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Coupling Spatial Multiattribute Analysis and Optimization to Identify Reforestation Priority Areas

A Case Study in Central Mexico

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Reforestation programs have been proposed as a remedial measure to tackle deforestation and forest ecosystems degradation. Because one of the main constraints to the implementation of restoration practices is lack of funding, these programs need to be carefully planned to efficiently use the economic and human resources invested. In this study we present a geospatial decision-making tool to identify suitable areas for restoration. The overall approach entails (1) the use of the simple multiattribute rating technique (SMART) to identify and rank the attributes according to their importance for prioritizing areas for restoration and (2) the implementation of 0–1 integer programming to select the areas that maximize the environmental benefit. The approach is exemplified through a case study in central Mexico's mountainous state of Estado de México, encompassing an area just above 2 million ha. Specialists in different aspects of reforestation selected the following attributes to identify priority areas for reforestation: erosion, land use/land cover, position in the watershed, soil type, terrain slope, and precipitation. In total, 644,642 ha were classified under very high priority for reforestation. Of these, 17,059 ha were selected to maximize the environmental benefit without exceeding the available budget. The selected sites were mainly in the forested zones of steeply sloped mountains. Although the multiattribute decision analysis, the optimization model, and the spatial analysis were only loosely coupled, their combination proved to be an innovative and practical approach to systematically identify priority areas for reforestation on a yearly basis.

Keywords: *Tree restocking programs; spatial decision analysis; SMART; integer programming; Mexico.*

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Introduction

Reforestation is a key element in efforts to counter the loss of forest lands around the world. According to the Food and Agriculture Organization (FAO) (2010), an average of 5.3×10^6 ha/year were reforested from 2000 to 2010. This is twice the rate reported for forest plantations during the same period. The national reforestation rate for Mexico ranked fifth in the world, with a reported rate of 247,000 ha/year in 2005 (an area equivalent to 0.12% of the national territory).

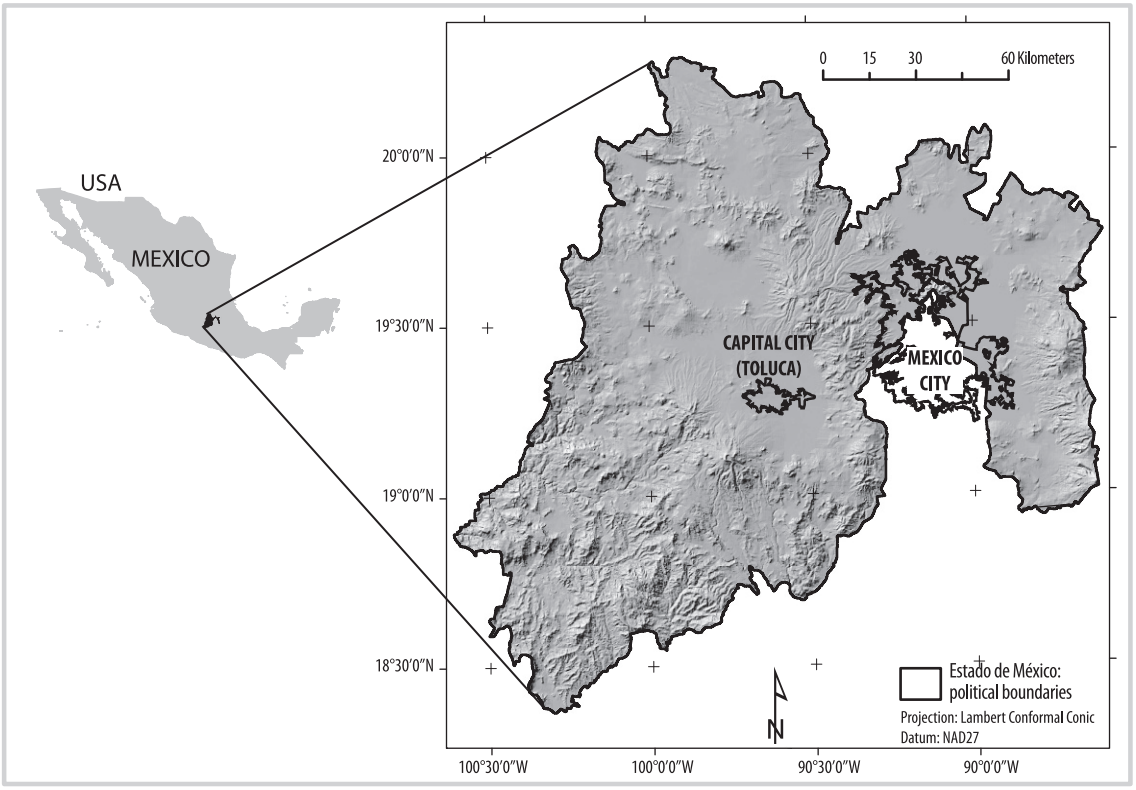
Nevertheless, the benefit of specific reforestation programs to the development of forest resources has in many cases been unclear. For example, the Forest Sustainable Development Program of the state named Estado de México (PROBOSQUE 2006) was aimed at restoring degraded forest lands, located mainly in the mountainous areas; the goal of its reforestation activities was to maximize the overall benefits of forest land restoration, with emphasis on the conservation of ecosystem services such as soil stabilization and the maintenance of the hydrologic cycle. Hence, locating the areas that maximize the restoration benefits is important for all the state, but it is critical for the mountainous areas where these ecosystem services are produced. However, the main weakness of this program has been a lack of prioritization of the sites suitable for tree restocking, since the necessary expert knowledge is not always available to the managers in charge of implementing the reforestation activities. Hence, managers often try to fulfill their programmatic goals without a thorough consideration of whether the areas selected for reforestation are the most suitable or even a priority.

It is fair to acknowledge that deciding where to carry out reforestation is a complex task. Because common sense alone is not enough, decision aid tools such as

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FIGURE 1 Study area. The central Mexico's state of Estado de México. (Map by the first author)



integrated spatial decision support systems have been developed. These systems combine spatial analysis and multicriteria modeling to enable informed decision-making under high uncertainty and lack of empirical information (Kangas and Kangas 2005; Geneletti 2007; Valente and Vettorazzi 2008). Multicriteria modeling helps the decision-maker to assess value judgments from individual or multiple experts to systematically analyze complex problems identifying the decision alternatives, as well as the attributes and their importance (weight) used to evaluate the alternatives' performance. These methods mathematically aggregate the attributes and their weights to score the alternatives facilitating the selection of the most desirable (Malczewski 1999; Kiker et al 2005). In addition, these systems can be linked to operations research tools (eg Hamaide and Sheerin 2011) to obtain a formal assignment of priorities to a set of potential sites, so that the global benefit of a reforestation program is maximized (eg soil stabilization).

The objective of the present study was to integrate a spatial decision support system to identify reforestation priority areas. This system combines the simple multiattribute rating technique SMART (to select and rank the attributes according to their importance) with an integer optimization model to select the combination of sites that maximize the reforestation benefit in a territory. The approach is illustrated through a case study derived from the Forest Sustainable Development Program of the Estado de México.

Material and methods

Case study

The case study corresponds to the political boundaries of Mexico's state of Estado de México, which encompasses 22,555 km^2 of largely mountainous terrain in the central region of the country (Figure 1). The landscape is characterized by lowlands in the southwest (400 m above sea level [masl]), sierras and volcanoes in the east (maximum elevation of 5460 masl), and high-elevation lacustrine plains in the central region (2570 masl). Three-quarters of the area is covered by five soil types of high productivity for agriculture and forestry: Andosols, 22%; Phaeozems, 21%; Regosols, 12%; Vertisols, 11%; and Cambisols, 9% (Sotelo et al 2010). Annual precipitation varies from 600 mm per year in the northeast to 1800 mm in the southwest. The dominant land use/land cover categories are agriculture (46%), forest (28%), and grassland (15%). Human settlements occupy almost 4% of the state area (INEGI 2005).

The annual deforestation rate in this state was estimated at 12,850 ha/year in 2006. At this rate, in about 50 years all the forest areas in the state will be lost. As a measure to counter the challenges posed by this

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deforestation trend, the state government implemented the Forest Sustainable Development Program in 2006. As a measure of success, the program reported a total of 20 million seedlings planted/year in a total of 90,000 ha from 2006 to 2010 (PROBOSQUE 2006; GEM 2010). These deforestation/reforestation data appear to indicate that there was a net reforestation in this period. However, considering that the survival rate of planted trees from 2004 to 2009 was approximately 60% (Aguirre-Calderón 2011), there is still a deficit of about 2000 deforested ha per year without tree restocking, in addition to the degraded land that also needs restoration practices.

Attribute weights

We used SMART to define the priority areas for reforestation (Edwards and Barron 1994; Goodwin and Wright 2000; Stewart and Joubert 2007). The decision alternatives in this study were sites in the state of Estado de México that required restocking in deforested or degraded forest lands in the mountainous areas.

SMART was implemented in a consultation scheme with the participation of 14 specialists (managers and academics) in reforestation-related topics in the study region (the areas of expertise included forestry, soils, ecology, forest plantations, and conservation). The specialists were consulted individually and were asked to compile a list of relevant land attributes following this technique and to rank them in an ordinal scale according to their relative importance for reforestation. Next, redundant, irrelevant, or nonoperational attributes were eliminated, as suggested by Keeney and Raiffa (1993). Additionally, those attributes that were not proposed by at least one-third of the experts were eliminated from the analysis. The specialists identified an initial list of 16 attributes for determining high-priority areas for reforestation. A closer inspection of this list revealed that 10 of these attributes had to be discarded from the analysis because the respective spatial data were lacking.

The final list consisted of erosion, land use/land cover, position in the watershed, soil type, slope, and precipitation. To elicit the weight of each of these attributes, the maximum weight ($w_i = 100$) was assigned to the most important attribute, whereas the minimum value ($w_i \sim 0$) was assigned to the least important attribute. The remaining attributes were rated between these value weights ($0 < w_i < 100$) by determining their importance relative to the attributes already evaluated. The specialists' individual weights were aggregated using a geometric mean (Lai et al 2002) and normalized by the following formula (Shepetukha and Olson 2001):

$$b_i = \left(w_i \Big/ \sum_{i=1}^{n} w_i \right) \cdot 100$$

Attribute rating and geographic information system database generation

Using a direct rating approach (Goodwin and Wright 2000), the specialists elicited the suitability of each attribute and transformed the value in its natural scale into a standardized scale in terms of priority for reforestation. This transformation entailed the use of the SMART procedure, and thus the best condition of an attribute for reforestation was assigned to the maximum transformed value or $x_i = 100$, whereas the worst condition was assigned to the minimum transformed value or $x_i \sim 0$, and the remaining conditions were assigned to a transformed value of $0 < x_i < 100$. The specialists' individual transformed values were aggregated through a geometric mean (Lai et al 2002).

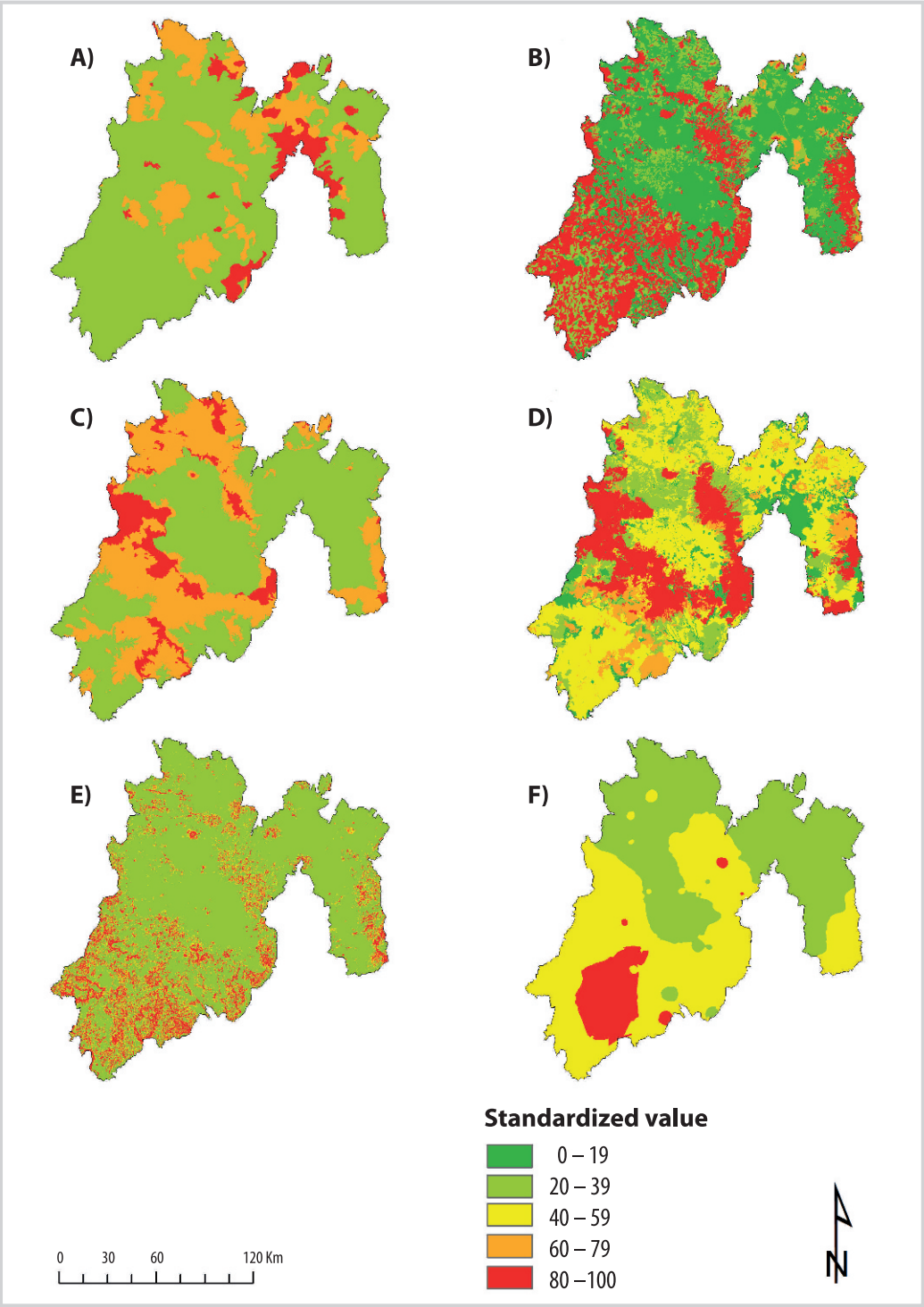
For each of the attributes, a raster map layer was generated using real data (Figure 2). Erosion information was obtained from a digital layer of a 1:250,000 national map of anthropogenic soil degradation (SEMARNAT-COLPOS 2003). This map was produced using Van Lynden's (1997) assessment of soil degradation (ASSOD), an approach based upon physiographic land units and estimations of the relative extent, degree, and rate of different land degradation processes, including erosion, within each physiographic unit. The precipitation layer was generated by interpolating the records of the National Meteorological System using the geostatistic method Kriging (Webster and Oliver 2007). To delimit the particular precipitation level given by the specialist, the precipitation range in the study area was divided into four classes according to the first, second, and third quartiles. The source for land use/land cover, soil type, and elevation data layers was INEGI (the Mexican government geographic and statistics agency). The attribute of land use/land cover was directly obtained from a 1:250,000 land use and vegetation digital vector map. This map was generated through interpretation of Landsat ETM satellite images and validated with ground-truth data (INEGI 2009). Soil type was digitized from the 1:50,000 edaphological maps. These maps were generated through review of ancillary information (climate, vegetation, geology, and relief), field work, photointerpretation, description of soil profiles, and analysis of soil samples (INEGI 2004).

The limits of the watersheds inside the state of Estado de México were generated with the program Soil and Water Assessment Tool (SWAT) (Winchell et al 2007), using a digital elevation model (DEM). Each watershed was divided into three levels, high, medium, and low, in terms of the respective altitude range. The terrain slope was derived from the state DEM.

All the input and results layers were registered to the Lambert Conformal Conic projection, Datum NAD 27. We used a spatial resolution of 100 m, so each pixel of 1 ha represented a unit of analysis; however, the attribute and final maps can be represented at cartographic scales not

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FIGURE 2 Standardized values assigned by the specialists to the attributes used to determine priority areas for reforestation. (A) Erosion; (B) land cover; (C) position on the watershed; (D) soil; (E) slope; (F) precipitation.



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bigger than 1:250,000, which corresponds to the coarse scale of the input data. All the spatial analyses were performed with the geographic information system (GIS) ArcGis 9.1®.

We explored the correlation between the weights of the attributes and the area of each different condition of those attributes for reforestation.

The priority for reforestation in each pixel was calculated by a weighted linear combination (Malczewski 1999):

$$y = \sum_{i=1}^{n} x_i b_i,$$

where y is the priority for reforestation, x_i is the standardized value of attribute i for each pixel, and b_i is the weight of attribute i.

The continuous scores of priority for reforestation resulting from the multiattribute technique were transformed to five ordinal categories: very low, low, moderate, high, and very high. Five categories were deemed appropriate for conveying meaningful geospatial information, since Cowan (2001) suggested that this number matches the short-term capacity of the human brain.

The definition of category limits followed the Weber–Fechner Law (Lanzara 1994; Saaty 2001), which considers the response of a person to variation of physical stimulus (in this case, the change of category) according to the following perception–stimulus relation (see Bojórquez-Tapia et al 2009):

$$S_h = S^* - (1+r)^h S_0,$$

where S_h is the cut for category h (S_h is a unitless number expressed in reforestation priority values); S^* is the maximum reforestation priority value (best state of a stimulus); r is the ratio between the "just noticeable difference" and the stimulus; $(1 + r)$ is the progression factor; and S_0 is the initial stimulus or the smallest detectable level of a stimulus calculated using the upper intensity level u (the highest category used):

$$S_0 = \frac{S_u}{(1+r)^u},$$

where S_u is the difference between S^* and the minimum reforestation priority value, and $u = 5$, corresponding to the five categories used in this study.

Next, we computed the Gower residuals (Gower 1966; Digby and Kempton 1987) to numerically compare the contribution of each attribute to a given category of priority for reforestation. Positive residuals indicate a high contribution of an attribute to a given category, while negative values indicate a low contribution. From the GIS layers we extracted the mean value of each attribute for each category and generated a matrix, Z, of dimensions $c \times a$, where c and a are the indices for reforestation priority categories and attributes, respectively. Matrix Z was adjusted by rows and columns through Gower's double-centering procedure:

$$z_{ca} = x_{ca} - \bar{x}_{c.} - \bar{x}_{.a} + \bar{\bar{x}}_{..}$$

where z_{ca} is the adjusted mean, x_{ca} is the mean value of the a-th attribute for the c-th category, $\bar{x}_{c.}$ is the mean of all attributes for each category, $\bar{x}_{.a}$ is the mean of each attribute for all categories, and $\bar{\bar{x}}_{..}$ is the mean of the whole matrix.

Optimization model

Given the difficulty in extracting the optimum areas for each of the 2,255,500 pixels that cover the study area, it was necessary to simplify the optimization problem formulation using map algebra to group pixels within the immediate eight-cell neighborhood with the same reforestation priority value. Accordingly, 108,930 zones were generated.

Next, we selected the zones that maximized the reforestation benefit through a 0–1 integer programming implemented with the software Lingo® (Lindo Systems 2006), based upon the following formulation:

$$Maximize \;\; Z = \sum_{i}^{I} y_i d_i$$

Subject to:

$$\sum_{i}^{I} d_i c_i \leq C \quad \forall i \in I \tag{1}$$

$$d_i = 0,1 \quad \forall i \in I \tag{2}$$

where Z is the priority; i is the index of zone; y_i is the priority of the ith zone; c is the cost of reforestation of zone i (calculated by multiplying the area of the zone i in hectares by the cost of reforestation per hectare [US$ 110 for this study]); C is the total annual budget for reforestation (US$ 1,875,152 for this study); and d_i is the decision variable, which is 1 if the unit is selected and 0 otherwise.

Restriction 1 ensures that the total selected area does not exceed the total annual budget. Restriction 2 is the binary restriction to ensure that a zone is selected only once.

The optimization model avoided the otherwise cumbersome task of manually selecting the areas to be reforested by simply selecting those areas with the highest reforestation values but complying at the same time with the available budget restriction.

We used a loose functional coupling for the definition of attributes and their weights, category limits, and the optimization with the GIS environment.

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TABLE 1 Attributes and their weights identified by the specialists for determining priority areas for reforestation.

Criteria	Weight	Normalized weights
Erosion	100	25
Land use and land cover	92	23
Position in the watershed	67	17
Soil type	55	14
Slope	46	11
Precipitation	43	11

Results

Priority areas for reforestation

As mentioned above, the specialists identified six attributes for determining high-priority areas for reforestation: erosion, land use/land cover, position in the watershed, soil type, slope, and precipitation. The standardized weights (Table 1) showed that erosion and land use/land cover were judged as the most important attributes for identifying reforestation areas, followed by position in the watershed, soil type, slope, and precipitation.

Regarding the ratings of the attributes (Table 2), although erosion was the most important attribute, only 25% of the state had standardized values above 78 (corresponding to the erosion classes moderate to extreme; Figure 2A, orange and red); the remaining 75% of the state had low erosion (Table 2; Figure 2A, light green), which diminished the contribution of this attribute to the very high priority category, although it dominated the high priority category, as shown by the Gower Residuals analysis (Figure 3). For the land use/land cover attribute, the class Forest was the only one with high standardized values (100) and significant cover extension (32.9%; Figure 2B, red), because none of the other four classes with standardized values exceeding 36 covered an area of more than 1% of the state (Table 2; Figure 2B, light green); nevertheless, this attribute completely dominated the very high priority category, although it made no contribution to the remaining priority categories (Figure 3). This attribute is particularly important to highlight the relevance of the mountains in determining high-priority areas for reforestation, since it is almost exclusively in these areas that there is still forest to provide ecosystem services in the study area. For the position in the watershed attribute, only 10% of the study area had high attribute values (Figure 2C, red), and more than one-half of the area had low values (Table 2; Figure 2C, light green), which reduced its contribution to the very high and high reforestation priority categories, with an increasing, but still low, contribution from the moderate to the very low priority categories (Figure 3).

For the soil type attribute, slightly more than 20% of the state fell in the class with the highest value (Figure 2D, red), and one-half of the state area had soils with intermediate values between 50 and 60 (Table 2; Figure 2D, yellow and orange), which corresponds to its dominant contribution in the moderate priority category and its high contribution in the high priority category (Figure 3). In the case of the slope and precipitation attributes, 77 and 44% of the study area, respectively, had standardized values of less than 40 (Table 2; Figure 2E, F, light green in both cases); hence, these two attributes contributed little to the definition of the very high and high reforestation priority categories, with the contribution of each increasing from the moderate to the very low priority categories and dominating the very low category (Figure 3). We found no correlation ($r = -0.09$) between the weights of the attributes and the area of each attribute's condition. That is, we can have an attribute with high weight, but not necessarily with large areas having high standardized values.

According to the multiattribute model, almost all the state (96%) had reforestation priority values ranging from moderate to very high (Figure 4; Table 3), which supports the government reforestation effort of the past 5 years (GEM 2010). Surprisingly, almost 30% of the state (644,000 ha) had very high priority for reforestation (Table 3), far more than the annual average area reforested during the past decade, viz. 17,062 ha (UAM 2003; GEM 2010). This result supports the use of the optimization model to select the areas that maximize the benefit of reforestation. The selected 17,059 ha that can be reforested with the available budget were mainly in the central part of the state in the forested zones of the steeply sloped mountains (Figure 5).

Discussion and conclusion

This study presents a loosely coupled decision support system that uses multiattribute decision-making, spatial analysis, and optimization to systematically identify priority areas for reforestation. These methods have been separately described and analyzed (Geneletti 2004; Kangas

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TABLE 2 Direct rating and standardized values of the attributes identified by the specialists for determining priority areas for reforestation.

Attribute	Category	Standardized value	% of the state
Erosion	Extreme	100	7.0
	High	88	0.6
	Moderate	78	17.6
	Low	23	74.8
Land use and land cover	Forests	100	32.9
	Bare soil	76	0.5
	Bushes, mezquital, chaparral	71	0.8
	Halophyte and subaquatic vegetation	39	0.1
	High altitude prairies	36	0.2
	Grass	30	14.5
	Agriculture	18	46.2
	Human settlements	2	3.9
	Water	0	0.8
Position in the watershed	High	100	9.7
	Medium	65	34.6
	Low	39	55.7
Soil type	Andosols	100	21.7
	Cambisols	60	8.8
	Vertisols, Phaeozems	53	30.7
	Regosols	51	11.8
	Other soils	38	15.9
	Solonchaks	15	1.7
	Lithosols	1	6.7
	No soil (water, urban)	0	2.7
Slope (%)	80 and above	100	0.2
	45–80	93	3.6
	30–45	80	7.7
	25–30	66	4.9
	20–25	59	6.5
	15–20	32	8.9
	0–15	27	68.2
Precipitation level in the watershed (mm)	Very high (1625–2000)	100	0.8
	High (1250–1625)	80	7.5
	Medium (875–1250)	59	47.0
	Low (0–875)	39	44.7

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FIGURE 3 Attributes' contribution to the reforestation priority categories computed with the Gower Residuals.

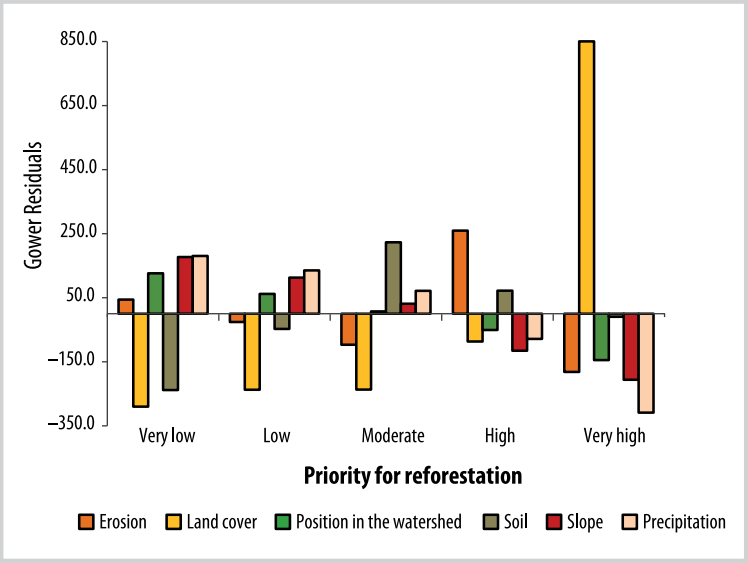
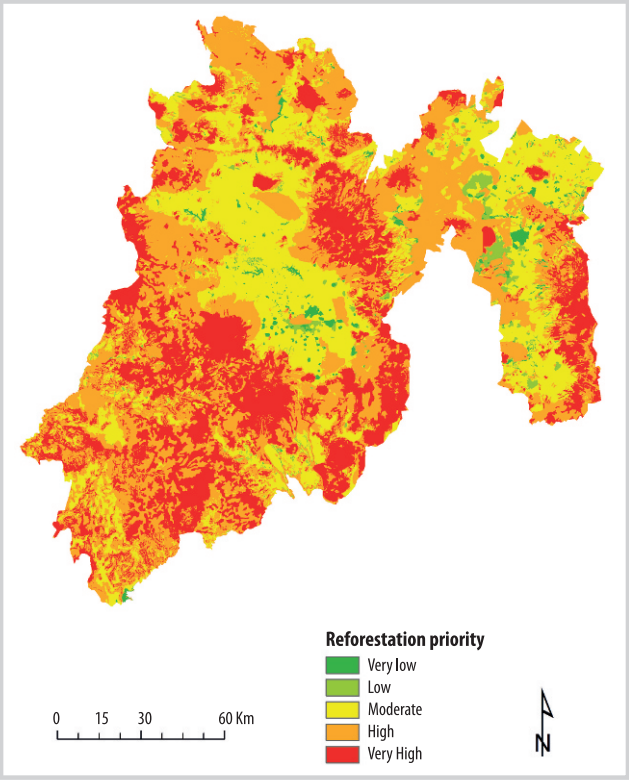


FIGURE 4 Reforestation priority areas identified through spatial multiattribute analysis.



and Kangas 2005; Valente and Vettorazzi 2008; Hamaide and Sheerin 2011); and although they were only loosely coupled in this study, their combination is innovative in the selection of sites that merit priority for tree restocking.

Essentially, this approach showed the steps to systematically select the areas for 1 year; however, the analysis can be extended for a long-term program by excluding at each iteration those areas already planted. However, this long-term program at a regional scale poses a computational challenge since these problems are combinatorial in nature, which makes them hard to solve by traditional approaches such as integer programming. Thus, heuristic approaches such as genetic algorithms, simulated annealing, and neural networks, among others, need to be used (Cruz-Bello, 2000). The advantage of using such approaches is that although they do not provide an optimal solution, they can offer a group of suboptimal solutions representing different spatial arrangements giving alternatives to the decision maker. Other studies have applied multiattribute analysis for other reforestation objectives; for example, Espelta et al (2003) used these techniques to evaluate the benefits of reforestation management activities (clearing, reforestation strategies, and soil preparation) by considering the plantation performance, economic cost, and ecological impacts.

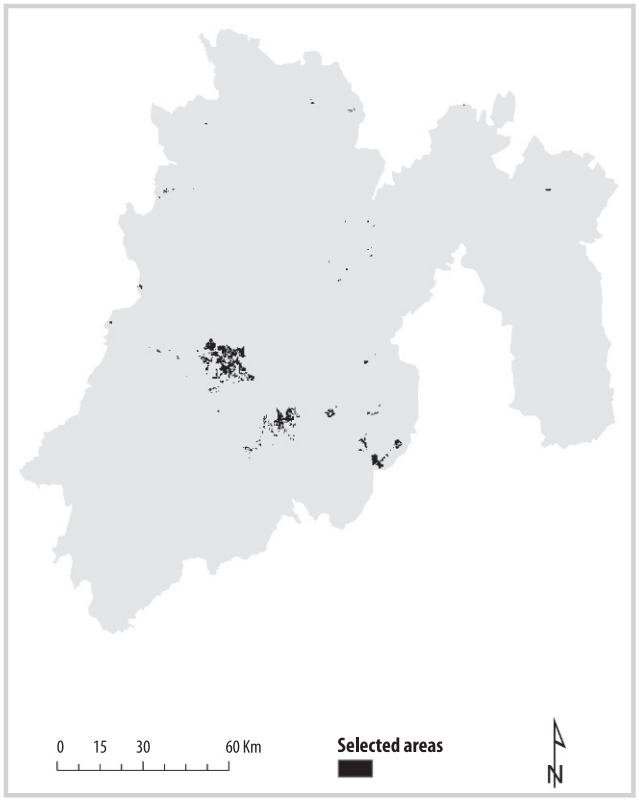
The decision support system implemented in this study made explicit the attributes used in the identification of the priority areas and tracked their importance in the process, as suggested by Geneletti (2004); this last point was complemented by the use of the Gower Residuals analysis. Additionally, this support system helped to clearly identify the main ecosystem services provided by regrowing forest and to understand

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TABLE 3 Priority reforestation categories identified through spatial multiattribute analysis.

Priority	Area (ha)	%
Very low	31,782	1.4
Low	39,027	1.7
Moderate	634,846	28.2
High	904,909	40.1
Very high	644,642	28.6

FIGURE 5 Reforestation priority areas selected through integer programming to optimize the environmental benefit of reforestation and complying with the annual available budget.



why given areas could be more successfully reforested than others, as has been proposed by Southworth and Nagendra (2010).

The variables used in this study can be grouped in two sets: (1) attributes that depict the degradation propensity and (2) attributes that favor the reforestation success. The first set is erosion, land use/land cover, position in the watershed, and slope; the second set is soil type and precipitation.

Land use/land cover has been reported in hydrologic literature (eg Dunne et al 1996; Heathcote 1998; Brooks et al 2003) as a crucial environmental component in the reduction of runoff and erosion, and more specifically some studies have demonstrated that reforestation has helped to reduce the severity of these hydrological processes especially in mountainous areas (Zhang et al 2004); hence, it was not surprising that erosion was chosen by the specialists in the present study as the first attribute to identify priority areas to be reforested. The selection of forest as the most important class of the land use attribute agrees with Gkaraveli et al (2004), since their ecological criterion to determine priority areas for native woodland expansion and restoration was "retain existing woods." It also relates to what Geneletti (2007) calls "Naturalness," which was assessed by considering the land cover type in order to identify the natural conservation value of forest lands. Both position in the watershed and slope have been reported elsewhere as factors that define the propensity toward forest degradation and cumulative impacts in a watershed (Dunne et al 1996; Heathcote 1998; Brooks et al 2003), so their inclusion in the multiattribute analysis as the third and fifth most important attributes was self-evident if the objective is to reduce the terrain vulnerability through tree planting.

Site classification, defined mainly by soil type, has been reported to have great importance to reforestation planning and success, although the importance may vary between tree species (Günter et al 2009); this supports the selection of soil type as a key criterion in selecting priority areas for reforestation. This can be explained by the fact that soil type defines the chemical components available to the plants, controls the depth to which the roots can reach, and consequently determines the bioavailability of soil nutrients and water.

This approach revealed the lack of information for decision-making, since some of the attributes selected by the experts were not operational. In particular, one of the factors that have been mentioned as key in forest management activities, including reforestation, is land tenure (Nagendra 2007). This criterion was ranked seventh in importance in the present study, but there was a lack of continuous information for the whole study area. On the other hand, although this criterion was not actually included in the analysis, it must be considered at some point, since one of the major restrictions to reforestation is the willingness of the landowners to allow tree planting on their land (Gkaraveli et al 2004). Another criterion considered in the expert workshop and reported in similar studies (Nagendra 2007; Valente and Vettorazzi 2008) that also lacked information for the whole study area was forest condition.

The approach outlined here can help decision-makers to decide, on a yearly basis, what areas should be reforested considering their priority and the available budget. This is important, since we found that the area with very high priority for reforestation far exceeded the possibilities of the annual reforestation budget. This coincides with the report by Gkaraveli et al (2004)

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indicating that the areas suitable for woodland establishment exceeded the policy objectives for their study case.

The final decision on which areas will be reforested entails complex negotiation with the landowners, since in Mexico most of the land does not belong to the government; however, using this systematic approach, the decision-makers could start the negotiation before the beginning of each new reforestation season. In addition, this study generated information about the factors that can help to promote a reforestation program with optimal results, the reasons why some areas could be more successfully reforested than others, and the benefits that can be derived from reforesting the selected areas as suggested by Southworth and Nagendra (2010).

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