Relief parameters and fuzzy logic for land evaluations of mango crops (*Mangifera indica* L.) in Colombia

Parámetros del relieve y lógica difusa para la evaluación de tierras para los cultivos de mango (*Mangifera indica* L.) en Colombia

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ABSTRACT

The aim of this paper is to illustrate the use of digital elevation models (DEM) to calculate relief parameters and include them in suitability studies of land for mango crops in Colombia. Data from SRTM (Shuttle Radar Topography Mission) DEMs with 30 meter of spatial resolution and elevation in meters were used to calculate the slope, aspect, curvature, solar radiation, and topographic wetness index for inclusion in a land evaluation study. Fuzzy logic rules were developed and applied to define the degree of suitability by matching land use requirements with land characteristics. When integrated with geographic information systems, DEMs have significant potential for quantitatively defining and characterizing relief and for generating more detailed data to improve land evaluation processes. The Fuzzy logic proved to be a more realistic approach for evaluating the degree of land suitability than traditional bivalent logic, allowing for the use of membership degrees.

Key words: DEM, SRTM, tropical fruits, land evaluation, fuzzy logic.

RESUMEN

El objetivo de este trabajo es ilustrar el uso de modelos digitales de elevación (DEM) para calcular los parámetros de relieve y utilizarlos en el análisis de la aptitud de la tierra para los cultivos de mango en Colombia. Se utilizaron los datos del DEM SRTM (Shuttle Radar Topography Mission) con una resolución espacial 30 metros y a partir de la elevación se calculó la pendiente, el aspecto o dirección de la pendiente, la curvatura, la radiación solar y el índice topográfico de humedad que fueron incluidos en un estudio de evaluación de tierras. Se desarrollaron reglas de lógica difusa y se aplicaron para determinar el grado de aptitud con base en cada uno de los requerimientos del cultivo de mango y de las características de la tierra. Los DEM integrados con los sistemas de información geográfica tienen un potencial significativo para definir y caracterizar el relieve de forma cuantitativa y para generar datos más detallados que permitan mejorar el proceso de evaluación de tierras. La lógica difusa demostró ser un enfoque más realista para evaluar el grado de aptitud de la tierra que la lógica bivalente tradicional permitiendo el uso de grados de pertenencia.

Palabras clave: DEM, SRTM, frutas tropicales, evaluación de tierras, lógica difusa.

Introduction

The occupation of much of the rural Colombian territories is done without considering the specific characteristics of the land, resulting in incompatibility between the current land use and the suitability of the land. The improper location of land use results in lower productivity, generating processes of land degradation and, consequently, decreasing the sustainability and competitiveness of the land use systems. In recent years, actions have been undertaken to guide land occupation according to its limitations and potentials. To achieve this goal, politics, standards and methods for land evaluation are being implemented for appropriate land use planning (UPRA, 2013).

The primary objective of land evaluation is the improvement and sustainable management of land for the benefit of people. It may be used for many purposes, ranging from land use planning to exploration of the potential for specific land use or the need for improved land management or land degradation control (FAO, 1976). Although relief is one of the main factors affecting spatial patterns of plant growth and yields (Austin, 2002; Valbuena *et al*., 2008; Muñoz and Kravchenko, 2012), it is usually not included as part of the land evaluation process because of the difficulty of characterizing and modeling it.

Bing and Farrell (2004) stated that topography can have a significant influence on crop yield; thus, a better

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understanding of the effects of topographical parameters on crop yield is important, especially for site-specific soil management. These authors found significant correlations between grain wheat yield and surface curvature, slope length and wetness index.

A digital elevation model (DEM) represents a regular array of elevation points (Chang, 2013). DEMs are considered important sources of data for generating edaphic and relief information (Pachepsky *et al.*, 2001; McBratney *et al.*, 2003), and are useful for the analysis of problems of use, management, and conservation of lands. The whole process of land evaluation includes biophysical, environmental, social and economic criteria to identify land suitability (FAO, 2007; UPRA, 2013). This study aimed to determine the usefulness of DEMs as a data source for the inclusion of relief as part of the land evaluation for the cultivation of mango (*Mangifera indica* L.).

Fuzzy logic, as proposed by Zadeh (1965), is a mathematical method to analyze and represent processes and objects that are not clearly defined and has achieved a wide range of applications in electronics, control systems and mechanical operations. Its use has been extended to the modeling of natural phenomena and processes whose characterization, delineation and classification have a high degree of uncertainty, as in the case of natural resources. Several studies (McBratney and Odeh, 1997) have concluded that fuzzy logic improves traditional land evaluation, which is based on classical logic, since it is a complex problem of an inaccurate nature, with considerable uncertainty inherent to the data. Besides, subjective-criteria treatment is usually performed on spatial units that have large variability within them. There have been applications of fuzzy logic in various topics of soils (McBratney and Odeh, 1997), agricultural land suitability (Ahamed *et al.*, 2000), and land quality modeling (Martínez, 2006; Ramos and Martínez, 2006; Martínez *et al.*, 2009; Martínez and Munar, 2010).

Materials and methods

The conceptual approach used to evaluate the suitability of the land was based on a comparative analysis of the characteristics of the land and the requirements for each crop needed for adequate yield (Martínez, 2006). The classification was performed by comparing the specific requirements of the crops with land characteristics to assess the level of fitness and establish the boundaries between suitable and unsuitable conditions for specific uses (FAO, 2007). This involves establishing the requirements of the types of uses that will be evaluated and identifying, defining and characterizing the spatial units or land units that will be evaluated.

The study area contained 20,898 ha and was located in the central part of Colombia, in the department of Cundinamarca; between the coordinates 74°35'0" and 74°25'0" W; 4°40'0" and 4°30'0" N. The area is considered to have potential for the production of mango. A SRTM (Shuttle Radar Topography Mission) system DEM with 30 m spatial resolution was used to calculate the slope, aspect, curvature, solar radiation, and topographic wetness index.

The information on fertility and other soil properties was taken from a soil survey at a scale of 1:100,000 (IGAC, 2000); the crop requirements were defined based on literature review and expert knowledge. The degree of fitness was determined by several criteria through fuzzy logic functions, establishing membership degrees (McBratney and Odeh, 1997). In a preliminary stage, the analyses were carried out to obtain each of the indicators, separately; generating a map that shows the status of each indicator for the entire study area. For each of the identified requirements, a fuzzy logic function was established that related them to the characteristics of the land.

Altitude

Elevation is the primary data given by DEMs. The fuzzy logic function (Fig. 1) was used to qualify the degree of suitability of the slope; optimum elevation values were taken from 0 to 400 m a.s.l. (degree of membership = 1) and, from this value, suitability decreased as a function (Fig. 1) until 940 m, an elevation that was considered unsuitable (degree of membership near 0) .

Slope

Slope is defined as the tangent of a plane relative to the surface topography. If we define the elevation (Z) of a point on a land's surface as a function of the location (X, Y), then the slope (S) is the first derivative of a surface and has both magnitude and direction (Chang, 2013).

$$S = \sqrt{(\partial_z/\partial_x)^2 + (\partial_z/\partial_y)^2} \quad (1)$$

Because mango is a perennial crop that does not involve the constant removal of soil and taking into account the characteristics of distribution and intensity of rain, it is considered a low risk to erosion. Therefore, it was determined that a slope that is less than 50% is suitable for the crop. The valuation of the degree of suitability was done based on the fuzzy logic function given membership values as shown in Fig. 2.

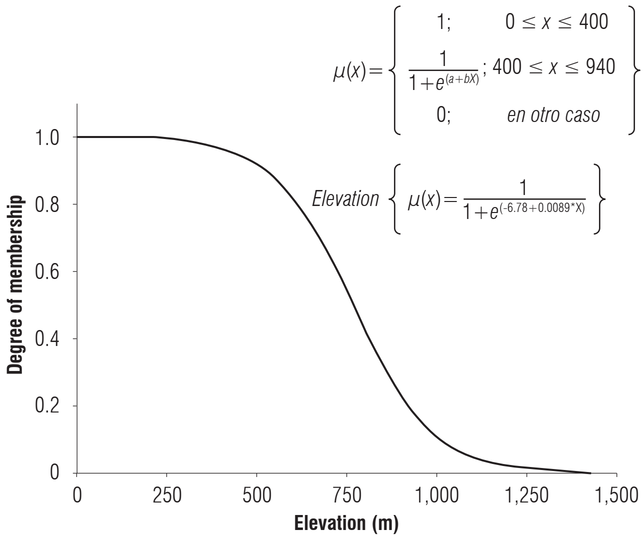

FIGURE 1. Fuzzy membership function used to define the suitability degree of elevation.

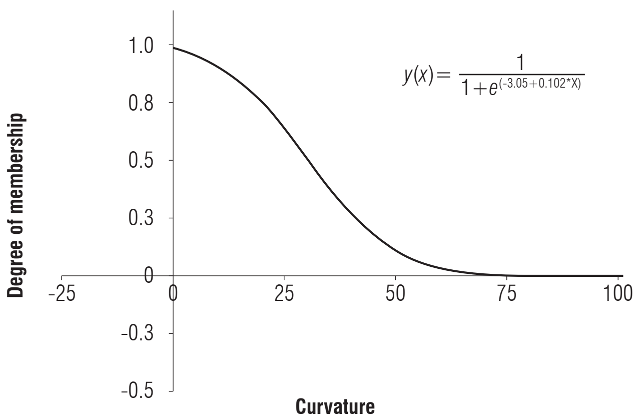

FIGURE 2. Fuzzy membership function used to define the suitability degree of slope.

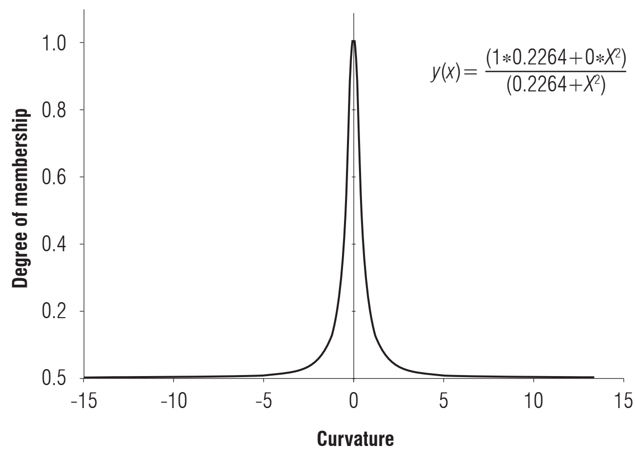

FIGURE 3. Fuzzy membership function used to define the suitability degree of curvature.

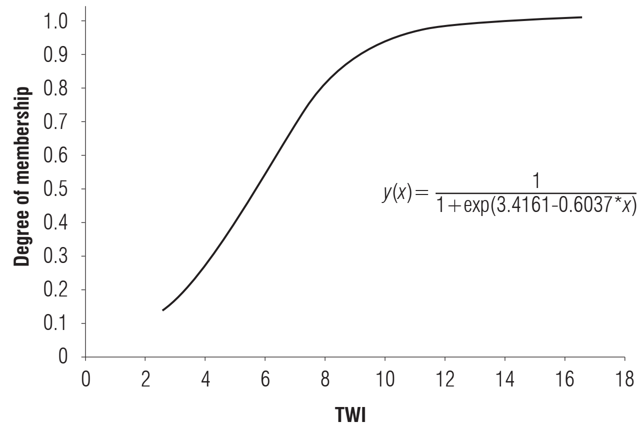

FIGURE 4. Fuzzy membership function used to define the suitability degree of TWI.

Curvature

Curvature is a topographic attribute that describes the convexity or concavity of a terrain's surface (Romstad and Etzelmüller, 2012). Curvature calculation is based on second derivatives; the rate of change of a first derivative such as slope gradient or slope aspect, usually in a particular direction (Gallant and Wilson, 2000). Figure 3 shows the function used to assign membership values for the curvature.

Topographic wetness index

The topographic wetness index is used as an indicator of water accumulation in an area of landscape where water is likely to concentrate through runoff (Beven and Kirkby, 1979). The TWI was calculated as a second-order derivative of the DEM, also known as a compound topographic index (Quinn *et al.*, 1991) and was calculated with the following equation:

$$\mathrm{TWI} = 1\mathrm{n}\left[\frac{A}{\tan(\beta)}\right] \quad (2)$$

Where A is the contribution area (m^2) of the watershed and β is the local terrain slope angle. In this case, the valuation of the TWI varied from higher values, which indicate more suitable areas (Fig. 4), to lower values, meaning less suitability.

Solar radiation

DEMs are an important alternative for estimating the radiation of areas, and, to this end, calculation algorithms have been developed as part of the computer programs of geographic information systems: ArcGIS, SAGA, and GRASS, among others. For the calculation of radiation from DEMs, algorithms that consider atmospheric conditions, elevation, orientation of the surface and the influence of neighboring topography are used (Austin, 2002). Figure 5

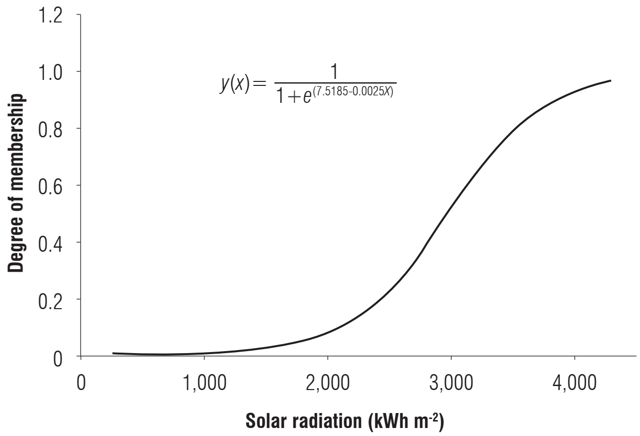

FIGURE 5. Fuzzy membership function used to define the suitability degree of solar radiation.

shows the fuzzy function used to assign membership values to the solar radiation.

Results

Land unit definition

A topographic profile (Fig. 6) facilitates a general view of the relief of an area, the establishment of the spatial variability and the definition of the principal land units present in the study area. It is equally important to identifying the geomorphologic units that give rise to the land units. As can be seen, the dominant relief is mountainous, with steep slopes and small valleys in the lower regions. A land mapping unit is a mapped area of land with specified characteristics (FAO, 1976). For the latter purpose, DEMs play an important role since relief is a forming factor for soil and, therefore, affects soil characteristics, on the other hand, relief affects other factors such as radiation, temperature and soil moisture and, thus, influences the adaptation, growth and development of plants.

The information about the topographic position and the attributes of the terrain in agricultural fields is very useful for interpreting yield maps. Studies on different crops show a correlation between yield, soil properties and the topographic features calculated from DEMs (Kravchenco and Bullock, 2002).

Altitude

In the tropics, altitude is a key factor in studies of zoning land suitability because it has an inverse relationship with temperature, thereby influencing crop behavior and production and the distribution of vegetation. As shown in Fig. 7A, the altitude in the study area varied between 441 and 1,415 m. Although mango production is higher in low areas, quality is higher at altitudes close to 1,000 m and areas with higher elevations are considered unsuitable for the establishment of this crop. In studies by Valbuena *et al.* (2008), an inverse relationship between altitude and mango production was found, further explained by the spatial variability of the soil properties.

After applying the fuzzy function to the elevation data, a map with membership values ranging from 0 to 1 was obtained; after defuzzification of that map, the assessment of the suitability degree was obtained (Fig. 7B); in this case, an optimum elevation range was established as 0 to 400 m a.s.l. and, from this value, suitability decreases as a function (Fig. 1) until reaching 940 m, an elevation that is considered unsuitable.

Slope

Figure 8A shows the calculated slope from the DEM. It varied between 1 and 139%, with the 12-25% range dominating. Slope is a factor of higher incidence in land suitability analyses due to its effect on erosion and crop requirements through mechanization or tillage conditions and soil workability. Therefore, a reliable estimate of the slope degree is required as an input for land evaluation models. This feature is presented in the soil survey map as a class; however, it represents a rough estimate of what

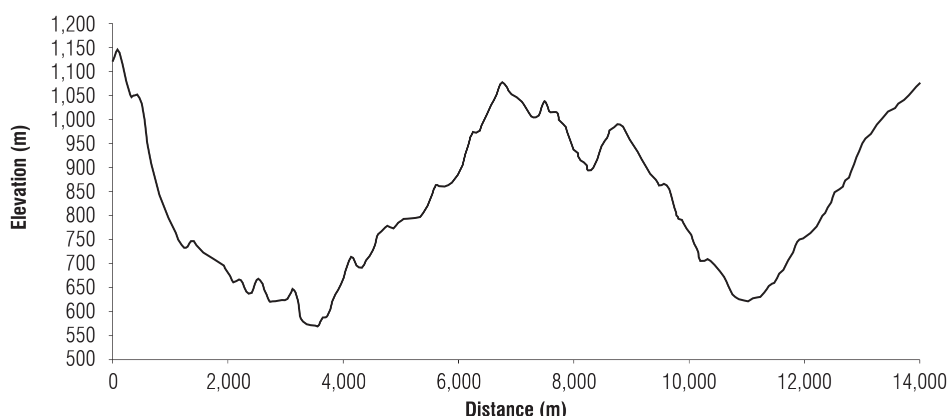

FIGURE 6. Topographic profile of the study area in the department of Cundinamarca.

is believed to be the dominant slope in each soil mapping unit. In the field, the slope was measured and great variation was found within the soil units, even outside the boundaries of the provided classes.

By comparing the slope calculated from the DEM with that of the soil map at a scale of 1:100,000 (Tab. 1), it was found that there were important differences in all of the cases. The 7-12% range, according to the map, occupied 30.8% of

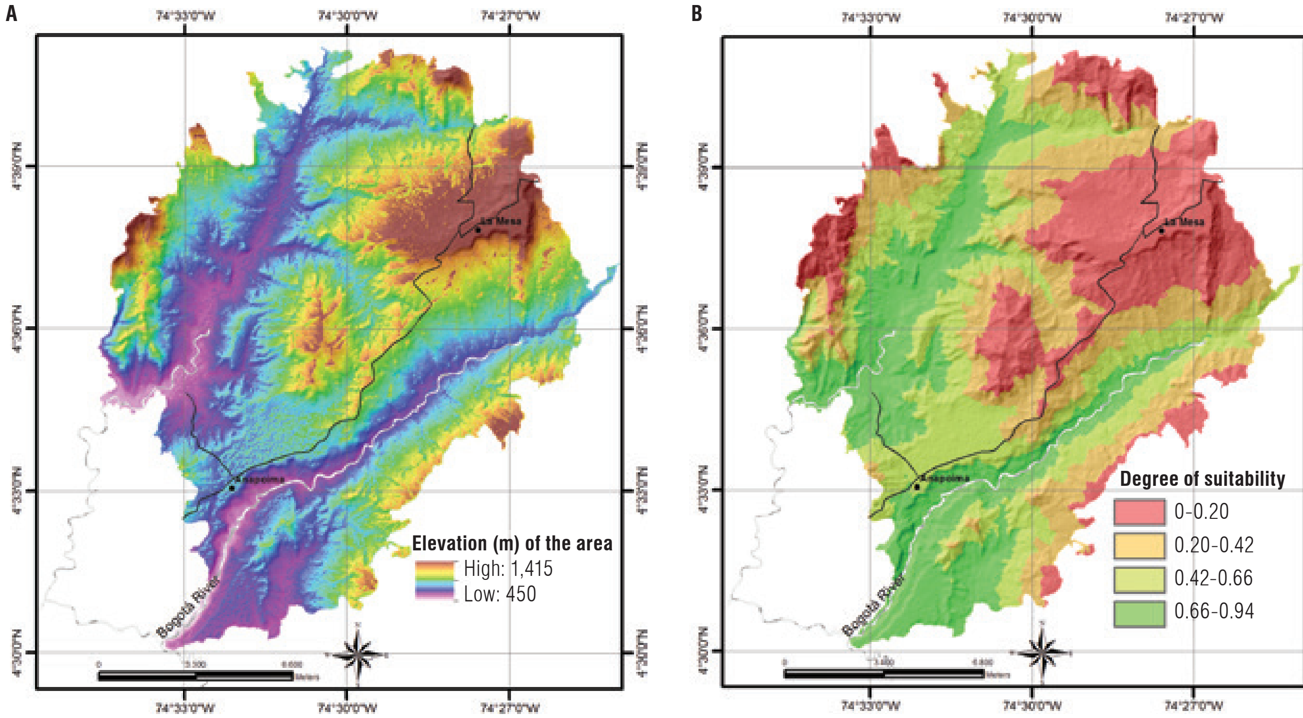

FIGURE 7. A, elevation of the study area; B, degree of suitability based on elevation.

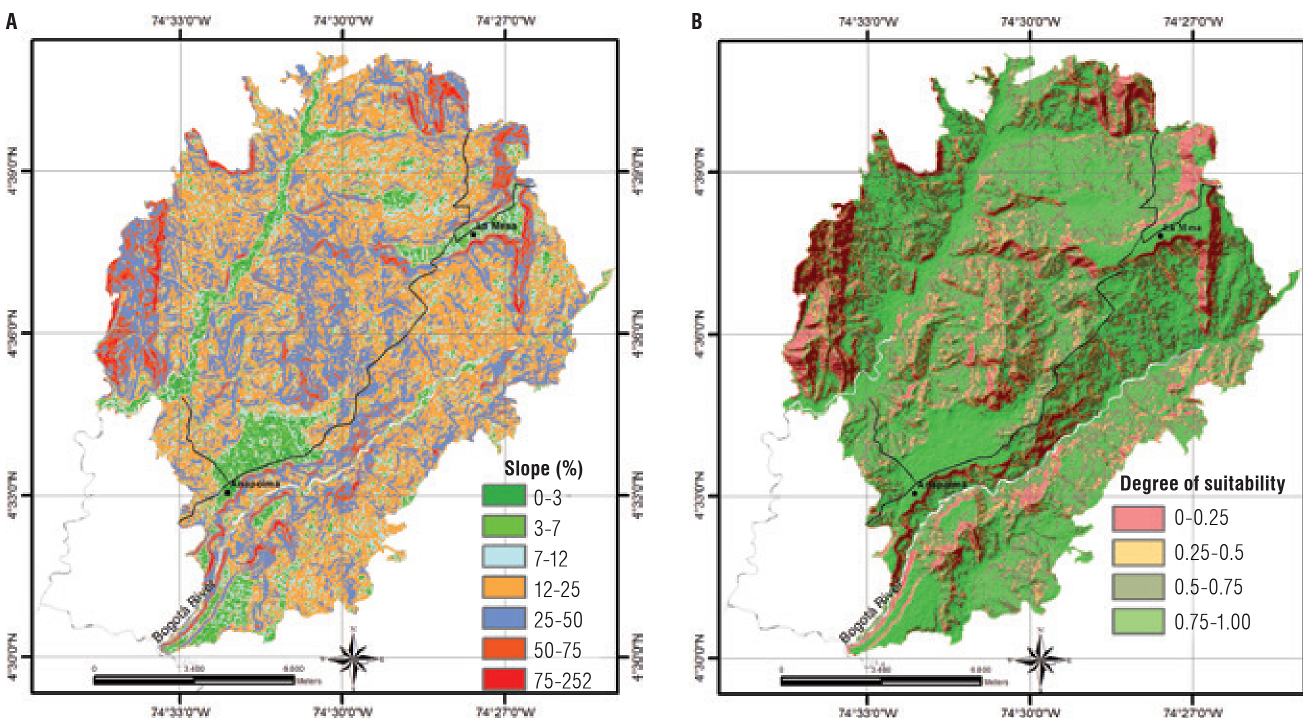

FIGURE 8. A, distribution of the slope classes; B, degree of suitability based on slope.

the study area, but when calculated from the DEM, it only corresponded to 8.2% of the area; 12-50% occupied 55.1% according to the map, while the DEM calculation showed 82.4%; and, for areas with slopes less than 7%, the result was 12.8% according to the map and 6.1% according to the DEM. The above results and field verification lead to the conclusion that DEMs are a source of more reliable data in the estimation of the slope when compared with soil maps. This implies an increase in the detail level of the information obtained and one can make a quantitative estimate of the slope with greater accuracy in the results; while in soil studies, generally, one carries out a qualitative rating of the slope that the person making the study considers dominant in each map unit.

Because the slope is a decisive factor in assessing land suitability, the previous differences significantly affected classification; therefore, the use of DEMs improves the reliability of the process. The SRTM DEM has been considered a suitable data source for land component mapping based on slope gradient and aspect (Mashimbye *et al*., 2014).

TABLE 1. Extension of slope classes.

Slope %	Area (%) from DEM	Area (%) from map
<3	0.1	4.4
3-7	6.0	8.4
7-12	8.2	30.8
12-25	55.4	40.3
25-50	27.0	14.8
50-75	3.3	0.6
>75	0.1	0.6
	100.0	100.0

Figure 8B shows the effect of the slope on the suitability of the land for mango crops after applying the fuzzy function (Fig. 2) to the slope map. Areas with slopes less than 50%, which occupy the largest extension, have some degree of suitability, while steeper areas that correspond to escarpments are considered unsuitable.

Topographic wetness index (TWI)

TWI is based on a mass balance consideration, where the total area of the basin is a parameter of tendency to receive water and the local slope and the length of the drains are parameters of tendency to remove water. TWI does not consider the conditions of infiltration and transmissivity.

In the study area, the TWI values ranged from 7.3 to 15.8 (Fig. 9A) and it was found that areas with high values for this index were concave and located in the lower regions and flat terrain with greater water storage capacity; while areas with low values of TWI were convex, with a lower water holding capacity. Higher TWI values indicate areas more suitable than those with lower values (Fig. 9B). This parameter is an important component in the assessment of land since, in most of our mountainous agricultural areas, rain is the only source of water for crops. In some studies, it was found that any topographic or soil attribute that contributes to water accumulation in the landscapes, such as upslope length, wetness index, and soil organic matter, was positively correlated to increases in the grain yield of wheat (Chi *et al*., 2009).

Curvature

A positive curvature (Fig. 10A) indicates that the surface is convex, a negative curvature indicates that the surface is concave and zero values indicate that the slope is uniform or flat. Curvature allows for the subdivision of land forms that are represented in the soil map at 1:100,000, and adds more detail to the map. This is important because concave shapes are usually associated with areas of accumulation of materials and, therefore, the soils are deeper and more fertile, with higher water accumulation and, therefore, a higher degree of suitability (Fig. 10B). Moreover, convex shapes are areas of erosion, shallow, less fertile and less capable of retaining moisture, with a lower degree of suitability (Fig. 10B).

Surface curvature is an important parameter for land suitability analysis due to relationships among yield, topography, and soil moisture content (Timlin *et al*., 1998). Some results have shown a clear relationship between crops yields and surface curvature due to the effect on soil moisture content. In dry seasons, high yields were found in the concave areas due to higher moisture availability; while, in rainy seasons, these areas presented lower yields (Kravchenko and Bullock, 2002). Sinai *et al*. (1981) found a strong correlation between soil moisture content and surface curvature which in turn affected crop yields.

Solar radiation

Figure 11A shows the calculation of radiation from the DEM. As noted, although the study area was relatively small, a large spatial variability of radiation was found, with values between 1,360 and 1,800 kWh m^{-2}. Solar radiation, as calculated with GIS models, represents direct gradients having physiological effects on plants and is preferable to indirect gradients; the source of correlation with vegetation having been identified (Austin, 2002). Figure 11B shows the degree of land suitability according to solar radiation, indicating some differences in the study area, with further research it will be possible to understand the effect of this distribution on crop yields. According to Reuter *et al*. (2005) little attention has been spent on how the spatial differentiation of solar radiation can alter crop production in agricultural fields. Until now, a constant

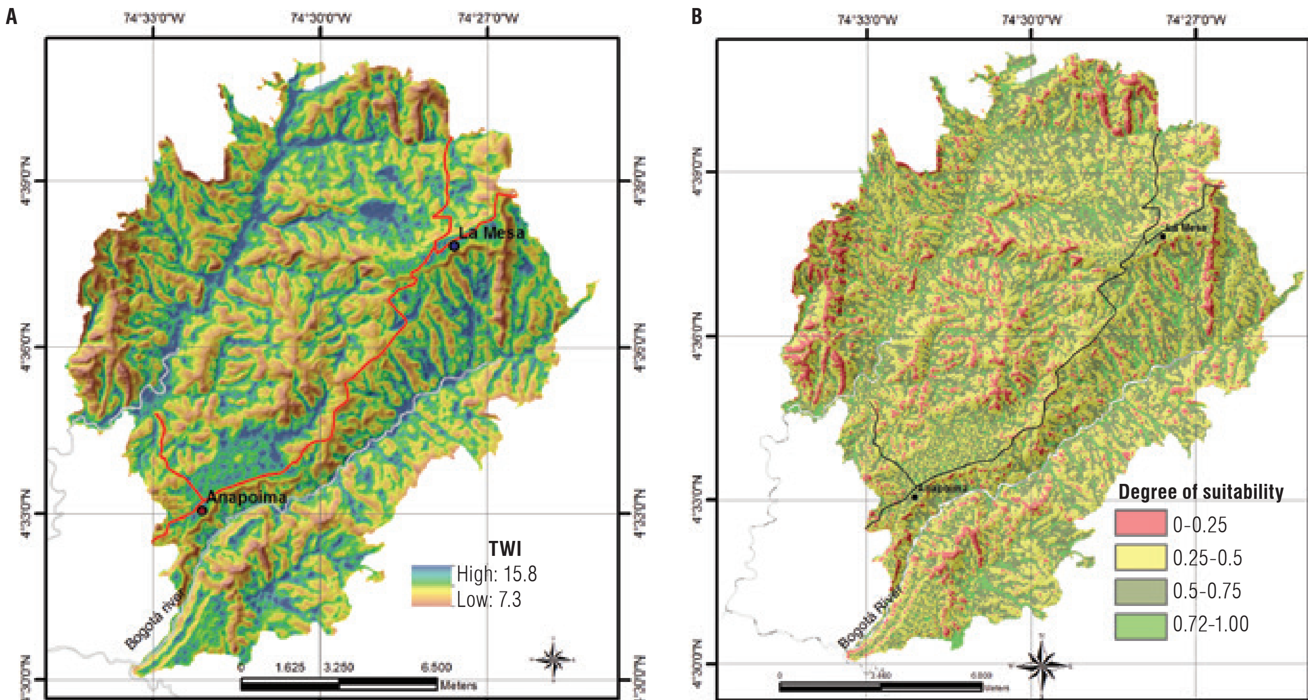

FIGURE 9. A, distribution of the topographic wetness index; B, degree of suitability based on TWI.

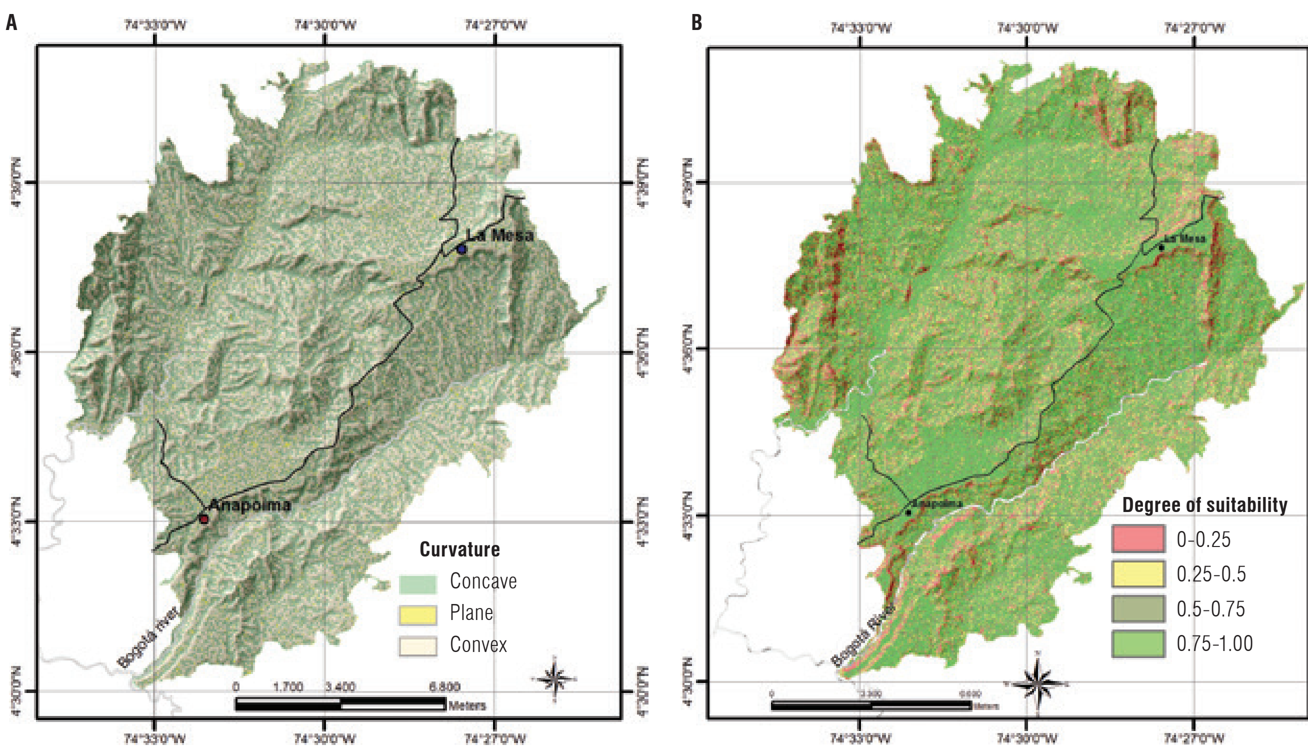

FIGURE 10. A, shape of the surface based on the curvature calculation; B, degree of suitability based on curvature.

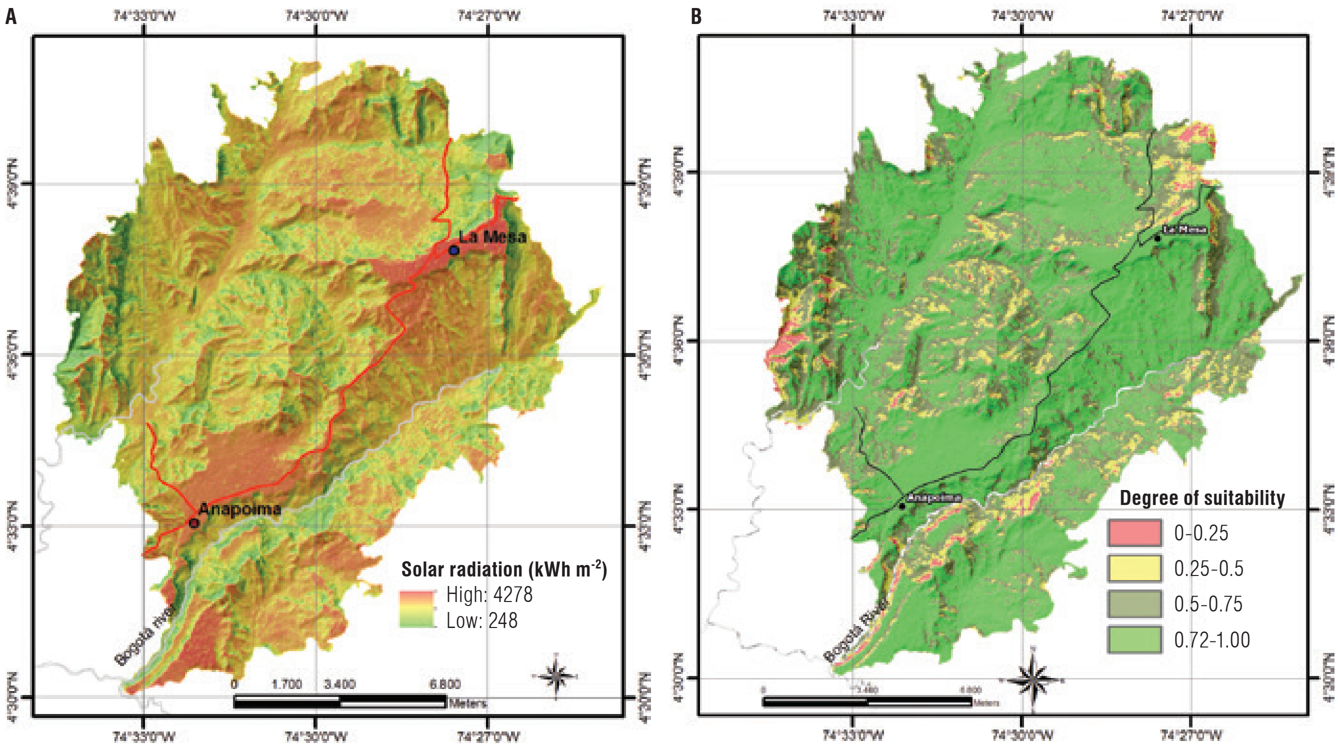

FIGURE 11. A, solar radiation calculated from the DEM; B, degree of suitability based on solar radiation.

solar radiation is assumed across a field site, even if terrain conditions affect the amount of incoming solar radiation.

Land suitability zoning

The final evaluation of land suitability was carried out based on the following equation proposed by Reynolds (2001), for integration of the evaluated criteria with fuzzy logic.

$$y\,(\mathrm{t}) = \min(\mathrm{t}) + [\mathrm{mean}(\mathrm{t}) - \min(\mathrm{t})] * [\min(\mathrm{t}) + 1] / 2 \quad (3)$$

Where: y (t) is the truth value of the node y, min (t) is the minimum truth value of the antecedents *and* node, and mean (t) is a weighted average of the truth values of the antecedents *and* node. The equation for calculating the value is fuzzy and is designed to produce a conservative estimate of the truth in the presence of negative evidence that is lacking or partial.

Figure 12 shows the zoning of the area according to land suitability for cultivation of mango, defined with four suitability classes: highly suitable; moderately suitable; marginally suitable; not suitable. It was found that 25% of the surface is very suitable, 65% is moderately suitable, 9% has low suitability and 1% is not suitable for the cultivation of mango.

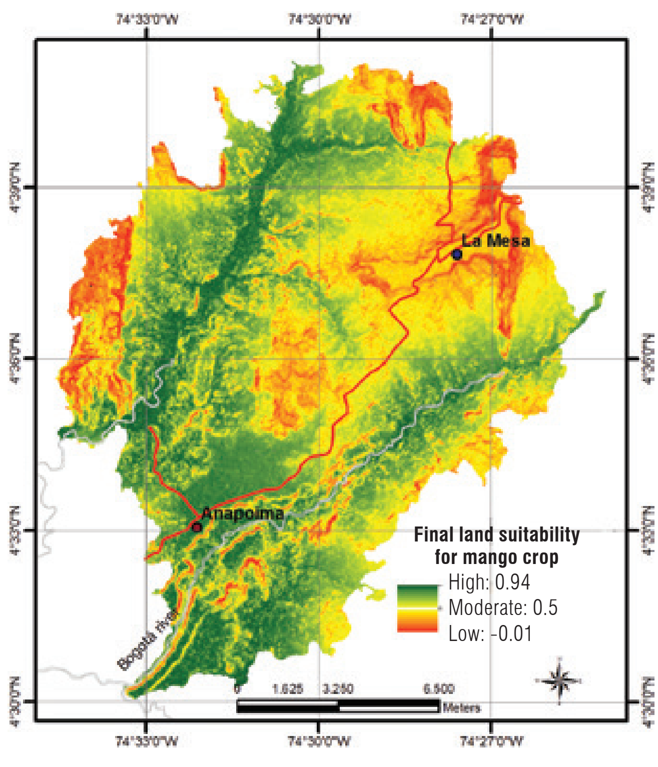

FIGURE 12. Land suitability zoning for mango crops.

The use of DEMs has been found to be useful for landscape prediction models and has shown acceptable accuracy and good spatial distribution of land suitability classification in arid areas(Al-Shamiri and Ziadat, 2012).

Conclusion

Traditionally, land evaluation does not include relief parameters for defining the suitability of the land and only takes into account the degree of slope through a very rough estimate based on soil survey. Relief parameters are important criteria to improve the current studies on land suitability, including new variables that have a significant effect on crop production. Digital elevation models are an important source of data for quantitatively characterizing the relief, calculating several parameters, and increasing the level of detail and the amount of data useful in the development of models to support decision-making concerning the use, management, conservation and reclamation of land. More research in needed to understand the effect of relief on crop yields and to identify the best algorithms to calculate relief parameters from DEMs.

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