents a cool, lowland (elevation 120 m) rainfed wheat environment of Chile, showed similarities only to a narrow zone completely within Chile (Fig. 3d). The same pattern of limited similarity also held for comparisons of Tarata with regions in Central America and Mexico (Fig. 4a) and Africa (Fig. 4b). Interestingly, the Tarata environment appeared to be similar to those of regions near CIMMYT's headquarters at El Batán, Mexico, and of areas in the highlands of Ethiopia and Lesotho. Ethiopia grows around 900,000 ha of wheat each year (Aquino et al. 1996). In the early 1970s, some 100,000 ha of wheat was sown annually in Lesotho, but in recent years this has dropped to 10,000-15,000 ha (FAO 1997).

The SCT-derived elevation for a given latitude and longitude differed from the elevation reported from other sources (Table 3). The SCT generally overestimated elevation, which reflects the fact that the agricultural areas were located in valleys surrounded by mountains: the SCT uses data from a digital elevation model that provides an average elevation over a 9 km square region. Since climate varies considerably with elevation, the difference is also a source of considerable bias. This error was apparent in comparisons of climate data from the SCT with meteorological station data from FAO (Table 3), where SCT temperatures tend to be cooler than the reported temperatures. To estimate how this error might affect the climate similarity maps, pairs of maps were created for sites where meteorological station data were also available (e.g., Fig. 5). The maps based directly on the SCT were created by entering the latitude and longitude of the location and then using the SCT directly to produce climate similarity zones based on the data of that grid cell. The maps based on climate data were produced by taking the station data (FAO 1985) and using these to calculate ranges (±20% or ±10%) for precipitation, evapotranspiration, and maximum/minimum temperature for the five consecutive wettest months. These ranges were

Table 3. Comparison of elevations and climatic conditions for Cochabamba, Oruro and Sucre, Bolivia, from the SCT and from FAO (1985). Climate data are for the five-month favorable growing season based on P/PET.

	Cochabamba		Oruro		Sucre	
Data source:	SCT	FAO	SCT	FAO	SCT	FAO
Elevation (m)	3,025	2,548	4,039	3,708	2,972	2,750
Total precipitation (mm):	540	430	374	277	524	512
PET (mm)	585	586	554	544	601	601
Mean maximum temperature (°C):	21	24.7	18	18.9	19	22.7
Mean minimum temperature (°C):	8	11.7	3	2.9	8	10.6

then entered into the computer, and the appropriate zones were determined with the SCT's zonal analysis tool. Comparing the two maps for Cochabamba (Fig. 5), the zones clearly differed. The overall conclusion was still valid — ie., limited zones of similarity exist for highland environments — but the locations and areas of these similarity zones cannot be accurately predicted using the SCT methodology.

A 30 arc-second DEM (approximately 1 km x 1 km), GTOPO30, is now available (EROS Data Center, U.S. Geological Survey), suggesting the possibility of improving the climate surfaces by enhancing the resolution of the elevation data used to generate the surfaces. Although this would help define the similarity zones with greater precision, we should not be overly optimistic about obtaining improvements via reduced grid sizes: the accuracy of the interpolated surfaces is also limited by the number and quality of the meteorological stations available, and mountainous regions require much higher densities of data than relatively flat regions.

Given their complex topology and the low resolution DEM used, we took additional measures to improve the characterization of highland environments. Variation in rainfall in highland environments (regions over 2,000 m) was examined for South America and for Central America and Mexico (Fig. 6) by splitting the highland environments into three favorable-season rainfall zones. The driest and intermediate zones (300-500 mm, and 500-700 mm) correspond most closely to the areas where most wheat production occurs (including the marginal areas) and where technologies to address moisture stress would find most application. All highland study sites considered in this paper fell within these zones. For South America, these two zones would include most of the Ecuadorian, Peruvian, and Bolivian high Andes, and the northern Andes of Argentina. In Central America and Mexico, a large part of the eastern slopes of the northern Sierra Madre in Mexico would also form part of these climatological zones.

Lowland regions

Figure 7 shows zones of climatic similarity for three sites in the Santa Cruz wheat growing region. In all cases, this region showed climates similar to large regions in Brazil, Argentina and Paraguay, as well as a smaller area in northern Venezuela and Colombia. Using Paraiso as an example, large areas in Central America and Africa also showed similarities (Fig. 8). However, these results must be interpreted with caution. The favorable five-month growing season was defined as the period with the largest values of P/PET. For this region, the period coincides with the hot, wet season when soybean and other warm-season crops are grown. For wheat, which is grown in the coolest and driest months of the year, some regions identified as similar might be completely inappropriate.

This consideration led us to modify the SCT to permit definition of growing seasons as the dry season* or coolest quarter of the year. Results of similarity analyses using these two criteria for Paraiso in South America (Fig. 9) produced maps that were quite different from the map based on the favorable growing season. Of the two new maps, the coolest quarter is probably more representative of the wheat growing season, since it corresponds to June through August, whereas the dry season map is for July to September.

* Defined as the longest run of consecutive months where P/PET < 0.5.

If the need to understand similarities among sites were restricted solely to the wheat growing season (e.g., for a disease with no interactions with off-season climate), then Figure 9a would be sufficient. However, for studies of crop rotations or any wheat production problem that interacts with the off-season environment, a more appropriate similarity map would combine the cool season and favorable season criteria (Fig. 10). For South America, this intersection zone constitutes a much smaller area that is basically restricted to parts of Bolivia, two regions in Brazil, and small areas in Venezuela.

Conclusions

For lowland wheat regions of Bolivia, climate similarity analyses allowed identification of other regions where wheat production conditions should be similar enough that technologies can be transferred either to or from Bolivia with a low investment in adaptive research. However, the regions were smaller than might have been expected.

In highland areas, problems stemmed from the topology of the Andean region combined with the low resolution DEM incorporated into the SCT. This resulted in little confidence in the precise location and extent of the generated site similarity zones, other than the likelihood of these zones not covering extensive areas. An alternative approach, which divided the highland areas into different rainfall zones during the favorable cropping season, provided a potentially more realistic characterization of highland environments. The nature of these zones were more in line with traditional agroecological regions, yet quite refined due to their climatic component. Given the special problems associated with highland regions, these zones were considered to represent the most feasible potential areas for technology transfer/exchange.

All zonations produced in the present study could be further refined with the addition of data on soils or land use. The SCT can produce similarity analyses using these data as surface layers, but available data were not considered to be of a suitable scale for inclusion in this analysis. Moreover, using these data would further reduce the regions considered similar.

The present study has demonstrated the potential of applying GIS applications — particularly the SCT— to help identify comparable production environments and facilitate the efficient exchange of knowledge among research in such regions. The complexity of the Andean region presented numerous problems and highlighted potential deficiencies associated with current systems and datasets when trying to work in mountainous areas. More flexibility may be obtained by coupling tools such as crop simulation models with GIS, to enable users to compare crop or system performance across regions.

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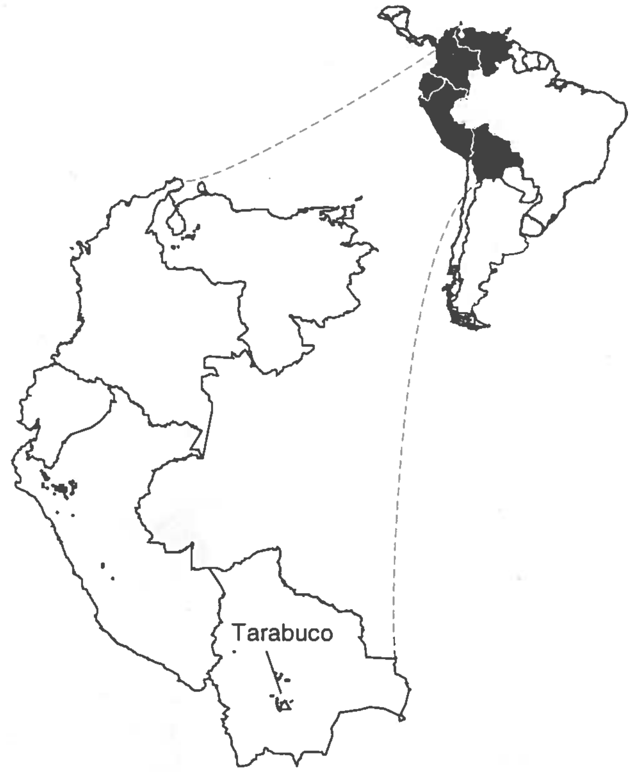
a. Tarata, Bolivia.



b. Tarabuco, Bolivia.

Figure 2. Zones that are climatically similar to Bolivian highland sites for the 5-month optimal crop growth period (± 20% similarity for precipitation and evapotranspiration; ± 10% similarity for maximum and minimum temperature).

c. Yamparaez, Bolivia.

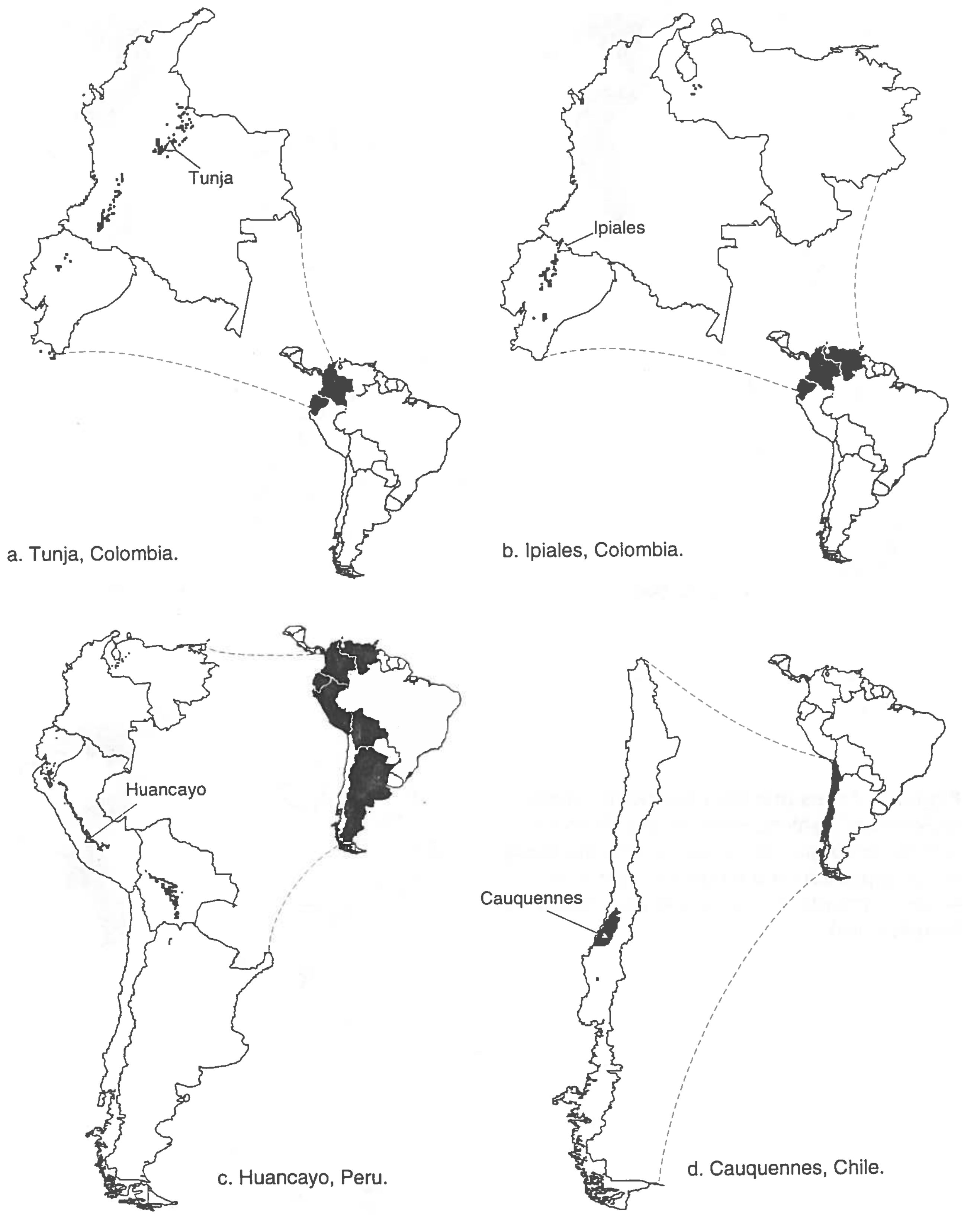
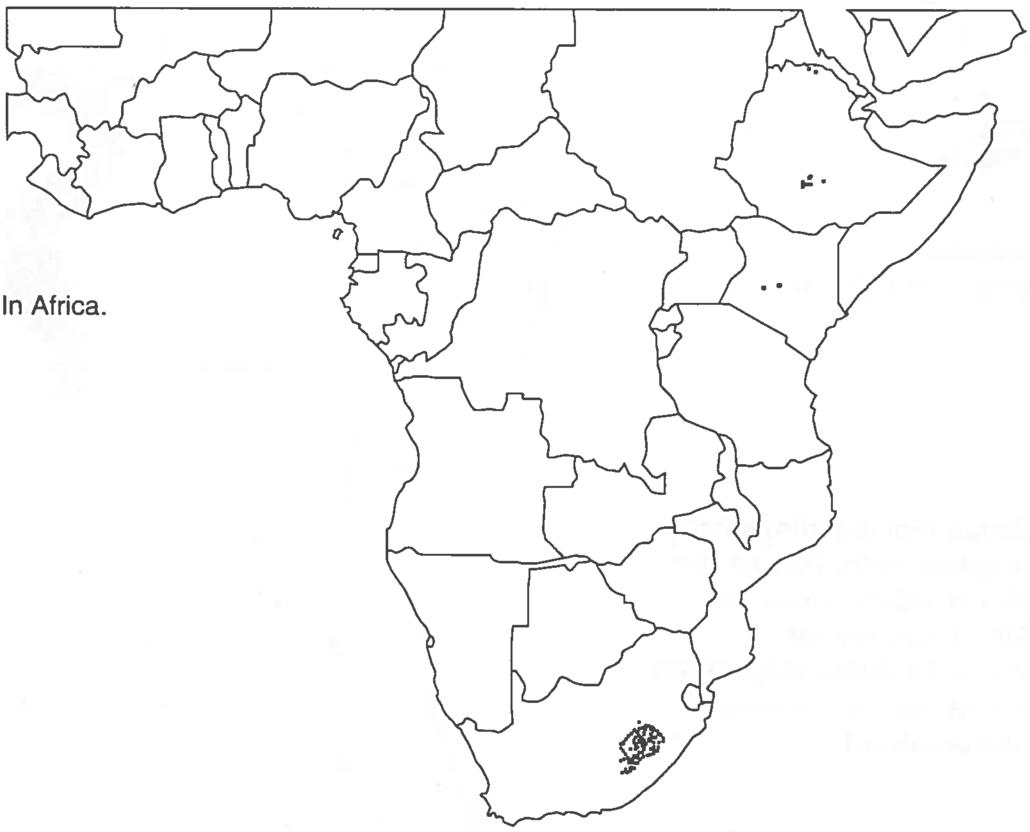


Figure 3. Zones that are climatically similar to other sites in South America for the 5-month optimal crop growth period (± 20% similarity for precipitation and evapotranspiration; (±10% similarity for maximum and minimum temperature.

a. In Mexico and Central America.



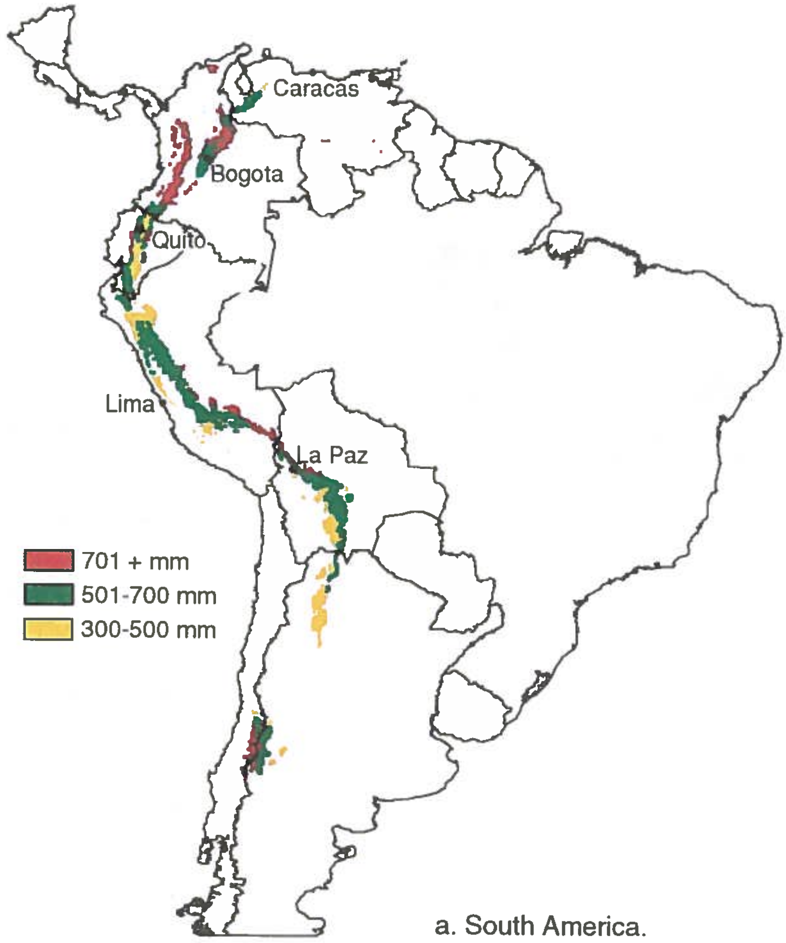
b. In Africa.

Figure 4. Non-Andean zones that are climatically similar to Tarata, Bolivia, for the 5-month optimal crop growth period (± 20% similarity for precipitation and evapotranspiration; ± 10% similarity for maximum and minimum temperature).

a. Based on Spatial Characterization Tool (SCT) values.

Figure 5. Zones that are climatically similar to Cochabamba, Bolivia, for the 5-month optimal crop growth period (± 20% similarity for precipitation and evapotranspiration; ± 10% similarity for maximum and minimum temperature).

b. Based on FAO meteorological station values.



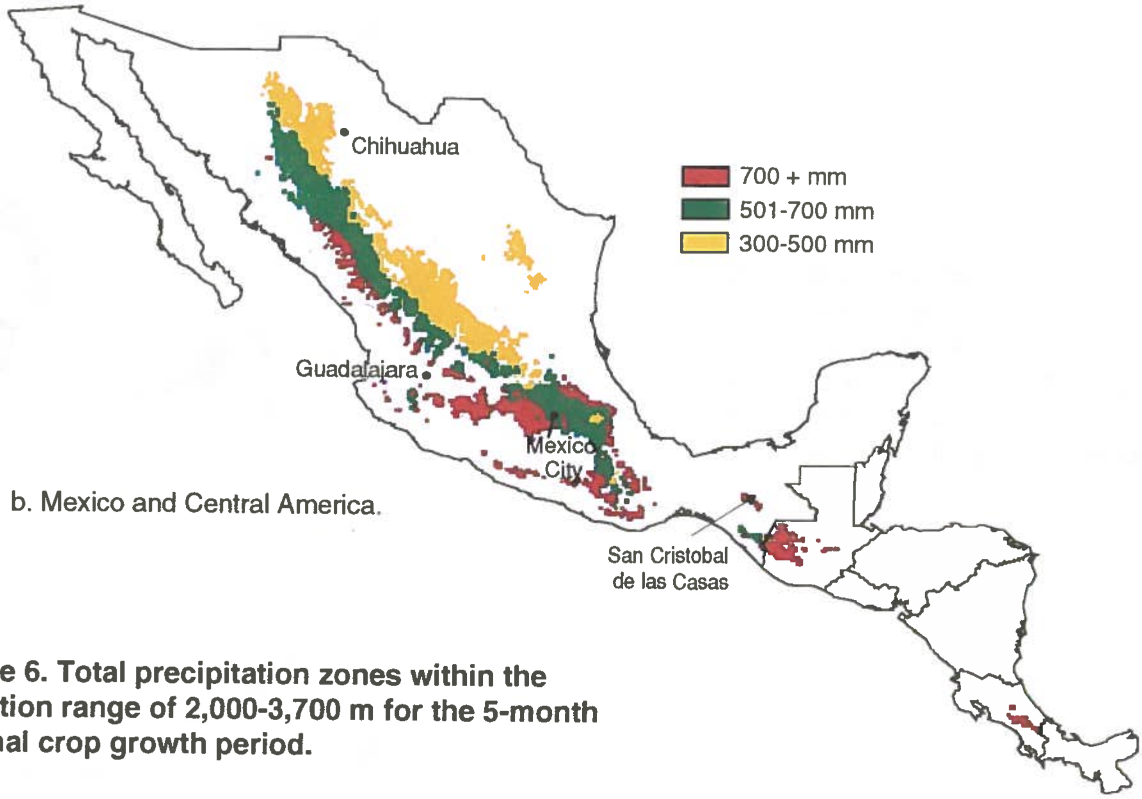


Figure 6. Total precipitation zones within the elevation range of 2,000-3,700 m for the 5-month optimal crop growth period.

a. Paraiso, Bolivia.

b. Cañada Larga, Bolivia.

Figure 7. Zones that are climatically similar to lowland wheat regions of Bolivia for the 5-month optimal crop growth period (± 20% similarity for precipitation and evapotranspiration; ± 10% similarity for maximum and minimum temperature).

c. San Rafael, Bolivia.

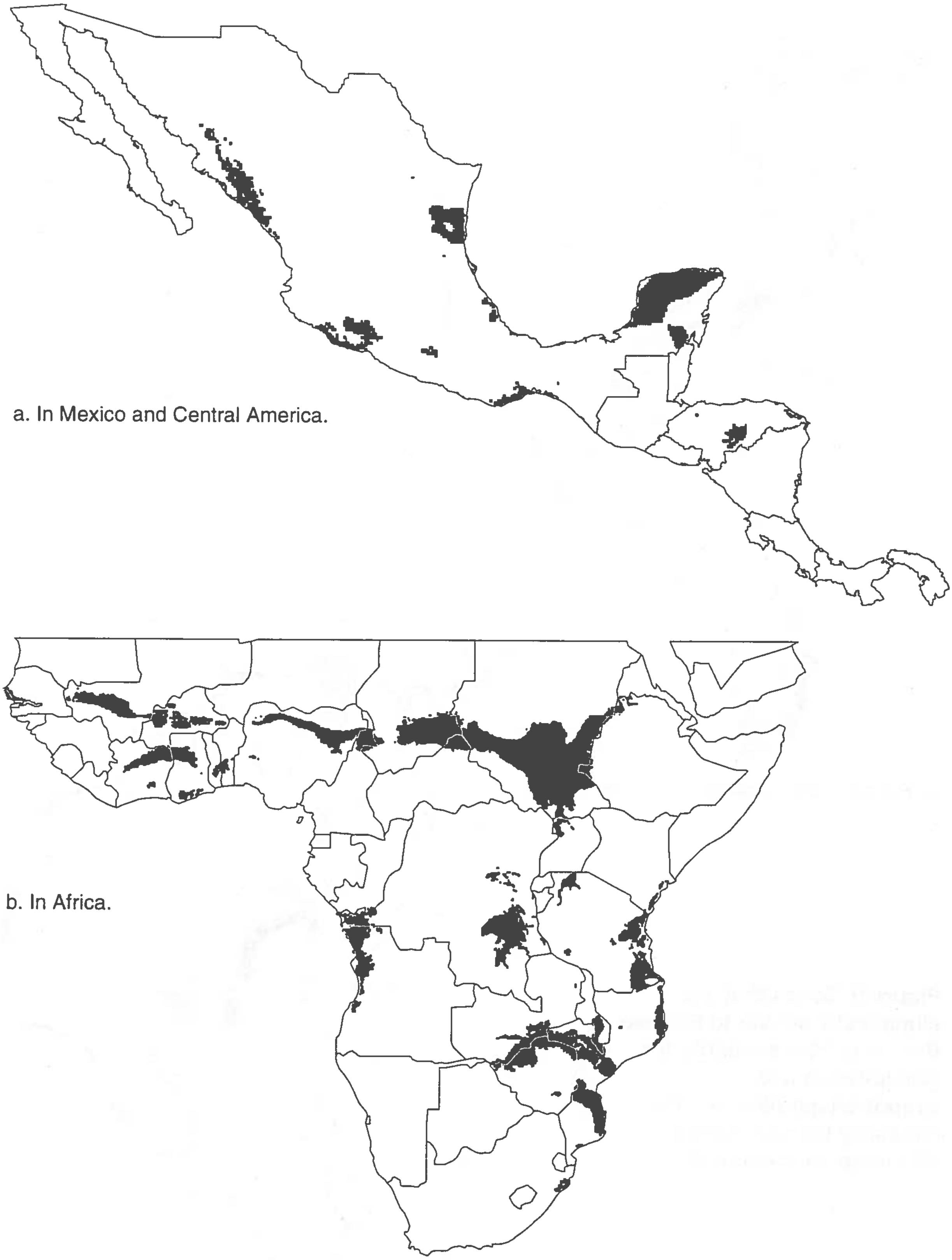


Figure 8. Zones that are climatically similar to Paraiso, Bolivia, for the 5-month optimal crop growth period (± 20% similarity for precipitation and evapotranspiration; ± 10% similarity for maximum and minimum temperature).

a. For the coolest quarter of the year.

b. For the dry season.

Figure 9. Zones that are climatically similar to Paraiso, Bolivia (± 20% similarity for precipitation and evapotranspiration; ± 10% similarity for maximum and minimum temperature).

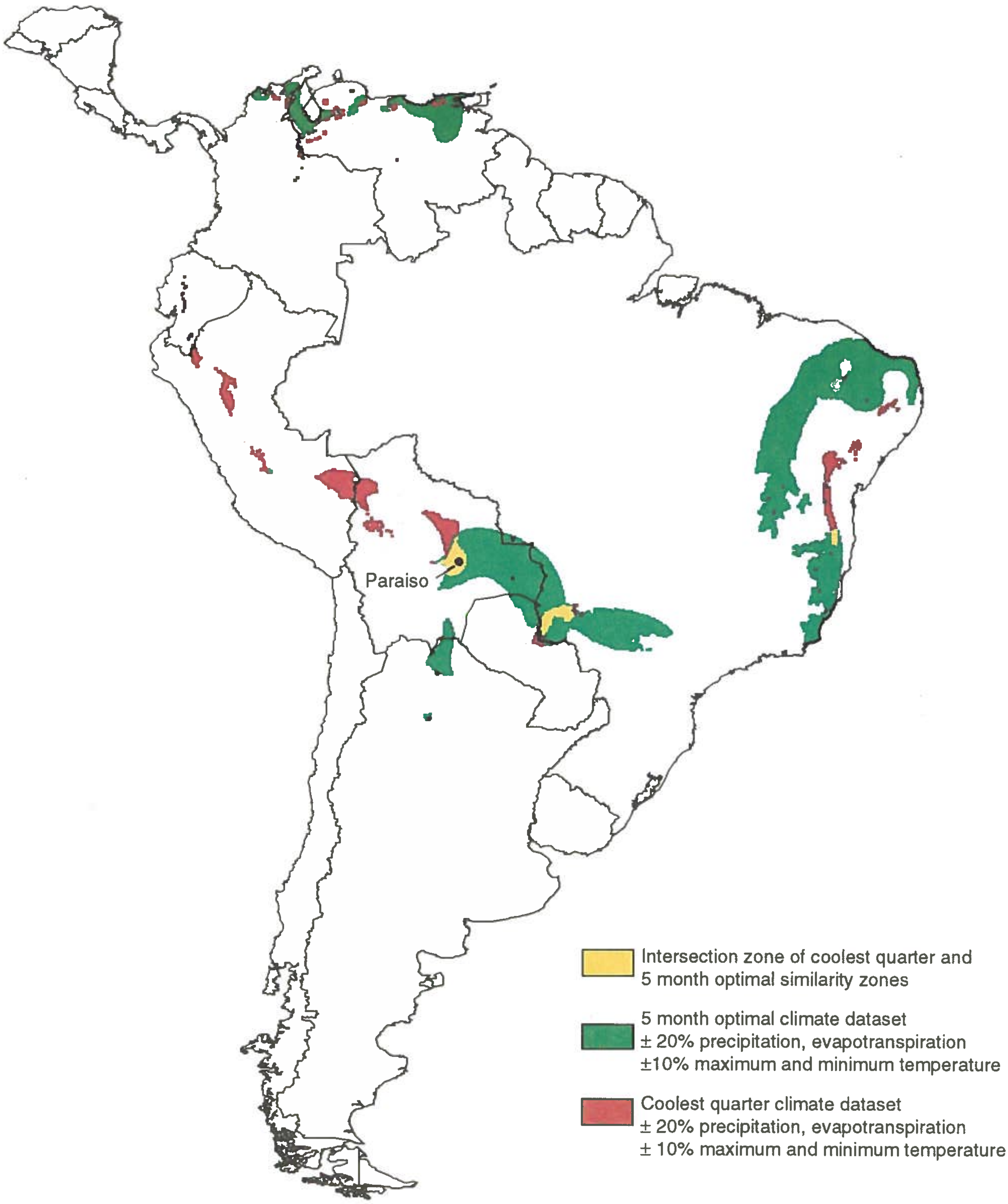


Figure 10. Zones that are climatically similar to Paraiso, Bolivia, for the coolest quarter of the year, the 5-month optimal crop growth period, and the intersection zone of both.