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ASSESSMENT OF SOIL DEGRADATION SUSCEPTIBILITY IN THE CHACABUCO PROVINCE OF CENTRAL CHILE USING A MORPHOMETRY BASED RESPONSE UNITS APPROACH

ABSTRACT: MAERKER M., PAZ CASTRO C., PELACANI S. & SOTO BAEUERLE M.V., *Assessment of Soil Degradation Susceptibility in the Chacabuco Province of Central Chile using a Morphometry Based Response Units Approach*. (IT ISSN 1724-4757, 2007).

In this study the intensity and distribution of degradation processes in the Chacabuco Province of Chile was assessed focusing on water related degradation processes. The assessment is based on a morphometry based response units approach. Therefore a detailed DEM with 25 resolution was generated and analyzed. The combination of different indices allowed a separation of the terrain in different terrain units with specific degradation potential. The information is further used to identify areas that are suitable for the deposition of heavy metal rich sewage sludge of the Santiago metropolitan area. The study shows that, with a detailed geomorphological description and terrain analysis, areas susceptible to degradation processes can be identified. Hence, in a further step a classification and regression tree approach was used to derive a model to predict the degradation susceptibilities in the Chacabuco Province. The analysis was calibrated with exiting information on the geomorphology as well as intensity and distribution of degradation processes in the Metropolitan Region of Santiago, Chile.

KEY WORDS: Terrain analysis, Geomorphology, Degradation processes, Central Valley Chile, CART.

RESUMEN: MAERKER M., PAZ CASTRO C., PELACANI S. & SOTO BAEUERLE M.V., *Evaluación de la Susceptibilidad a la Degradación de los Suelos a sustentado en el enfoque de las Unidades de Respuesta Morfométrica. Provincia de Chacabuco, Chile*. (IT ISSN 1724-4757, 2007).

En la Provincia de Chacabuco, Chile, se estudió la distribución e intensidad y de los procesos de degradación a través de la relación existente entre estos y el agua. La evaluación estuvo sustentada en una morfometría basada en unidades de respuesta. Consecuentemente se generó y analizó un modelo digital de terreno (DEM) con una resolución de 25 metros. La combinación de varios índices llevó a la identificación de diferentes unidades territoriales caracterizadas por una degradación potencial específica. La información ha sido usada para identificar áreas posiblemente adecuadas para la depositación de lodos residuales (biosólidos), con metales pesados, provenientes del área Metropolitana de Santiago. El estudio da cuenta que, con una detallada descripción geomorfológica y análisis de terreno, se pueden identificar áreas susceptibles a procesos de degradación. Consecuentemente, en un siguiente paso, se aplicó un árbol de clasificación y regresión para derivar un modelo predicativo de susceptibilidad de degradación en la Provincia de Chacabuco. El análisis fue validado con la información geomorfológica existente, como también con la intensidad y distribución de los procesos de degradación en la Región Metropolitana de Santiago, Chile.

PALABRAS CLAVE: Análisis de terreno; Geomorfología, Procesos de degradación, Valle Central de Chile, CART.

INTRODUCTION

Degradation processes and forms such as water related erosion processes are mainly influenced and interlinked by the hydrological dynamics of a drainage basin. The response of three dimensional terrain units to degradation can be delineated by modifying the concept of areas with hydrological catchment's response. The concept of Response Units (RU) was applied by several authors in the past for the assessment of hydrological processes (Beran & *alii*, 1990; Falkenmark & Chapman 1989; Fluegel 1995; Bongartz 1999), erosion processes (Fluegel & *alii*, 2003) as well as for geomorphic processes (Bartsch & *alii*, 2002; Bracken & Kirkby 2005). Considering the «soil vegetation atmosphere transfer interface (SVAT)» as an ecosystem with certain atmospheric, vegetation, soil, geologic and geomorphologic characteristics it is obvious that an input to this system must be followed by a specific system response. The way in which the system is reacting depends on the systems characteristics. To get more information

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about the sensitivity of the system one has to separate the system into components as shown in figure 1 for erosion processes.

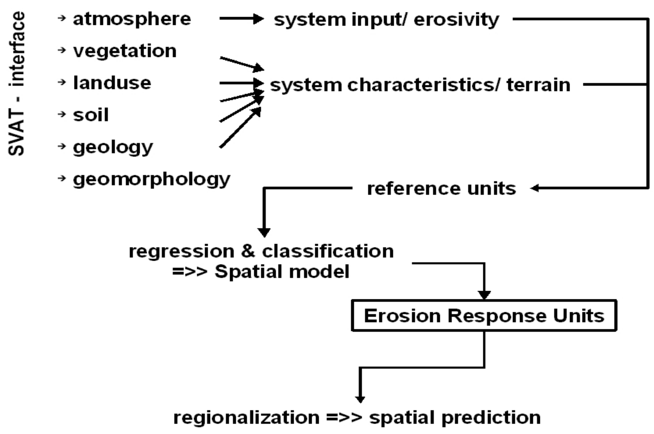

FIG. 1 - Scheme of ERU concept after Maerker & *alii*, 2001.

Different process dynamics are linked with certain associations of system component properties. Entities with the same process dynamics, which means with the same system response, consequently consist in certain associations of system characteristics and system inputs.

According to this definition the drainage basin is conceived as an assembly of spatial process entities with different degradation potentials. The latter are in turn determined by the configuration of their natural capital and the respective human management. Once delineated the RUs, this entities can be used for spatial scale transfer in regional modeling because of preserving their properties.

In this study a detailed geomorphological investigation of the study area as well as a morphometric analysis was conducted in the Chacabuco province, Chile. In the morphometric part we used topographic indices to delineate the degradation potential for water related erosion processes. Moreover, the topographic indices and other information such as geologic setting, soil distribution and landuse were statistically investigated using classification and regression analysis (Breimann & *alii*, 1984) to derive Degradation Response Units (DRUs) for the Santiago metropolitan area. This analysis was calibrated with exiting information on the intensity and distribution of degradation processes in the Province of Chacabuco, Metropolitan Region of Santiago, Chile. Moreover, the model was applied in the regionalization of degradation response units.

GEOGRAPHICAL LOCATION AND PHYSIOGRAPHY OF THE STUDY AREA

The study area is located north of Santiago de Chile and belongs to the metropolitan area of Santiago de Chile. Figure 2 shows a DEM image with details of the Province. The route network is colored in grey, the river network in black as well as the study area. The climate is characterized by mean annual precipitation from 300 mm in the central valley to more than 1500 mm in the highest zones of the Andean catena. Mean annual temperature ranges form 14°C in the costal areas to 0°C in the highest parts of the Andean catena.

The province of Chacabuco presents two different geologic and morpho-tectonic settings. On the one hand the Eastern flank is of Andean dominion, with stratified and folded volcanic and detritic cover and on the other hand the North flank that closes the Mapocho river basin, characterized by cross-sectional of monoclinales with considerably lower elevations. The level of tectonic faults and fractures are considerably higher in the Andean flank. According to the geologic data (Wall & *alii*, 1999), the Andean edge in this part of the river basin corresponds to rocks of Superior Eocene-Miocene age, emphasizing the wide predominance of the Abanico Formation. This Formation has great territorial representation in the Andes of Chile, and is conformed by andesitic volcanic to basaltic sequences with continental phyroclastic and sedimentary interleaves. It is a formation, with an intense network of faults. Locally intrusive rocks crop out in form of ambos, necks and dikes.

The western flank, corresponds to the coastal range, with typical processes, such as the culminating residual surfaces, modeled on rocks of intrusive nature. The western edge corresponds to rocks of cretasic age. The most characteristic lithologic formation consists in a phyroclastic sequences of andesitic to rhyolitic composition with insertions of lava and continental sedimentary rocks. These formations show inclinations of 20º to 30º.

The other formation in the geomorphologic landscape corresponds to volcanic and sedimentary sequences that crop out in the Eastern zone of the coastal range and can be observed in the Northern Western parts of the province. These sequences are characterized by inclinations of 20º to 30º. Moreover, only few lineaments and faults are observed in this area besides smaller outcrops of a volcanic and subvolcanic unit, consisting of basaltic lava and intrusive andesits. The lithologic characteristics of the westhern edge valley of the province of Chacabuco are extensive cretasic medium intrusive rocks, of a multiplutonic complex.

The quaternary units correspond to basal slope deposits of alluvial and colluvial origin often showing fluvial terraces.

METHODS

Ecosystems are very much depending on topography, since the hydrology of a slope, it's micro-climate, soil characteristics and vegetation is directly influenced. Furthermore topography in turn is itself a result of underlying geological structures (Wilson & Gallant, 2000). Thus, morphometric analysis allows the description of ecosystems and their functioning. In this study the morphometric analysis is based on a DEM of the Chacabuco Province. The DEM was interpolated with the ARCInfo topogrid

FIG. 2 - Study area of Chacabuco province.

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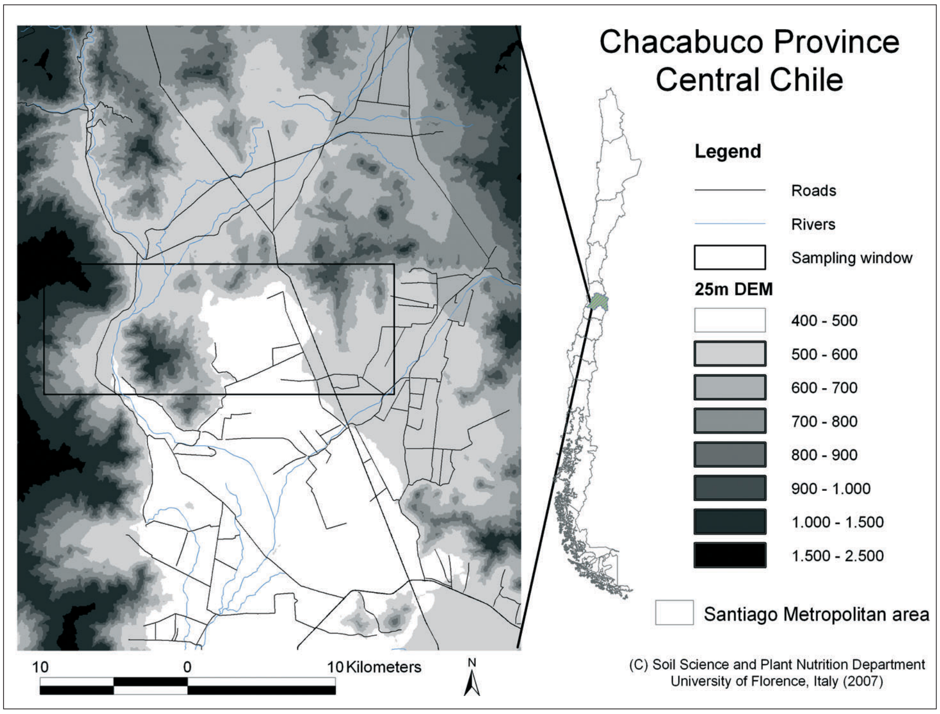

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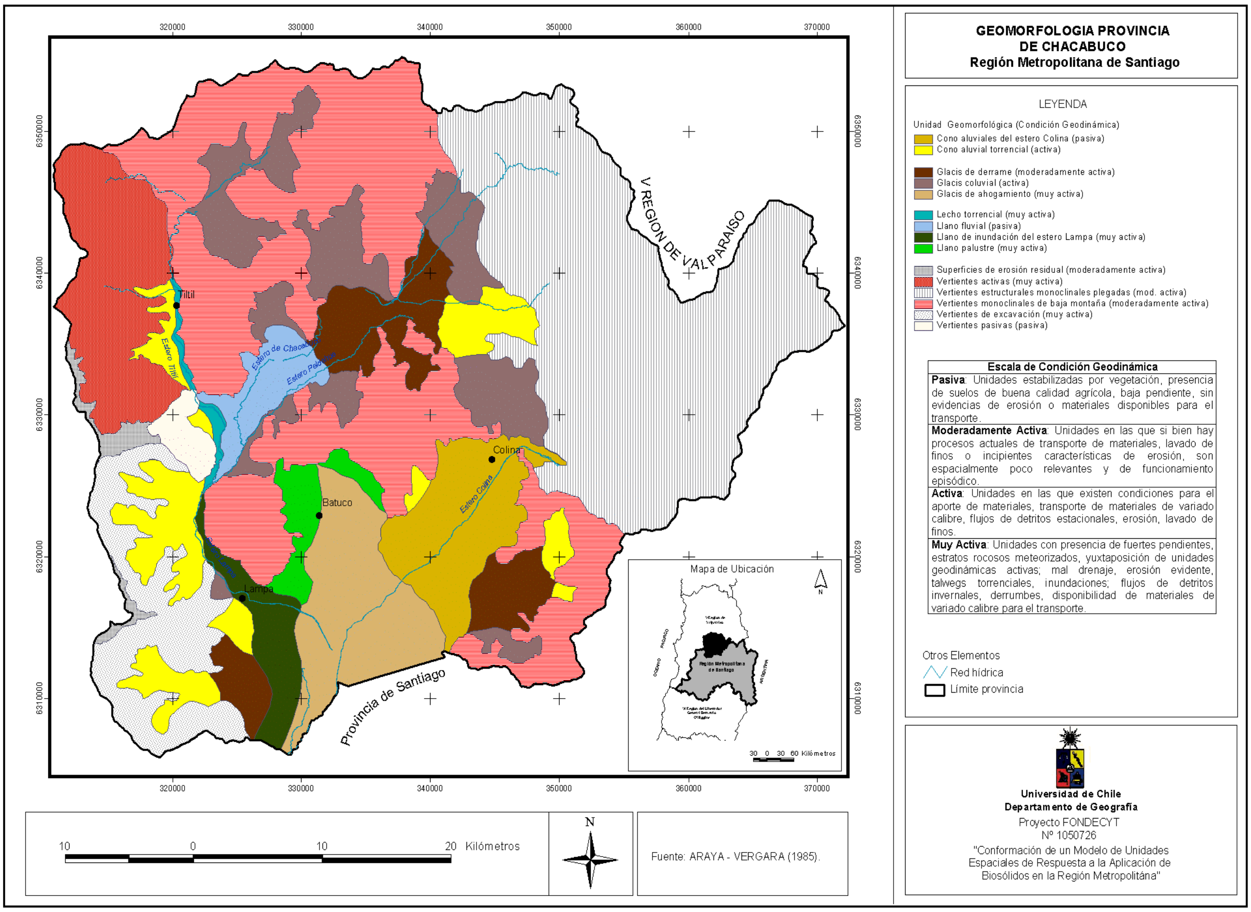

FIG. 3 - Geomorphologic map of the Chacabuco province.

module after Hutchinson (1989). The interpolation is based on contour line data of the 1:10000 topographic map. Subsequently, the resulting DEM with a 25m pixel length was preprocessed removing sinks. Moreover a «Low Pass» (3*3 kernel) smoothing algorithm was applied to reduce errors due to artifacts («terrace effects») (Behrens 2003). The morphometric analysis was performed with the SAGA-GIS terrain analysis module. This tool provides the following derivatives of continuous surface:

- The first derivate of DEM is slope in percent.
- The second derivate of DEM is curvature. This is the gradient of slope. Here we derived the profile, horizontal and combined curvature.
- Exposition, flow direction and flow accumulation.
- Combined indices like topographic wetness index, stream power index and transport capacity, radiation indices which allow already a first evaluation of erosion susceptibility.

For water related degradation processes primarily the effects of the terrain on runoff characteristics are of mayor importance. However, slope influences the overall rate of movement downslope whereas curvature effects runoff convergence or divergence as well as the relative acceleration of runoff. Slope was derived with the Zevenberg & Thorne (1987) algorithm. This method is adequate for relative smooth surfaces. Aspect influences flow direction and flow accumulation and has also implications for the local climate and thus for evapotranspiration processes. To determine the flow direction and flow accumulation a multiple flow algorithm was applied following Tarboton (1997). The combined indices describe complex runoff characteristics (Wilson & Gallant, 2000). Stream Power Index (SPI) was derived as a product of specific catchment area by gradient. Topographic Wetness Index (TWI) was calculated as logarithm of the ratio of specific catchment area and gradient. Transport Capacity Index (TCI) following Moore & Burch (1986) is a specific 3D implementation of the slope length factor of the USLE. In this study we used an overlay procedure to combine the different indices to get topographic terrain units describing slope morphology and the degradation potential of these areas. Hence, we get information of topographic position and surface runoff characteristics. The latter ones in turn are triggering water related soil erosion processes.

Subsequently overlay analysis and reclassification procedures are applied to analyze specific combinations of topographic units including geological settings, soil and vegetation or landuse characteristics. Using reference units containing information on the susceptibility to soil degradation, finally Degradation Response Units (DRU) can be derived. Therefore a classification and regression tree approach was applied.

Based on work of Sonquist & *alii* (1964) and Breimann & *alii* (1984) the method of classification and regression trees (CART) was introduced to a broader scientific audience and in consequence also in geosciences. The CART method is widely used to identify processes or to detect and analyze relationships between variables that trigger these processes. Thus, the causal relationships between the variables can also be employed to predict spatially distributed processes. In the last decade there are a variety of application examples in pedometrics and remote sensing (e.g. Cialella & *alii*, 1997, Gessler & *alii*, 1995, Lagacherie & Holmes, 1997, McBratney & *alii*, 2000, McKenzie & *alii*, 2000). However, to the knowledge of the author there are no studies where the CART technique is applied to delineate homogeneous degradation susceptibility units. The resulting DRUs can be defined as three dimensional entities with the same degradation response caused by a given system input. The procedure is described in detail in Maerker 2002. Once delineated the DRUs in characteristic test catchments, this information can be regionalized for the entire basin. Here, we use a random sample of 4000 points selected within the sampling window (see fig. 2). In the area enclosed by the sampling window the degradation processes were mapped. Consequently, we know the degradation potential for the 4000 points selected. The CART model is then regionalized on the entire sampling window area.

RESULTS AND DISCUSSION

Geomorphologic features and degradation susceptibility is directly linked to the geologic and morphostructural characteristics of Andean coastal range. Morphogenetically the processes of denudation are related to the depositional forms of the central Chile Graben unit. Thus, degradation susceptibility can be modelled for typical units of slopes and relative deposits.

The Eastern side of Chacabuco is formed by structural slopes. These slopes occur in the lower mountain ranges, whereas the rocky layers are mainly exposed in the culminating parts. The lower ranges are covered with soil and vegetation. Basal slope deposit correspond to torrential alluvial cones of small size compared to the alluvial fans of the Colina river (fig. 3), or the great regular alluvial fan of the Mapocho and Maipo river.

The colluvial glacis have a greater territorial extend in the North part of Chacabuco province. In addition these forms present a morphologic continuum since the evolution of spilling glacis can be associated with coalescent systems of torrential alluvial fans and colluvial glacis slopes. Although it was stated that these depositional systems presently are not evolving (Araya-Vergara, 1985), an active torrential talweg erosion leading to a wide dissection of slopes with a seasonal dynamic (wet winter month) can be observed as well as associated depositional forms. Thus, present day geodynamic conditions affect slopes, alluvial fans and spilling glacis actively. The associated processes correspond to material supply, material transport of a wide range of dimensions, seasonal debrisflows and erosion processes leading to of the diffusion and enlargement of talweg systems.

In Chacabuco area the landscape with rolling hills and alluvial deposits has been considered as having a passive geodynamic condition presently. From the colline alluvial fans, distal forms of a glacis have evolved, based on fine materials form surface wash erosion. This units are morphogenetically associated with the systems of slopes of the western edge and to the Pudahuel fault in the south, forming a large depression. This depression is characterized by a blocked drainage and subsequently the Batuco lake developed (Araya-Vergara 1985). These territorially very extensive units represent a very active geodynamic setting, due to the juxtaposition of lake units and the glacis consisting of fine material due to weathering processes and surface wash. The area shows and endoreic behavior.

However, this area is characterized by dynamic processes during extreme events, inducing flooding of wide areas. Moreover, this area is susceptible to soil degradation due to polluted groundwater that is ascending. Pollution is caused by industrial areas in the surroundings that drain the wastewater into the ground, subsequently polluting the aquifers.

The Chacabuco cross-sectional mountain (E-W), North limit of the river basins of Santiago corresponds to a system of monoclinale slopes of low elevation, with outcrops of rocky layers in summit areas. Due to limited slope angle soil cover established and active slope processes such as surface wash erosion and transport of materials occur with high intensities in the winter month. In this section the correlative deposits correspond to alluvial-colluvial torrential fan and glacis of small size. These deposits are dissected by episodic occurrence of debrisflows along the talweg system leading to a further excavations and erosion of these systems.

The western valley edge, of the coastal range presents a set of unique forms in the Province of Chacabuco. These forms are denominated by alveoli (Araya-Vergara, 1985). Thus, Systems of linear, gully-type erosion of great dimensions, whose tops are characterized by former erosional surfaces. The forms are similar to cirques, with steep walls and related alluvial and colluvial deposits. They are dissected by torrential talwegs,. It is important to emphasize that these features evolved in the higher areas of the coastal range, with heights of about 2000 m a.s.l. associated with seasonal nival conditions.

These form of incisions follows quaternary systems. Thus, conforming a very dynamic landscape over time. If enough detritic material is available the material will be removed by torrential discharges forming the talweg system and consequently predominate on the upper slopes, even if abundant vegetation cover, of native scrub is protecting the surface. In the Lipangue river valley the torrential alluvial fans produced by the incising slope processes and an extensive spilling glacis has been developed, whose distal part is controlled by the Lampa river.

Morphometric assessment of degradation processes

The overly analysis of slope and curvature yielded topographic terrain units shown in figure 4. We classified 9 classes with the following characteristics: i) flat surfaces with slope 0-3%, ii) low concave slopes with 3-15% slope, iii) steep concave slope with 15-60%, iv) linear low angled slopes with 3-15% slope, v) linear steep slopes with 15-60% slope, vi) low convex slopes with 3-15% slope, vii) steep convex slope with 15-60%, viii) steep slopes with 60-70%, ix) very steep slopes above 70%. This classification allows the discretization of topography in units with specific hydrological response. Classes 2 and 3 are collecting water and show flow accumulation whereas classes 6 and 7 are characterized by a distributive, dissipative behavior. Classes 4 and 5 are dominated by transport processes. Moreover, flow path length was delineated as well as aspect which was transformed using the following equation: Transformed aspect = [cos (aspect/180*pi-45/180*pi)+1] (Beers & *alii*, 1966).

Further indices delineated are the Stream Power Index (SPI) which is an indicator for concentrated runoff and thus, an indicator for linear erosion processes. In this case we used the multiple flow accumulation algorithm (Tarboton 1997). Furthermore the Topographic Wetness Index (TWI) describes accumulation zones and thus, gives information about soil characteristics like the relative distribution of soil moisture, soil thickness and saturated zones. The latter are in turn connected to the river network because surface runoff occurs due to saturation excess. The Transport Capacity Index (TCI) shows the zones where transport of sediments dominates in relation to areas with erosion or deposition processes. This morphometric analysis allows the characterization of the topography in order to detect the areas that are most susceptible to erosion, transport and deposition processes. The classifications used are relative ones.

Delineation of DRUs

The delineation of the DRUs is based on a classification and regression tree analysis. The predictors are land use, geomorphology including geologic settings, erosion, transport and deposition processes approximated by primary and combined topographic indices such as slope, aspect, curvature, flow length, SPI, TWI and TCI. As response variable the degradation susceptibility was used, classified in three relative units (moderate 1; high 2, and low 3) which are related to water erosion processes mapped in the field. This analysis was based on preliminary studies conducted in the FONDECYT project Nº 1050726 (Paz Castro & Soto Baeuerle, 2006). Figure 5 shows the CART tree derived containing combinations of predictors and respective susceptibility classes. The predictor variables actually used in the CART tree construction are the geomorphological unit (geomorph), elevation (filled DEM), land use (uso), stream power index (spi), slope, transport capacity (ls) as well as aspect. In this tree 25 terminal end nodes were built. Residual mean deviance is 1.085 (4314 / 3975) and the misclassification error rate is 0.2008 (803 / 4000).

The model based on a sample of 4000 points was subsequently utilized to predict the spatial distribution of the degradation susceptibility in the sampling window (see fig. 2).

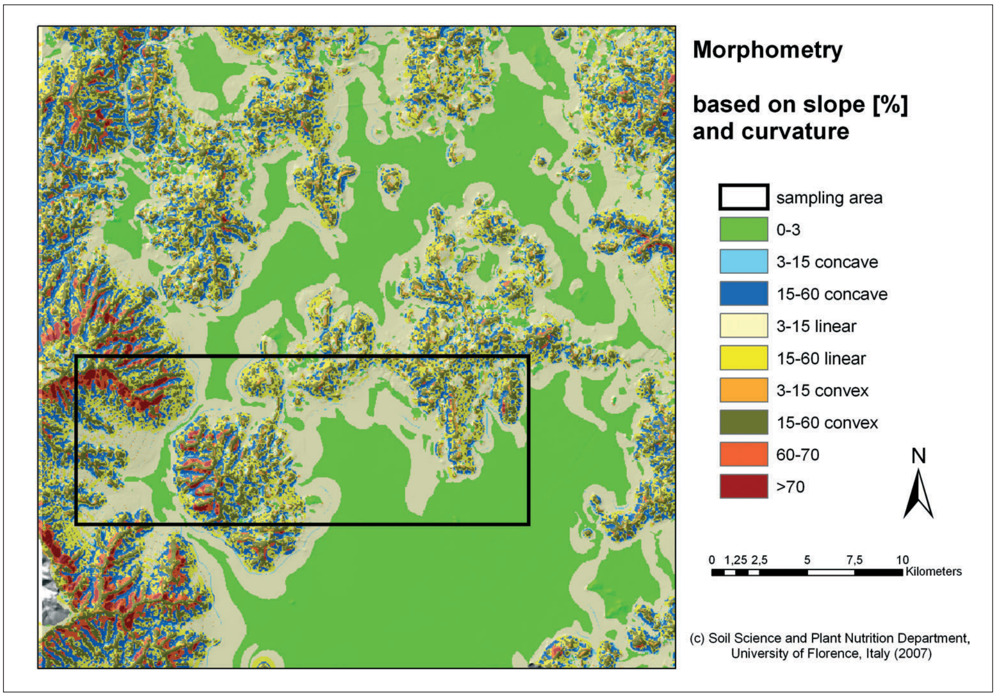

FIG. 4 - Topographic terrain units based on curvature and slope.

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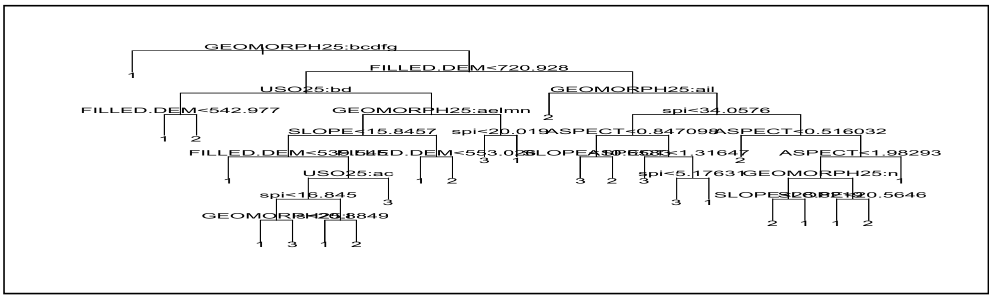
FIG. 5 - CART tree for degradation susceptibility classes. Nodes with split criteria (values or classes).



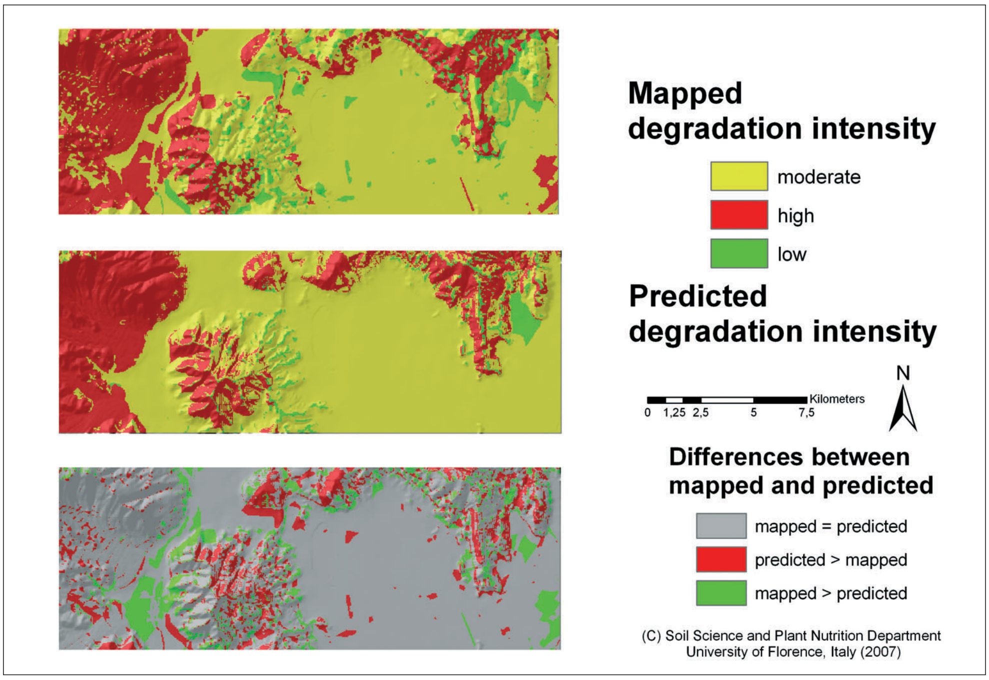


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FIG. 6 - Mapped degradation intensities (above) and predicted degradation susceptibility (middle); differences between mapped and predicted (below).

Figure 6 shows the mapped degradation intensities (above) and predicted degradation susceptibility (below). As it can be observed, both maps show a similar behavior of the spatial distribution of degradation intensities. In the predicted map the units follow slightly more the topography and seem to be more realistic. This is due to the scale of mapped information which was done on a 1:50.000 scale and then generalized, whereas the analysis for the map prediction was done on a 25 m raster resolution. The prediction with a misclassification error of about 20% can be considered as encouraging. Thus, with the tested predictors such as topographic indices and further physiographic information a prediction for larger areas of the central valley in Chile can be performed.

CONCLUSION

The morphometric analysis conducted for the Chacabuco province was based on a 25 m DEM. Thus, specific topographic features with a typical spatial scale of less than 25m are not considered in this study. However, as the comparison with the detailed geomorphological description shows major geomporphic featues were detected and with combined topographic indices a detailed study of erosive power of runoff as well as of erosion and deposition zones was achievable. Thus, revealing the spatial distribution of degradation susceptibility. The susceptibility in turn was modeled with a CART approach and subsequently a spatially larger area was predicted. The results presented show that there are certain characteristic predictor combinations for the region of the Chacabuco province in central Chile. Consequently the delineated DRUs can be utilized to analyze the degradation susceptibility due to water related erosion for physiographically similar areas in the Central valley area of Chile.

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