Toward A Dynamic Definition of Agroecological Zones Using Modern Information Technology Tools

R. Quiroz[1], P. Zorogastúa[1], G. Baigorria[1], C. Barreda[1], R. Valdivia[2], M. Cruz[1], and J. Reinoso[2]

Agroecological zoning (AEZ) is a method that uses biophysical attributes of the land to cluster land-use types into more homogeneous areas. This exercise facilitates planning for the sustainable use of natural resources. The application of AEZ is limited by the lack of geospatial data, particularly in mountainous areas. Remote sensing and process-based models for both climate interpolation and crop and livestock production were used in a watershed above 3800 m. With the incorporation of these new tools, AEZ can become a dynamic and more robust method.

One of the most striking characteristics of mountains is their spatial variability. This makes the planning of the use of natural resources in the mountains more complex than in any other area. A practical approach is to subdivide the area of interest into smaller zones with similar biophysical attributes. This is the process defined as agroecological zoning (AEZ) (FAO, 1997).

The AEZ method calls for the use of biophysical attributes of the land such as soils characteristics, physiography, climate, land use/land cover, and productivity (FAO, 1997) as input for production models. These are constructed based on expert knowledge of the adaptation of crops to local environments. The accuracy of any model, therefore, is directly proportional to the understanding of uncertainties associated with soil, climate, and management variations.

Natural resources management in mountainous areas is also characterized by the lack of precise, reliable, and accessible data. This is further complicated by the fact that, due to spatial variability, the requirement for data is more demanding than for more spatially homogeneous areas.

This paper describes some of the methods used to perform AEZ in data-scarce mountainous environments. Emphasis is given to the improvement of the AEZ method with the use of climate interpolation models, remote sensing (RS), and process-based biophysical models.

Materials and Methods

The process used in this study is outlined in the flow diagram in Figure 1. This section further describes the process.

Location

The Ilave-Huenque watershed (3825-5550 m) of the Andean high plateau or *Altiplano* was the subject of this case study. This is one of the most important watersheds; its effluent drains into Lake Titicaca, sustaining the lives of thousands of resource-poor households that depend on agriculture. The northernmost points in

[1] CIP, Lima, Peru.
[2] Centro de Investigaciones en Recursos Naturales y Medio Ambiente, Puno, Peru.

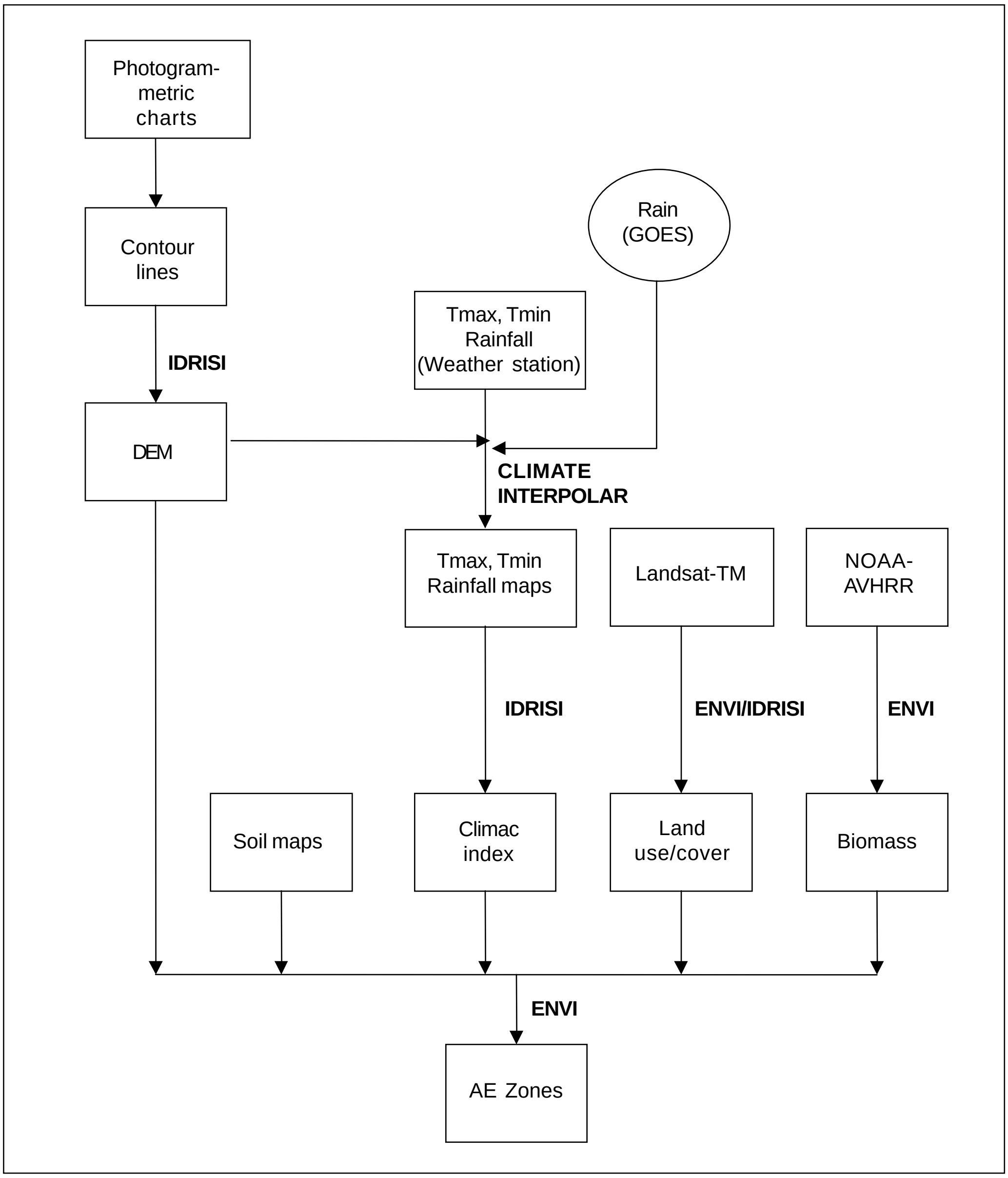

Figure 1. Flow Diagram of the method for agroecological zoning (T_{max} = maximum temperature, T_{min} = minimum temperature). Abbreviations: ARC/INFO software = (www.esri.com/software), AVHRR = Advanced Very High Resolution Radiometer (NOAA), DEM = digital elevation model, ENVI = Environment for Visualizing Images (Research Systems Inc.-Kodak, Boulder, CO, USA), GOES = Geostationary Operational Environmental Satellite (NOAA, USA), IDRISI = IDRISI software (http://www.clarklabs.org/), NOAA = National Oceanic and Atmospheric Administration (USA).

the watersheds are at latitude 16° 10’ S and longitude 69° 30’ W and southernmost at latitude 17° 05’ S and longitude 70° 05’ W. The total area comprises about 777,000 ha.

Soils

Thirty-three soil classes were used in the AEZ. In general terms, the soils are mostly shallow to moderately shallow, low in organic matter content (less than 4%), and low in P (< 14 mg/kg soil). There is also a predominance of acid soils (pH < 6). A low clay content across the watershed makes the soils highly vulnerable to water erosion. This is particularly important in the lower part of the watershed where farmers crop even steep slopes because they are less frost prone (Grace, 1985; Arguelles and Estrada, 1990).

Topography

Photogrammetric charts 1:100,000 were digitized and the digital elevation model (DEM) generated. The slope and altitude maps were derived from the DEM and used as input both to the AEZ directly, as well as for the climate interpolation procedures.

Land use/land cover

The land use/land cover data were derived from virtually cloud-free Landsat-TM imageries taken in 1990 and 1997. The images were geometrically corrected using mapping polynomials (Richards, 1993) with 18 control points from a 1:100,000 map. A mosaic of the imageries was then constructed. An unsupervised classification produced a first draft of the land use/land cover map. These classes were ground-truthed before performing a supervised classification, thus producing the final land use/land cover map.

Biomass

A functional relationship between monthly cuttings of green dry matter (DM) and the Advanced Very High Resolution Radiometer (AVHRR) normalized difference vegetation index (NDVI) was established. Three years of data (1995–1997) were used to derive the equation:

$$DM = 1.615 * NDVI^{1.318}; \quad R^2 = 0.90$$

where DM = green dry matter (kg fresh wt/m^2), and NDVI = normalized difference vegetation index.

The Mardquart procedure of SAS (1988) was used to derive the parameter of the nonlinear equation (Rawlings, 1988). The goodness-of-fit was assessed by the following ratio:

$$R^2 = \frac{SS_{regression}}{SS_{total}}$$

where SS = sum of squares.

Climate

A method based on the geographic information system (GIS) was used for spatial climate analysis (Baigorria et al., 2000a). Raster maps of rainfall and maximum and minimum temperature were generated with process-based interpolation models. These models combine point-measures of climate variables and topographic data (slope and aspect) as input to mathematical models that integrate state-of-the-art knowledge of the physical laws ruling the spatial variability of climate. The Geostationary Operational Environmental Satellite (GOES) was used to determine the movement of clouds for the rainfall interpolation model (Baigorria et al., 2000b).

Monthly climate data from four weather stations were used. The accuracy of the interpolation was not assessed due to the lack of independent weather stations. Outstanding agreement between interpolated and independent weather data in a similar setting in northern Peru showed the reliability of the procedure. The climate maps generated with pixel sizes of around 50 x 50 m for the frost-free season (November – April) were summarized into a thermal-rain index. The index is directly related to rainfall and inversely related to the thermal range (difference between maximum and minimum temperature):

$$I_{tr} = 7.1 + Ln \left[\frac{PP + 1}{((T_{max} - T_{min}) + 1)^{1.66}} \right]$$

where, I_{tr} = thermal-rain index (0 – 14), PP = rainfall (mm), T_{max} = maximum temperature (°C), T_{min} = minimum temperature (°C), and Ln = natural logarithm.

The constant 7.1 scales the index between 0 and 14. The addition of 1 unit to both the numerator and the denominators is to guarantee having a real logarithmic number when either the rainfall or the thermal range are equal to zero. The denominator is raised to the power of 1.66 to match the units of the thermal range with the rainfall.

AEZ Procedure

Using all the characteristics described above as layers of a GIS, an unsupervised classification was run to arrive at the classes termed AEZs.

Process-based biophysical models

Both crop and livestock models have been validated for the soil, climate, and management conditions encountered in the Altiplano. The potato model SUBSTOR (Bowen et al., 1999), alpaca (Arce et al., 1994), sheep (Aguilar and Cañas, 1991), and llama (Murillo, 2000) are models that have been tested for the Andes.

A generic method described elsewhere (Quiroz et al., 2000) might be used to simulate crop or livestock production, either for each zone or on a pixel-by-pixel basis.

Results and Discussion

The land attributes used to assign each pixel to a cluster or AEZ are divided into two categories. Category I (soil classes, altitudes, and slopes) includes variables obtained in a way similar to other AEZ studies (FAO, 1997). Summary maps of these attributes are presented in Figure 2.

The remainder of this section is devoted to the variables of Category II (land use/land cover, biomass, and climate) and the AEZ resulting from the exercise.

Land use/land cover

Figure 3 shows a summary of eight land use/land cover classes. These classes correspond to the classification system of Anderson et al. (1976) as modified by Sabins (1997). We list the Category II classification that corresponds to image scales between 1:80,000 and 1:125,000:

- 110 Residential,
- 210 Cropland and pasture (mainly alfalfa),
- 310 Grassland,
- 320 Shrub and brushland,
- 510/520 Streams + lakes and ponds,
- 620 Vegetated wetlands or year-round naturally irrigated grasslands (bofedal),
- 730/740 Sand and gravel other than beaches + exposed rocks, and
- 910 Perennial snowfields.

Of the 777,000 ha, cropland and pasture account for 4%; grasslands, 49%; bofedal, 5%; shrubs, 32%; snowfields, 1%; and stream, lakes, and ponds combined with residential, 2%. Cropping areas are located in the lower part of the watershed. That is a less frost-prone area closer to local markets. It is also a highly populated area, thus putting the sustainability of the system at risk. There are a few spots of cropland and pasture in the middle of the watershed. These are areas suitable for pasture, but some cereals grown as forage and bitter potato are also found. It is in this part of the watershed that deep gullies are evidence of much water erosion.

Grasslands dominate the use of the land across the watershed. They are grazed mainly by sheep in the lower part of the watershed and by camelids (alpacas and llamas) in the medium and high parts. Bofedales are used almost exclusively by camelids, mainly alpacas. The padded hooves of these animals prevent the damage done by other ruminants to this highly productive, highly valued, and fragile grassland. Bofedales are found mainly in the higher part of the watershed that receives water from snowmelt.

Shrubs cover a relatively high proportion of the land. The dominant species are *Parastrephia lepidophylla* and *Baccharis incarum*. They grow to an average height of 2 m, which usually takes around 6 years

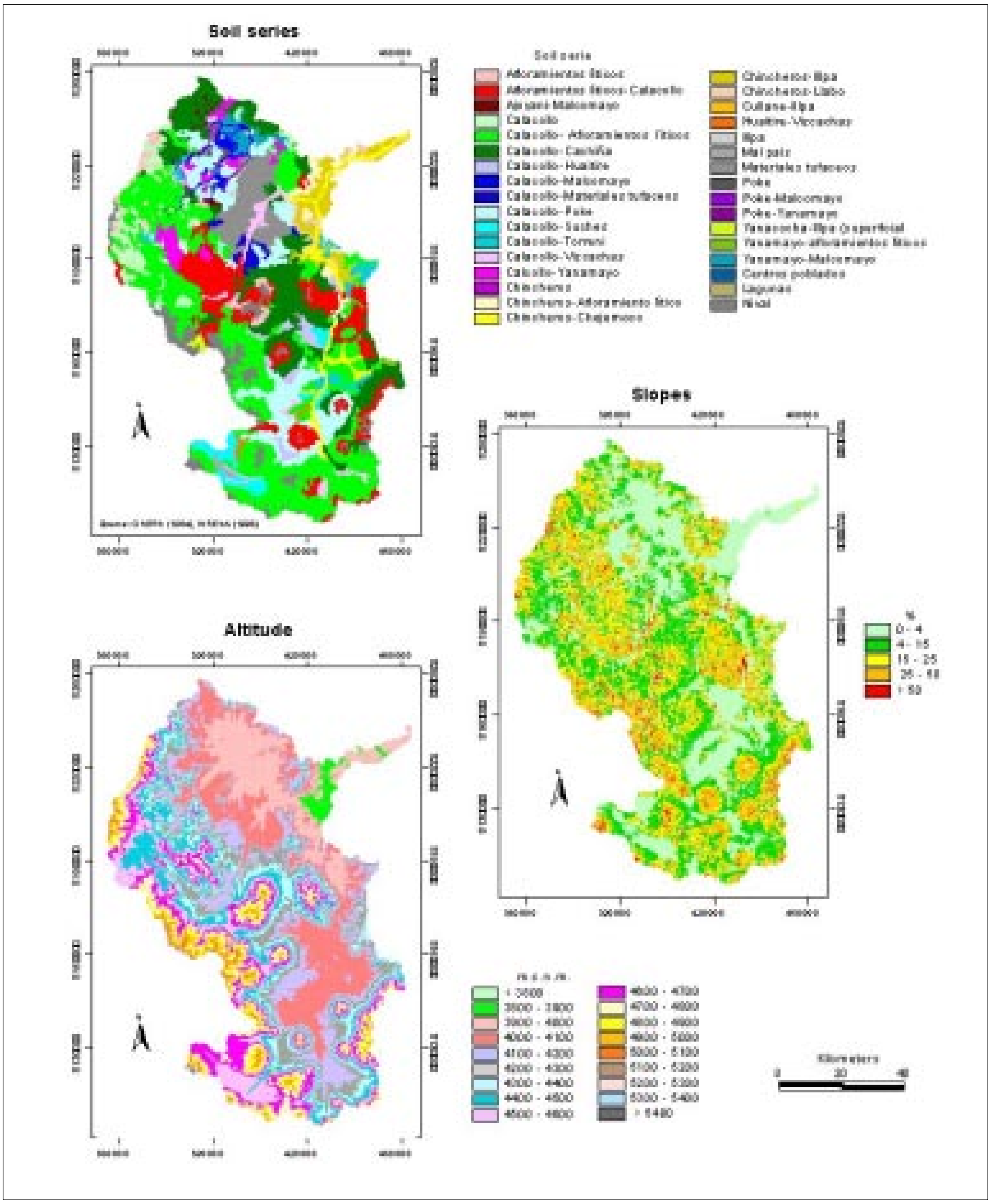

Figure 2. Soils and topography of Ilave-Huenque watershed.

(Perez Mercado, 1994). Within the watershed, shrubs cover the less fertile areas and are commonly found in rocky soils. Ruminants graze the pastures within the shrubs and feed on the shrubs during shortages. Shrub leaves constitute less than 5% of their diet (Genin et al., 1995).

Our results show that remote sensing can be used to map land use/land cover in mountain areas as effectively as in other settings (Sabins, 1997; Anderson et al., 1976). New high-resolution satellites will improve our capability for this task even in areas with higher fragmentation of land use than the one reported here.

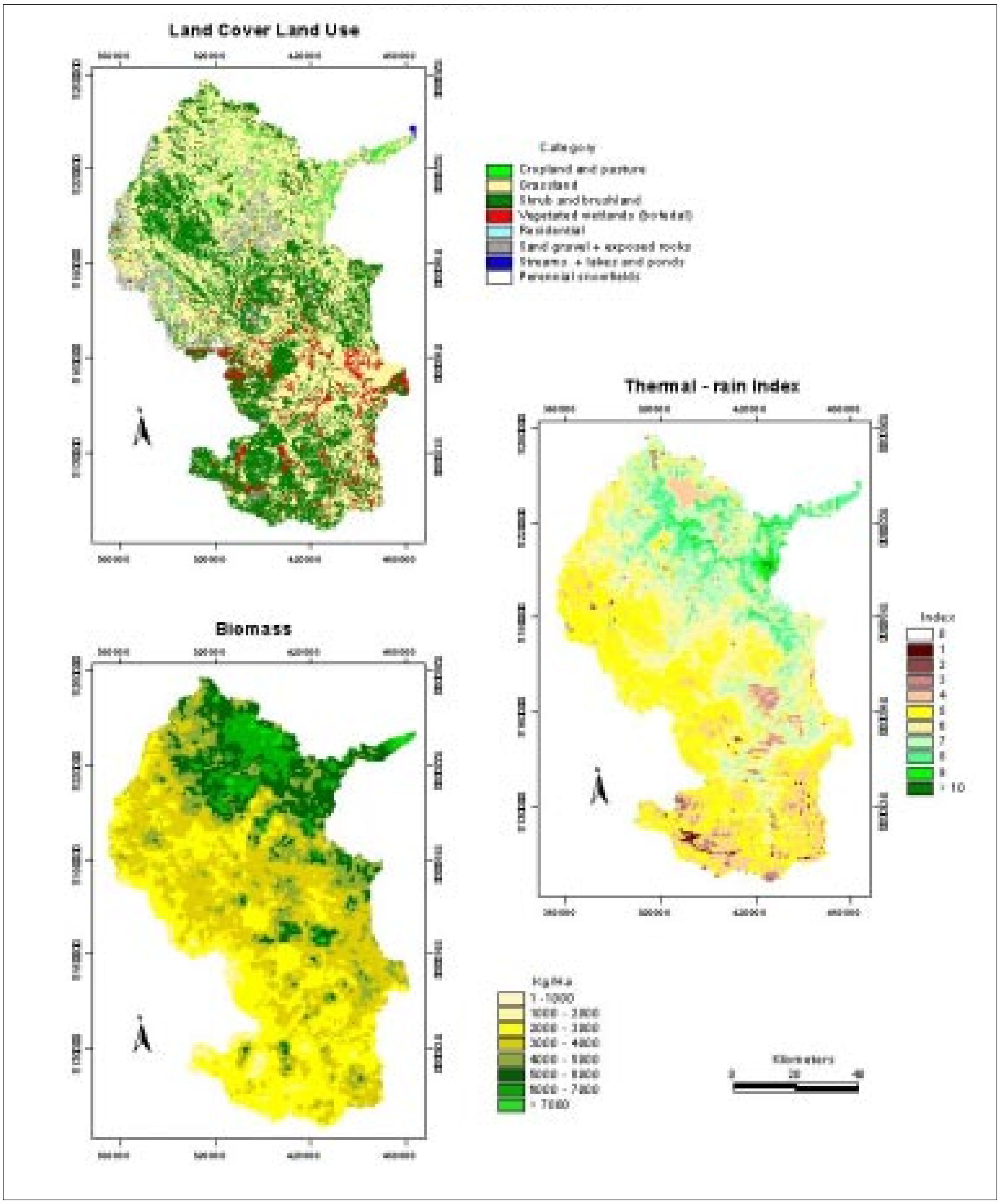

Figure 3 Land cover and land use, biomass, and climate of Ilave-Huenque watershed.

Biomass

Using NDVI to estimate standing green biomass proved to be a reliable source of biomass data. There are two sources of data that complement each other. On the one hand, high-resolution biomass maps can be derived from Landsat-TM (30-m resolution) or from Ikonos (4-m resolution). The tradeoff using these data is the higher cost. On the other hand, lower resolution (1-km) AVHRR might be used. The advantage of this sensor is its continuous and synoptic coverage plus the availability of data on the Internet (USGS EDAC, 2002).

Both sensors (Landsat-TM and AVHRR) were used in this study. The AVHRR data were resampled to generate biomass maps with the same resolution used for other input in the AEZ exercise. AVHRR data was also used to analyze the growth pattern within a growing season. The map shown in Figure 3 corresponds to the extraction of the pixels with highest biomass in the year. This map is also a high-level aggregation of the biomass map into just five classes. Highest production corresponds to cropland and pasture, bofedales, and well-managed grasslands on the lower part of the watershed (18% of total area). The medium range production (1.5–2.5 t/ha) is associated with shrubs and grassland growing in areas with adequate moisture, often referred to as temporal bofedales (49%). A large proportion (32%) corresponds to low-quality bunch grasses and shrub-bunch grass associations growing in drier areas with a very low carrying capacity.

Cloudy skies during the rainy season constitute a major problem using NDVI to estimate biomass. This is of particular importance when satellite data are used to assess biomass availability for grazing animals throughout the year. Combining remotely sensed data with a pasture growth model (Jongschaap, 2001) has circumvented this limitation.

The satellite data acquired during clear days provide the models with the parameters needed to 'steer' it; i.e., the data correct the simulation results by providing the model with actual or remotely sensed figures of the biomass. The model in turn fills in the blank spaces produced by overcast skies. Based on the experiences in the Altiplano, this synergy seems to be very useful.

Climate

Both frost and water deficit are common in Ilave-Huenque, even within the year-long growing season. Therefore, the ability to map areas vulnerable to these abiotic stresses is an important contribution to planning the management of the watershed. When the climatic maps were summarized into the I_{tr} index, the following distributions for each quintile were encountered: 3% for the first, 44% for the second, 50% for the third, 2% for the fourth, and 1% for the fifth. Values of I_{tr} between 8 and 10 were associated with cropland and pasture, and some grassland. There also seems to be a good association between the I_{tp} value (5 and 6) and the existence of bush and brushland. For the other land cover classes, a direct association was less apparent.

AEZ

Four AEZs were derived from the analysis (Figure 4). The zone with aptitude for crop and pasture production comprises 42,000 ha. Using process-based models to simulate the potential production of this zone indicates that productivity can be significantly increased with technologies to intensify agriculture in the zone. For example, potato production could be increased from 5–6 t/ha to 10–12 t/ha under rainfed conditions; up to 18 t/ha with irrigation.

The second zone corresponds to the area where livestock can be intensified. It comprises roughly 110,000 ha or 14% of the area. These areas have high carrying capacity for cattle, sheep, and alpaca. In the areas near local markets, dual purpose or dairy production is recommended. In the areas with bofedales, alpaca production is a better alternative. Sheep constitute a flexible buffer alternative that can be accommodated throughout this AEZ. Current biomass production of less than 5 t/ha and low quality might be increased to more than 8 t/ha of good quality pasture (alfalfa, ryegrass, and white clover). Increments on the order of 40% to 50% in gross income are feasible.

The third zone was classified as extensive livestock production. With 51% of the area, equivalent to 394,000 ha, this zone

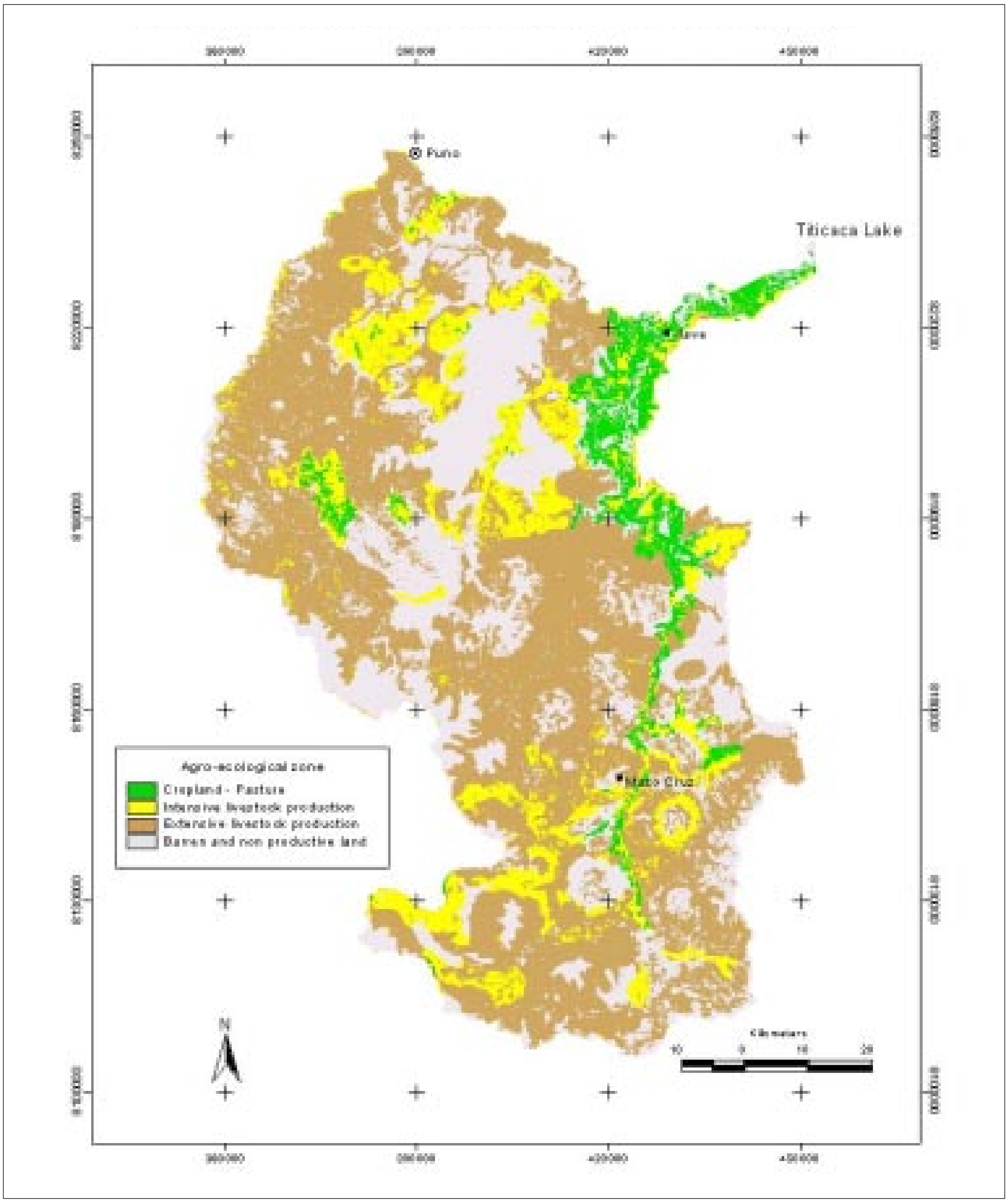

Figure 4. Agroecological zones of Ilave-Huenque watershed.

corresponds to subsistence livestock production based on sheep and llamas. Very few technological alternatives have been tested for this type of production system. Low cost, external inputs such as blocks of molasses and urea might be worth trying.

The last AEZ was related to barren land and areas under grazing with very shallow soils. It also includes snowfields.

Previous exercises on ecological zoning that included the study area have been conducted (ONERN, 1976; ONERN-CORPUNO, 1984; INRENA, 1996; Pulgar

Vidal, 1996; Tapia, 1995). It is difficult to make a comparative analysis due to the coarse resolution used or the lack of a georeferenced map, particularly with the last two studies. The present paper uses higher spatial resolution than any of the previous studies. The inclusion of quantitative variables for different attributes, on a pixel basis, provides a substantial refinement over previous results.

Conclusions

The paper described new tools and methods to be incorporated into the AEZ method. Through the inclusion of the methods presented, scientists and decision makers have access to a dynamic tool for AEZ, even in data-scarce environments. The inclusion of remote sensing in different parts of the method, together with process-based climate interpolation models, add robustness to existing procedures.

In a practical sense, several alternatives have been assessed to improve the management of the natural resources of the watershed. Since the work was jointly executed with local professionals, the chances to positively impact the sustainable management of the watershed are greatly enhanced.

Acknowledgement

The Peruvian National Natural Resources Institute (INRENA) kindly provided the soil maps for the study area.

References

Aguilar, C. and R. Cañas. 1991. Producción ovina para el Altiplano de Puno, Perú. Ciencia e investigación agraria 18:1&2. p. 23–46.

Anderson, J.T., E.T. Hardy, J.T. Roach, and R.E. Witmer. 1976. A land use and land cover classification system for use with remote sensor data: U.S Geological Survey Professional Paper 964. Washington, D.C., USA.

Arce, B., C. Aguilar, R. Cañas, and R. Quiroz, 1994. A simulation model of an alpaca system in the dry Puna of the Andes. Agricultural Systems 46:205–225.

Arguelles, L. and R.D. Estrada (eds.). 1990. Perspectivas de la Investigación Pecuaria para el Altiplano. Centro Internacional de Investigaciones para el Desarrollo / Proyecto de Investigacion de Sistemas Agropecuarios Andinos. Lima, Perú. 504 p.

Baigorria, G.A., W.T. Bowen, and J.J. Stoorvogel. 2000a. Climate/Weather interpolation: A process-based spatial interpolation model. Proceedings of Annual meetings of American Society of Agronomy - Crop Science Society of America – Soil Science Society of America (SSA) held 5-9 Nov. 2000. SSA, Minneapolis, Minnesota. p. 421. (Abstract.)

Baigorria, G.A., J.J. Stoorvogel, and W.T. Bowen. 2000b. Spatial-interpolation rainfall model based on topography and wind circulation. Proceedings of Annual meetings of American Society of Agronomy - Crop Science Society of America – Soil Science Society of America (SSA) held 5-9 Nov. 2000. SSA, Minneapolis, Minnesota. p. 421. (Abstract.)

Bowen, W., H. Cabrera, V. Barrera, and G. Baigorria. 1999. Simulating the response of potato to applied nitrogen. In: Impact on a changing world. Program report 1997-98. International Potato Center, Lima, Peru. 458 p.

FAO (Food and Agricultural Organization). 1997. Zonificación agro-ecológica, Guía general. Servicio de Recursos, Manejo y Conservación de suelos. Dirección de Fomento de Tierras y Aguas, FAO. FAO, Rome, Italy. 82 p.

Genin, D., H.-J. Picht, R. Lizarazu, and T. Rodriguez. 1995. Waira Pampa: Un sistema pastoril camélido-ovinos del Altiplano árido Boliviano. IRD (Institut de recherche pour le développement (ex-ORSTOM)), La Paz, Bolivia. 299 p.

Grace, B. 1985. El clima del altiplano, departamento de Puno, Perú. Convenio Perú-Canadá-A.C.D.I. INIPA – INIA (Instituto Nacional de Investigación Agraria), Puno, Peru. 183 p.

INRENA (Instituto Nacional De Recursos Naturales). 1996. Inventario y Evaluación de los Recursos Altoandinos de la Microregión Ilave-Puno. Ed. Oficina Nacional de Evaluacion de Recursos Naturales (ONERN), Lima, Peru.

Jongschaap, R. 2001. LINPAS model: Dynamic simulation of rangeland production in the Altiplano of Peru and Bolivia. In: Proceedings - Third International Symposium on Systems Approaches for Agricultural Development. CD-ROM computer file. International Potato Center, Lima Peru.

Murillo, E. 2000. Estudio de la crianza de llamas en el Altiplano Boliviano. Un modelo de simulación. Pontificia Universidad Católica de Chile. 70 p.

ONERN (Oficina Nacional de Evaluacion de Recursos Naturales) 1976. El mapa Ecológico del Perú. ONERN, Lima, Peru.

ONERN (Oficina Nacional de Evaluacion de Recursos Naturales) and CORPUNO (Corporacion de Fomento y Promoción Social y Económica de Puno). 1984. Inventario, Evaluación e Integración de los Recursos Naturales de la Microregión Puno. ONERN, Lima. 237 p.

Perez Mercado, R.M. 1994. Comportamiento hídrico fisiológico y fases fenológicas de la Thola *(Parastrephia lepidophylla y Baccharis incarum)*. Ingeniero agrónomo Thesis. Universidad Técnica de Oruro, Oruro, Bolivia.

Pulgar Vidal, J. 1996. Geografía del Perú, Las ocho regiones naturales. 10th Edition. Promocion Editorial Inca S.A. (PEISA), San Isidro, Lima, Peru.

Quiroz, R., P. Zorogastúa, R. Jongschaap, C. Ibarra, C. León-Velarde, and M. Cruz. 2000. Grazing in the Andes with Remote Sensing. Geoinfo Systems. http://www.geospatial-online.com/0800/apps/apps_19.html

Rawlings, J.O. 1988. Applied regression analysis: A research tool. Wadsworth & Brook/Cole Statistical/Probability series. Pacific Grove, CA, USA. 553 p.

Richards, J.A. 1993. Remote sensing digital image analysis: An introduction. Second, Revised and Enlarged Edition. Springer-Verlag, Berlin, Germany. 340 p.

Sabins, F.F. 1997. Remote sensing: Principles and interpretation, Third Edition. W. H. Freeman and Company, NY, USA. 495 p.

Statistic Analysis System Institute Inc. 1988. SAS/STAT; User's guide, release 6.03 Edition. Gary, NC, USA. 1028 p.

Tapia, M. 1995. Ecodesarrollo en los Andes Altos. Fundación Friedrich Ebert, Lima, Peru. 195 p.

USGS-EDAAC. 2001. USGS-EROS Data center distributed active archive center (NASA). http://edcdaac.usgs.gov/1KM/comp10d.html