MODELLING SITE SELECTION FOR TREE PLANTATION ESTABLISHMENT UNDER DIFFERENT DECISION SCENARIOS

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AGUIRRE-SALADO CA, VALDÉZ-LAZALDE JR, SÁNCHEZ-DÍAZ G, MIRANDA-ARAGÓN L & AGUIRRE-SALADO AI. 2015. Modelling site selection for tree plantation establishment under different decision scenarios. The growing worldwide demand for forest products cannot be sufficiently provided by natural forests. The federal government of Mexico has identified three areas (north-east, Huasteca and Gulf of Mexico) to foster forest development via tree plantation establishment to meet industrial demand for forest products both locally and globally, and to diminish pressure on natural forest. This paper focuses on spatially determining available areas for establishing new plantations in the Huasteca Potosina region as landscape planning tool for decision-makers. Different levels of land suitability were classified based on their potential to satisfy the agro-ecological requirements of *Eucalyptus grandis*, *E. urophylla*, *Gmelina arborea*, *Tectona grandis*, *Cedrela odorata* and *Acrocarpus fraxinifolius* using the weighted linear combination method by integrating climatic, edaphic and topographic factors as well as constraints such as land availability. Land suitability maps for each species were combined through the multi-objective land allocation (MOLA) approach considering four scenarios: (1) equal importance for all species, (2) species growth rate, (3) species quality of wood for furniture production and (4) potential tree health problems that could affect the plantation during its growth period. Results indicated that over 80% of the area available for tree plantations has a medium, high or very high land suitability for adequate growth of the tree species of interest. The maps obtained are useful for those wishing to invest funds in the establishment of new tree plantations of the selected tree species in the study area.

Keywords**:** Landsat, bare soil, multi-criteria analysis, land suitability, membership function, multi-objective land allocation, pairwise-comparison matrix, Huasteca Potosina

INTRODUCTION

Site selection is crucial in establishing tree plantation for industrial purposes. This selection is largely dependent on sustainable use of the productive potential of soil and existing climatic conditions for optimum growth of the chosen species (Muñoz-Flores et al. 2011). There are two main approaches for mapping land suitability areas, namely, multi-criteria and multi-objective. Multi-criteria approaches focus on one goal at a time and integrate a weighted number of factors, previously standardised, into an index that indicates land suitability for each particular purpose. Additionally, it integrates constraints to ensure that chosen areas are in locations that are actually available for a predefined purpose.

Applications of multi-criteria methods for defining land suitability are varied, e.g. landfill siting, prioritising areas for forest conservation, identifying potential areas for wind energy utilisation, location of future camping sites within a forest park based on user preferences, evaluation of fire danger in forest areas, location of good ski areas in mountainous terrains and rainwater harvest to mitigate droughts.

Multi-objective methods combine single-use suitability maps generated by multi-criteria methods to produce a conciliatory alternative.

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Applications of multi-objective methods are also found in several areas related to natural resource assessment, e.g. zoning applications within a forest park under different user preferences; identifying the best alternative for landuse based on environmental and ecological variables, defining potential landuse based on economic, social and environmental factors, and siting of infrastructure for incinerating industrial waste.

To determine potential areas for establishing tree plantations, researchers have solely focused on the use of multi-criteria methods for agroclimatic zoning of a single species at a time (e.g. Olivas-Gallegos et al. 2007, Delgado-Caballero et al. 2010, Muñoz-Flores et al. 2011, Falasca et al. 2012). However, there is a gap of applied research on landscape planning based on multi-objective land allocation techniques for determining the best configuration of to establish tree plantations for industrial purposes. In this sense, the aim of this paper is to describe an integrated multi-criteria/multi-objective methodology as support tool for landscape planners and decision-makers in identifying suitable and specific purpose-oriented agroclimatic areas for the establishment of tree plantations in Huasteca Potosina, Mexico. A novel aspect of this research includes digital processing of satellite imagery (2011) to accurately detect available land for the establishment of industrial tree plantations in the study area.

MATERIALS AND METHODS

Study area

The analysis was conducted in the well-known Mexican region, the Huasteca Potosina, located in the eastern tip of the San Luis Potosi. It is bounded by the coordinates 22° 44'–21° 09' N and 99° 32'–98° 19' W, totaling 1,129,186 ha (Figure 1). The National Forestry Commission of Mexico (CONAFOR, its acronym in Spanish) has special interest in this region because it forms part of a greater area called the industrial–forestry basin Las Huastecas, a potentially important area for forest industry development (FOA & INDUFOR 2009). CONAFOR plans to promote forestry development in this basin by implementing highly competitive supply chains of products that come from both managed natural forests and industrial tree plantations. Altitude in the Huasteca Potosina region ranges from 100 m on the coastal plain (east) to 2200 m in the upper mountains of the Sierra Madre Oriental (west). On the coastal plain, the climate is warm subhumid with summer rains (Aw, according to the Köppen climate classification), while in the high areas, climate is warm and humid. In some areas, rainfall is abundant in summer (Am) and in others, it rains throughout the year (Af). Mean annual rainfall varies between 950 and 2400 mm, mean annual temperatures range from 19 to 27 °C and mean temperature of the coldest month varies between 15 and 19 °C (IMTA 2006). Soils vary according to relief. On the coastal plain soils are vertisols and phaeozem, in foothills chernozem soil predominates, while in the mountainous zone, leptosol soil prevails (INEGI 2006). Landuse and vegetation types also correspond to the physiographic conditions of the region. Coastal plains are used for agriculture (irrigated and rainfed) and livestock (pasture), while in mountainous land, natural plant formations such as tropical deciduous forest, dominate. In the highlands of the Sierra Madre Oriental, oak forest can be found as well as tropical rain and cloud forests, all with some degree of disturbances due to landuse changes for agriculture (SEGAM & UASLP 2008).

Methodology

The prioritisation of areas for the establishment of forest plantations for industrial purposes was carried out in two phases (Figure 2). In phase 1, we identified the land suitability of the region based on climatic and soil criteria for six species of interest, namely eucalyptus (*Eucalyptus grandis* and *E. urophylla*), melina (*Gmelina arborea*), teak (*Tectona grandis*), red cedar (*Cedrela odorata*) and pink cedar (*Acrocarpus fraxinifolius*). These tree species were identified as suitable for the region in the 'Feasibility Study of Industrial Forest Basin of the Huasteca' conducted by FOA and INDUFOR (2009). Available areas for planting trees were determined (e.g. bare soil) by digital processing of recent Landsat satellite images and by considering legal and operational restrictions. Finally, in phase 2, a multi-objective land allocation (MOLA) analysis was applied powered by an optimisation algorithm to harmonise different preferences for

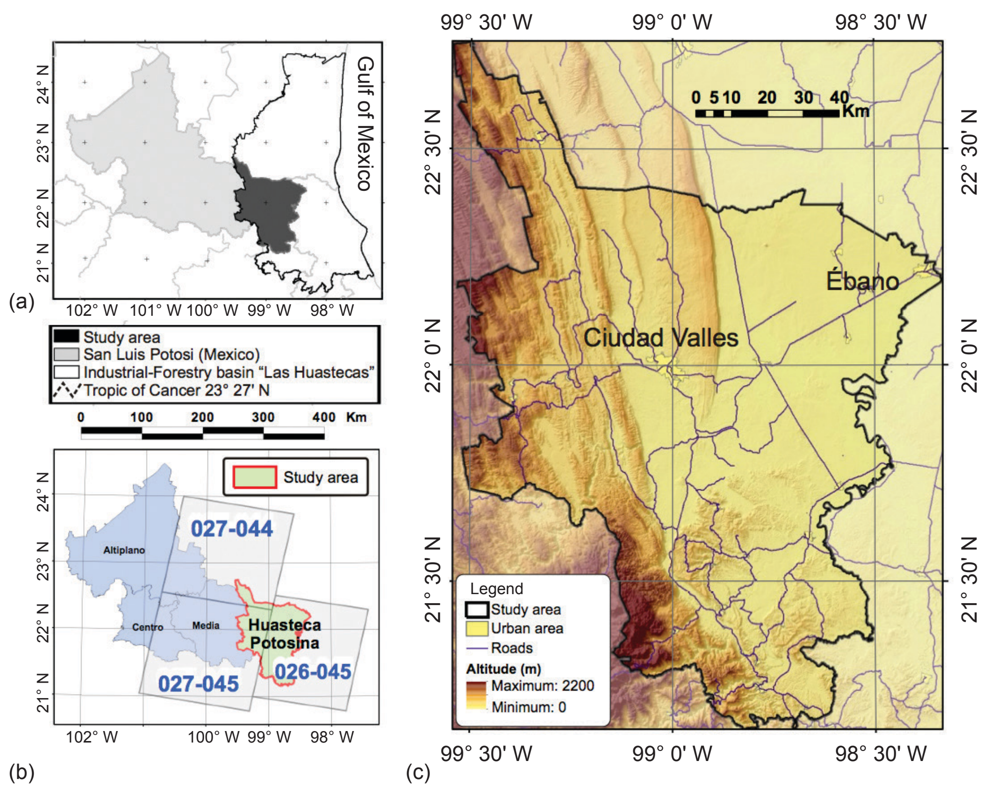

Figure 1 (a) Study area in San Luis Potosi, Mexico, (b) Landsat 5 Thematic Mapper satellite imagery used and (c) main cities over digital elevation model used

each objective in particular into a single decision map (Eastman 2006).

Phase 1—land suitability by species

In phase 1, a spatial database was built to determine the land suitability for each species under the multi-criteria framework. Maps of climatic factors such as mean annual precipitation and mean annual temperature were built from point data obtained from 83 meteorological stations (IMTA 2006). Mean annual precipitation and temperature point values were interpolated by the ordinary kriging method using a spherical variogram. Root mean square error values were 228.58 mm and 1.27 °C for mean annual precipitation and temperature respectively. Altitude values were obtained from a 30 m pixel size digital elevation model available from the National Institute of Statistics and Geography, Mexico (INEGI 2012). Climatic and altitude criteria were scaled from 0 to 1 using a sigmoidal membership function for each species (Figure 3). Extreme values were determined based on ecological requirements for each species (Vozzo 2002, ICRAF 2010). We used series II soil map based on the World Reference Base classification (INEGI 2006). Soil types were rated on a suitability scale ranging from 0 to 1 based on information found in the literature, relating both requirements of tree species with physical, chemical and biological properties for each type and subtype of soil. Spatial distribution of soil types and their respective assigned grades are shown in Figure 4.

Accessibility to location plays an important role in the feasibility for establishing, maintaining and harvesting products generated by an industrial forest plantation. The motivation for including this criterion in the analysis followed the logic of minimising the distance from roads, which is especially important during harvest. The factors considered to determine accessibility to the areas were slope (%) and distance to roads (m). Slope values were obtained from processing a 30-m digital elevation model.

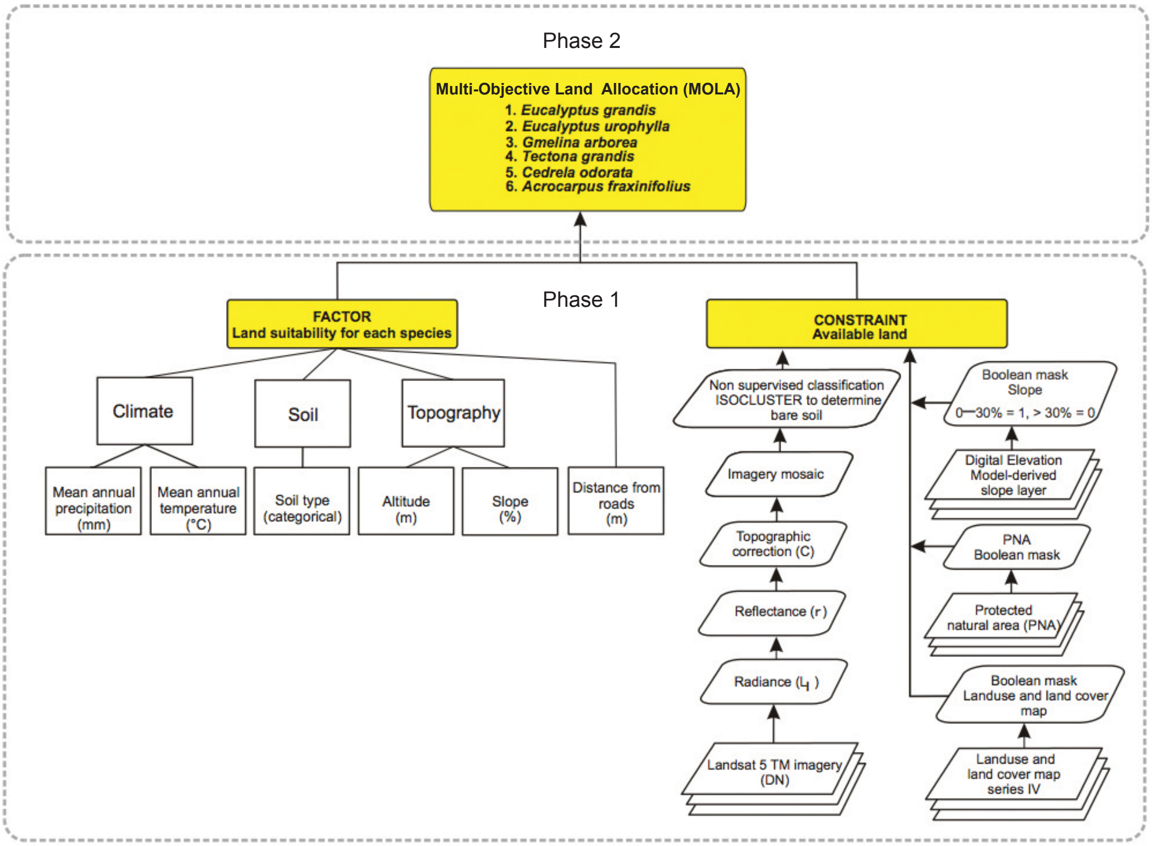

Figure 2 Methodology used to define areas suitable for industrial tree plantations in Huasteca Potosina, Mexico

Distance to roads was generated by rasterising the road vector data scale 1:50,000 (INEGI 2003) (Figure 5). To standardise these two factors, we used a monotonically decreasing membership function whose inflection points were defined based on a literature review (Figure 6). For the case of slope factor, we considered a range between 0 and 30%, while for the case of distance to roads factor, we used a range between 0 and 1000 m. This is considered as optimal skidding distance (Hayati et al. 2012).

To integrate the factors previously standardised into an indicator of land suitability for each particular species, we used the weighted linear combination approach (Malcewski 2004, Nyerges & Jankowski 2010, Tenerelli & Carver 2012). Land suitability for a given pixel was computed as follows:

$$S = \sum_{i=1}^{n} w_i x_i \cdot \prod_{j=1}^{k} c_j \qquad (1)$$

where S = land suitability for planting trees ranging from 0 to 1, w_i = importance of factor i, x_i = score of factor i, $\prod_{j=1}^{k} c_j$ = products of the j constraints.

Scores for each factor (x_i) were generated from the standardisation of the variables used such as mean annual precipitation, mean annual temperature and altitude based on the membership functions selected. We estimated the importance of factor w_i through pairwise comparisons as part of the analytical hierarchy process (Saaty & Vargas 2001). In this technique, weights were obtained from the calculation of the eigenvector of reciprocal square matrix used for the comparison of all possible pairs of factors. This matrix is called the pairwise-comparison matrix. If the comparison value is greater than 1, the first factor is more important than the second, while if the value is equal to 1, both factors are equally important. If the value is less than 1 (expressed in fractions), then the first factor is less important than the second. Table 1 shows

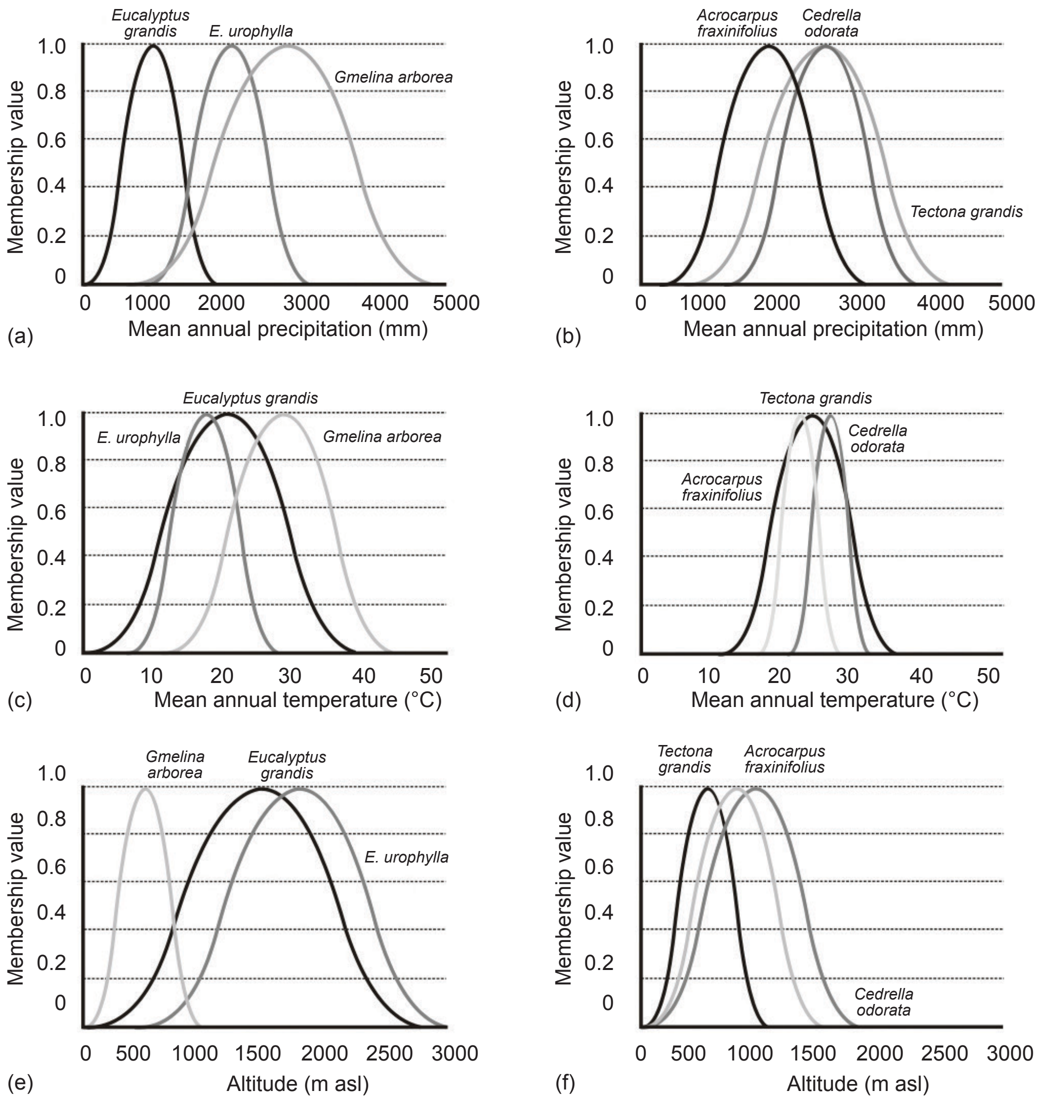

Figure 3 Membership function assigned to (a and b) mean annual precipitation, (c and d) mean annual temperature and (e and f) altitude by species for establishing tree plantations in Huasteca Potosina, Mexico; asl = above sea level

the scale used for making these judgments, while Table 2 indicates the final pairwise-comparison matrix. The judgments were done by assigning importance to each pair of factors. The final weights obtained from the comparison of factors were as follows: precipitation = 0.2507, soil = 0.224, distance to roads = 0.1902, temperature = 0.1521, slope = 0.1021 and altitude= 0.0809. We also determined the consistency range of the matrix to indicate the probability that the matrix had been randomly generated. Consistency range of less than 0.1 indicates that the matrix is acceptable; if this value is greater, the pairwise-comparison matrix must be reevaluated. Further details of computing consistency range can be seen in Nyerges and Jankowski (2010).

Constraint products ($\prod_{j=1}^{k} c_j$) were acquired by multiplying all the Boolean masks that were obtained when determining available land for the establishment of forest plantations. Determination of available land was conducted in three stages, namely, (1) generation of a bare soil map from recent satellite images, (2) selection of areas suitable for planting based on the current landuse map and (3) discrimination of areas classified as protected natural areas or with a slope greater than 30%.

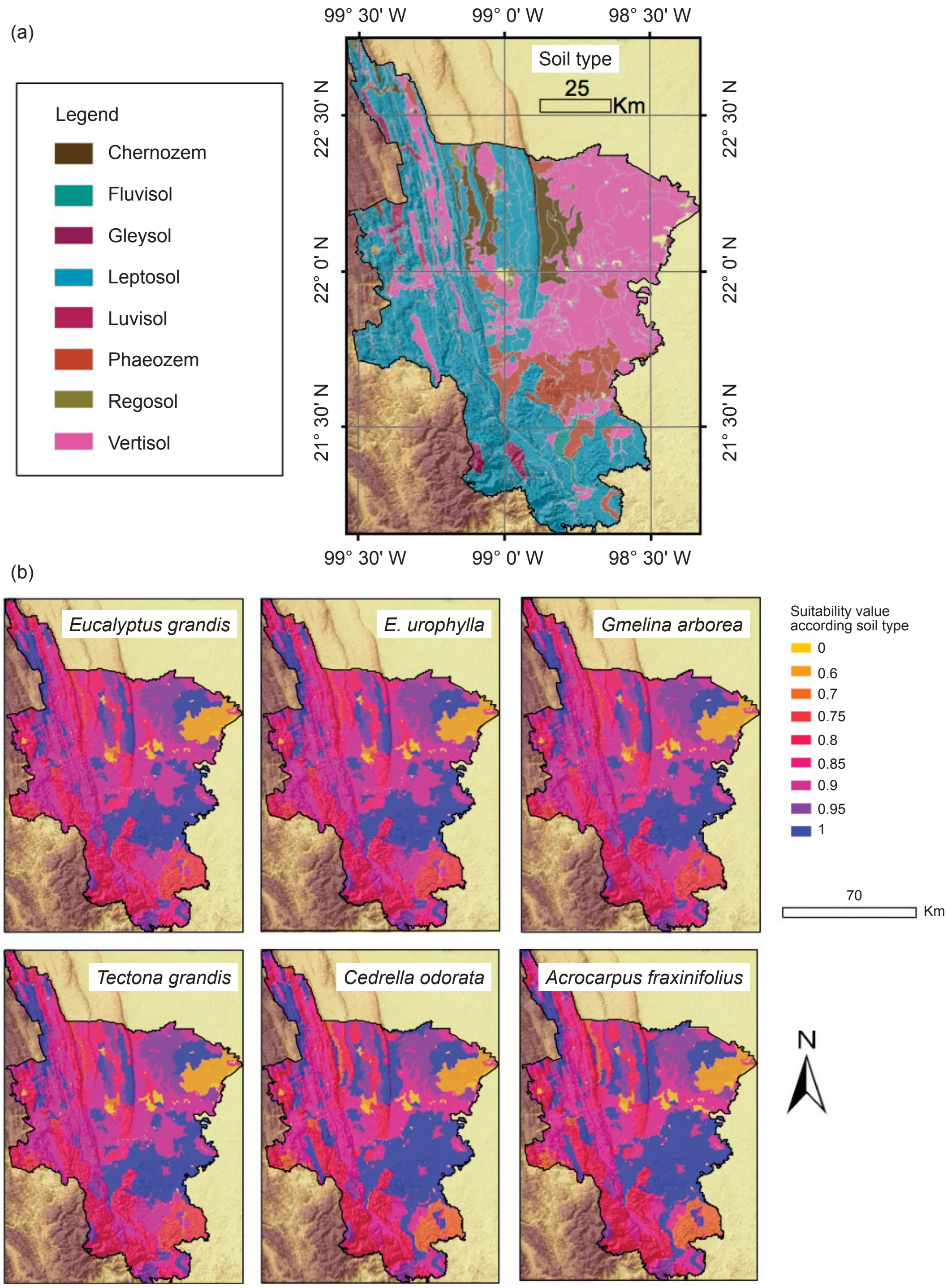

Figure 4 (a) Soil type and (b) corresponding land suitability values for tree plantation establishment in Huasteca Potosina, Mexico

The bare soil map was generated through an unsupervised classification of three dry-season Landsat 5 Thematic Mapper (TM) satellite images obtained via Glovis (http://glovis.usgs.gov). Scenes 027-044 and 027-045 taken on 4 April 2011, and scene 026-045 captured on 13 April 2011 were used. Imagery was radiometrically standardised by converting digital numbers to radiance (Wm^{-2} sr^{-1} μm^{-1}) and consequently determining dimensionless exoatmospheric reflectance (Amiri et al. 2009, Chander et al. 2009). Individual scenes were topographically normalised through C-correction algorithm to avoid distortions in the classification

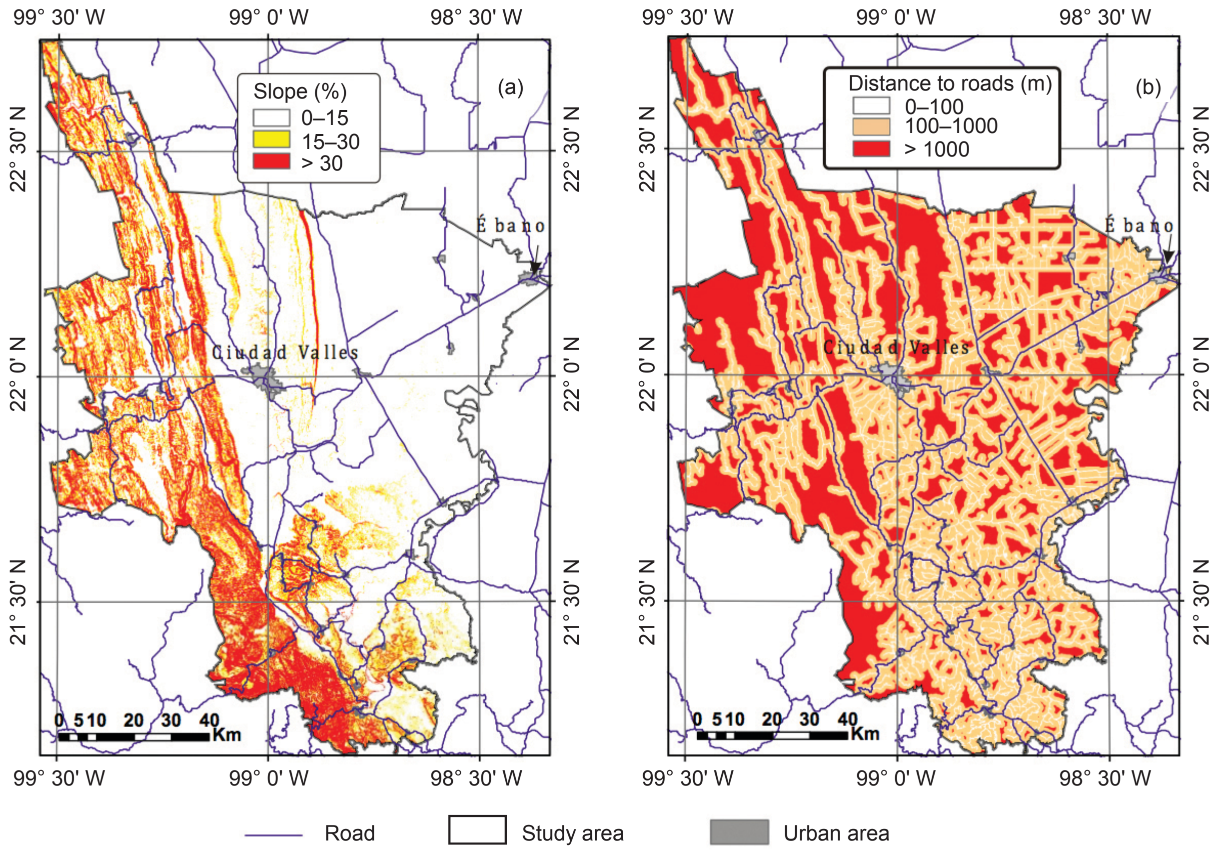

Figure 5 Spatial distribution of factors used in multi-criteria analysis for tree plantation establishment in Huasteca Potosina, Mexico, (a) slope and (b) distance to roads

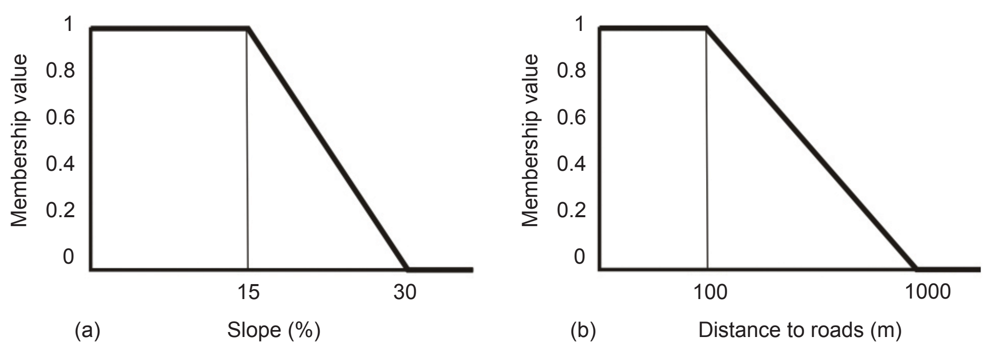

Figure 6 Membership functions assigned to (a) slope and (b) distance to roads as factors used in the multi-criteria analysis for tree plantation establishment in Huasteca Potosina, Mexico

from the effect of shadows induced by mountains and sun position when the Landsat imagery was taken (Riaño et al. 2003, Teferi et al. 2010). A 30-m pixel size digital elevation model covering each individual Landsat scene was used for this purpose (INEGI 2012) (Figure 7). Standardised images were merged into a mosaic (Figure 8a). Algorithm Isocluster (Eastman 2006) was applied to the imagery mosaic to determine 10 landuse categories. Two of them corresponded to bare soil and were reclassified into a Boolean mask. Accuracy of the bare soil map was evaluated by error matrix constructed with 152 sampling sites. Overall accuracy obtained from the bare soil map was 91.4%.

To assure that bare soil areas were located in available landuse classes, vegetation and landuse map series IV (INEGI 2009) was used

Table 1 Scale used in the pairwise comparison of factors

Less important					More important			
1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely	Very strongly	Strongly	Moderately	Equally important	Extremely	Very strongly	Strongly	Moderately

Table 2 Pairwise-comparison matrix used for assigning weights to factors involved in determining land suitability for each species in Huasteca Potosina, Mexico

Factor	Precipitation	Temperature	Soil	Altitude	Slope	Distance to road	w_i
Precipitation	1						0.2507
Temperature	1/2	1					0.1521
Soil	1/2	2	1				0.2240
Altitude	1/2	1/2	1/3	1			0.0809
Slope	1/2	1/2	1/3	2	1		0.1021
Distance to road	1	1	1	2	2	1	0.1902
Consistency ratio = 0.04						Total	1

w_i = importance of factor i

to select grassland, agriculture and natural vegetation (forest, forest and scrub with secondary vegetation) to generate a Boolean mask. This meant that solely bare soil pixels located in landuse and land cover categories were used in the analysis. Natural reserves map was also reviewed to exclude any protected area from the analysis (CONANP 2003). Finally, all areas with slope values exceeding 30% were also excluded (Figure 8b). Image processing was performed using interactive programming language of macros available in the IDRISI platform (Eastman 2006).

Phase 2—multiobjective land allocation

MOLA makes heuristic decisions to resolve conflicts among competing objectives. It requires clear definition of the different objectives, specifically: (1) name of the objectives, (2) value of importance for each objective, (3) suitability map for each objective and (4) area feasible to be allocated to each objective. The algorithm iteratively reclassified suitability maps to develop a first allocation to each objective defined (in our case, the establishment of tree plantations with any of the six species of interest). It also checked for conflicts and assigned pixels based on the rule of minimum distance to the ideal point using different importance values for each objective (Eastman 2006, Hajehforooshnia et al. 2011).

A scenario analysis was performed to explore possible answers to the question 'what if?' by generating different decision scenarios: (1) equal importance for all species, (2) species growth rate, (3) species wood quality and (4) potential species health problems. The scenarios were configured by calculating importance values for each species (objectives) using a pairwise-comparison matrix. Judgments on the importance of each species were based more on literature review than expert knowledge. The survey was applied to 10 recognised experts on forest plantations and wood technology in Mexico and only two of them answered it. So, we based our weighting criteria mainly on literature review that focused on exploring growth rate, timber quality and health problems of selected species. Opinions from experts were also considered so as to have more detailed threshold values. When ranking species based on growth rate with the focus on timber production, approximate time (years) from planting to harvest that a species needs to grow was investigated from literature. The values were as follows: *E. grandis*

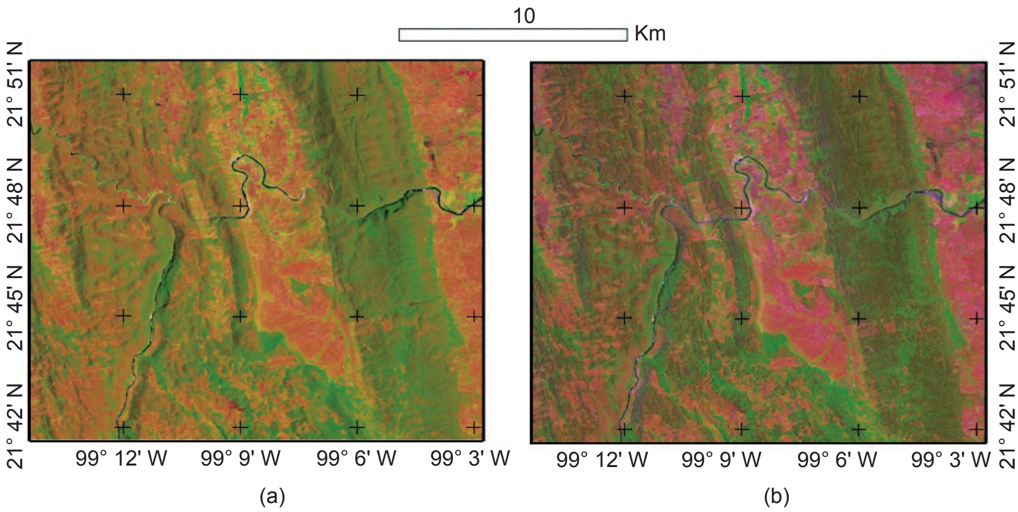

Figure 7 Zoom-in to a portion of the Landsat 5 TM image (red: Band 5, green: Band 4, blue: Band 3) to visualise the effects of topographic normalisation via C-correction (a) before and (b) after correction

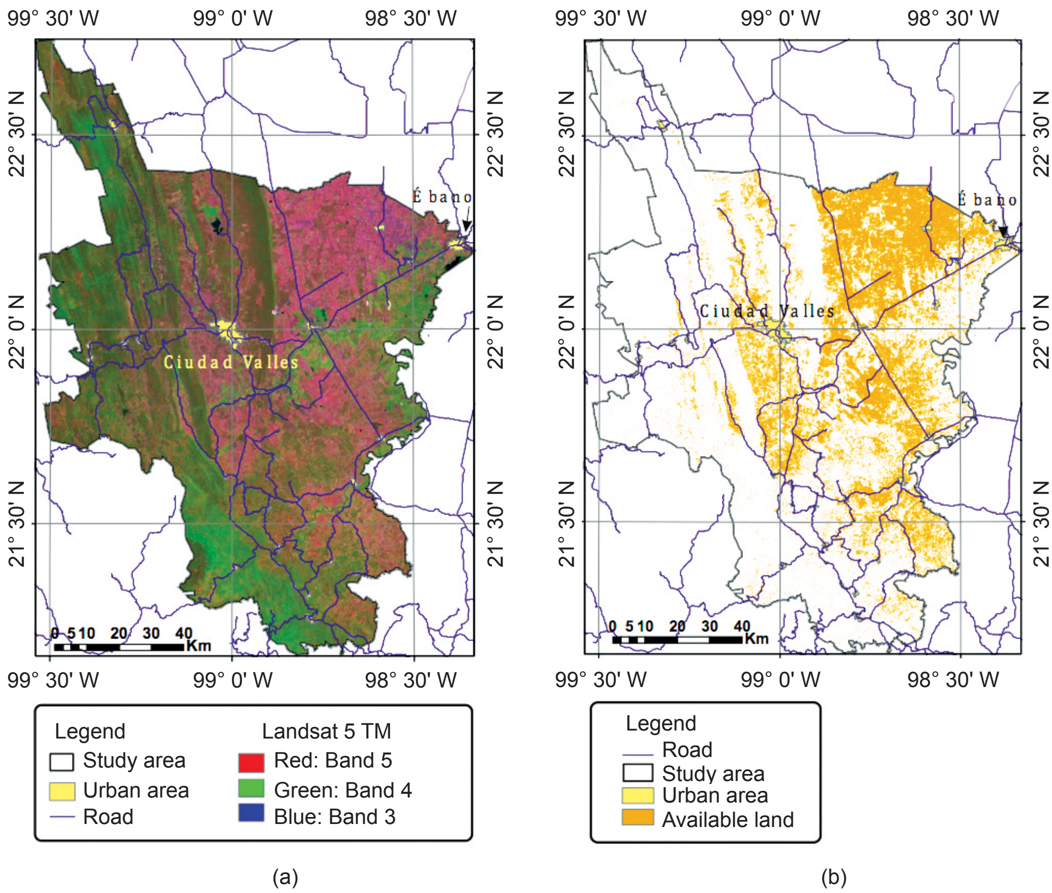

Figure 8 (a) Radiometrically-corrected mosaic built with Landsat 5 TM imagery and (b) available land for tree plantation establishment in Huasteca Potosina, Mexico

= 10 years, *E. urophylla* = 12 years, *G. arborea* = 12 years, *T. grandis* = 20 years, *C. odorata* = 20 years and *A. fraxinifolius* = 12 years (FOA & INDUFOR 2009). This information was used to rank species based on their growth rate (Table 3). Ranking species to be planted based on wood quality required investigation into species wood properties and uses giving priority to timber production for the manufacture of furniture (Table 4). To rank tree species based on plant health problems that might affect trees during growth, judgments were made favouring species with fewer known health problems (Table 5).

Suitability maps for each species generated as explained in phase 1 by the weighted linear combination method were used as input into the multi-objective procedure. Since the purpose of the study was to classify land suitability for the entire study area, area considered for allocation by the MOLA procedure was that which was identified as available land. Both weighted linear combination and MOLA procedures were performed using the Decision Making Wizard implemented in the IDRISI software (Eastman 2006).

RESULTS

Phase 1—land suitability by species

Figure 9 illustrates the spatial distribution of land suitability scores estimated for each species. Original values, ranging from 0 to 1, were reclassified into five classes, namely, 1: very low (0 to 0.2), 2: low (0.2 to 0.4), 3: moderate (0.4 to 0.6), 4: high (0.6 to 0.8) and 5: very high (0.8 to 1). Class 1 was weakly represented in the suitability maps. In contrast, over 80% of the total available area (286,267.9 ha) for establishing tree plantations ranked from moderate to very high suitability scores. These results revealed the overall high potential adaptability of the selected tree species to environmental conditions found in the Huasteca Potosina region. The tree species can be classified into two groups based on their land suitability scores. The first group included species with high and very high land suitability scores for plantation establishment: *E. grandis* (83.7%), *A. fraxinifolius* (75.3%) and *G. arborea* (74.7%). The second group contained species with moderate or high land suitability scores: *C. odorata* (96.8%), *T. grandis* (89.2%) and *E. urophylla* (80.0%).

Phase 2—multi-objective land allocation

Spatial distribution of the most suitable areas for each tree species, based on the ideal point searched within the multi-objective land allocation procedure, is illustrated in Figure 10. In scenario 1, assuming equal weight (importance) for each species is considered, *E. grandis* occupied 53.5%, *G. arborea* 18.3% and *A. fraxinifolius* 11.9% of the available land for industrial tree plantation establishment. In other words, they were the species that best matched their agro-ecological requirements with existing environmental conditions of the Huasteca Potosina region. In scenario 2, considering differential weight for the species growth rate, *E. grandis* and *G. arborea* coupled with productive characteristics of 55.5 and 23.7% of the available land respectively. In scenario 3, defined by the criterion of wood quality for furniture production, *C. odorata* and *A. fraxinifolius* seemed to be the best options for establishing plantations in 41.8 and 40.5% of available land respectively. Finally, in scenario 4, which did weighting by taking into account potential tree health problems, we found that *E. grandis* and *G. arborea* better matched in 54.7 and 24.4% respectively of available land.

Changes in the area obtained for each species can be explained by analysing the importance values calculated through the pairwise-comparison matrix. The higher the importance value for the species, the larger the suitable area defined on the multi-objective map. It is important to emphasise that environmental conditions of the Huasteca region largely coincided with the requirements of the selected species because they were previously identified as suitable for the region (FOA & INDUFOR 2009).

DISCUSSION

This work focused on the prioritisation of areas for the establishment of tree plantations for industrial purposes in the Huasteca Potosina while considering six tree species. Main results highlighted the possibility of describing quantitatively, at pixel level (30-m spatial

Table 3 Pairwise-comparison matrices to weight tree species according to growth rate

Species	SP_1	SP_2	SP_3	SP_4	SP_5	SP_6	w_i
SP_1	1						0.3040
SP_2	½	1					0.1896
SP_3	½	1	1				0.1896
SP_4	⅓	⅓	⅓	1			0.0761
SP_5	⅓	⅓	⅓	1	1		0.0761
SP_6	½	1	1	2	2	1	0.1646
Consistency ratio = 0.01						Total	1

SP_1 = *Eucalyptus grandis*, SP_2 = *E. urophylla*, SP_3 = *Gmelina arborea*, SP_4 = *Tectona grandis*, SP_5 = *Cedrela odorata*, SP_6 = *Acrocarpus fraxinifolius*; w_i = importance of species i

Table 4 Pairwise comparison matrices to weight tree species according to wood quality

Species	SP_1	SP_2	SP_3	SP_4	SP_5	SP_6	w_i
SP_1	1						0.0748
SP_2	2	1					0.0946
SP_3	2	2	1				0.1515
SP_4	2	2	1	1			0.1914
SP_5	3	3	2	1	1		0.2434
SP_6	3	3	2	1	1	1	0.2434
Consistency ratio = 0.02						Total	1

SP_1 = *Eucalyptus grandis*, SP_2 = *E. urophylla*, SP_3 = *Gmelina arborea*, SP_4 = *Tectona grandis*, SP_5 = *Cedrela odorata*, SP_6 = *Acrocarpus fraxinifolius*; w_i = importance of species i

Table 5 Pairwise-comparison matrices to weight tree species according to plant health problems

Species	SP_1	SP_2	SP_3	SP_4	SP_5	SP_6	w_i
SP_1	1						0.1808
SP_2	1	1					0.1808
SP_3	1	1	1				0.1808
SP_4	1	1	1	1			0.1808
SP_5	½	½	½	½	1		0.1266
SP_6	1	1	1	1	½	1	0.1503
Consistency ratio = 0.04						Total	1

SP_1 = *Eucalyptus grandis*, SP_2 = *E. urophylla*, SP_3 = *Gmelina arborea*, SP_4 = *Tectona grandis*, SP_5 = *Cedrela odorata*, SP_6 = *Acrocarpus fraxinifolius*; w_i = importance of species i

resolution), (1) the degree of land suitability for establishment of industrial tree plantations, (2) areas available for establishment of plantations and (3) proposed tree species to plant for each available spatial location. A planter can use this information to focus his/her efforts to undertake a detailed feasibility study of tree cultivation for industrial purposes.

The advantages of using geospatial tools in zoning for plantation establishment are discussed by several authors (Olivas-Gallegos et al. 2007, Delgado-Caballero et al. 2010, Falasca et al. 2012). However, our research has three innovative aspects. First, choosing more than two fast-growing tree species for plantation establishment for industrial purposes, compared

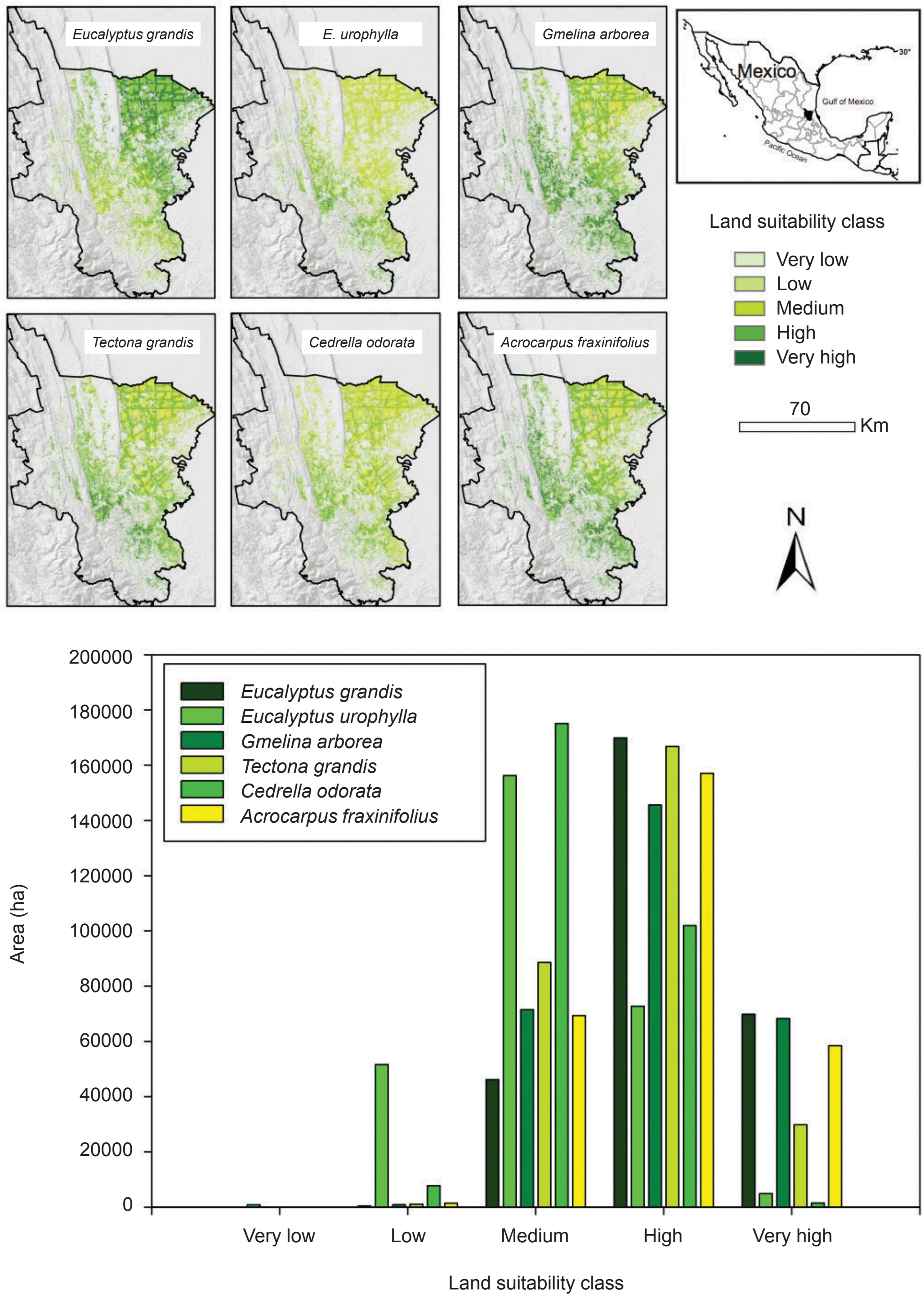

Figure 9 Land suitability by species for tree plantation establishment in the Huasteca Potosina, Mexico

with other studies dealing with one or two species. Second, the use of four decision scenarios based on expert knowledge for prioritisation of tree species characteristics related to growth rate, wood quality and potential tree health problems. Third, the use of remote sensing technology to accurately detect available land for establishing tree plantation projects. The modelling approach was developed in a comprehensive way so that it was easily repeatable and verifiable by land managers and tree planters.

The size of the study area usually determines the availability of information to construct the database. This study analysed an area of

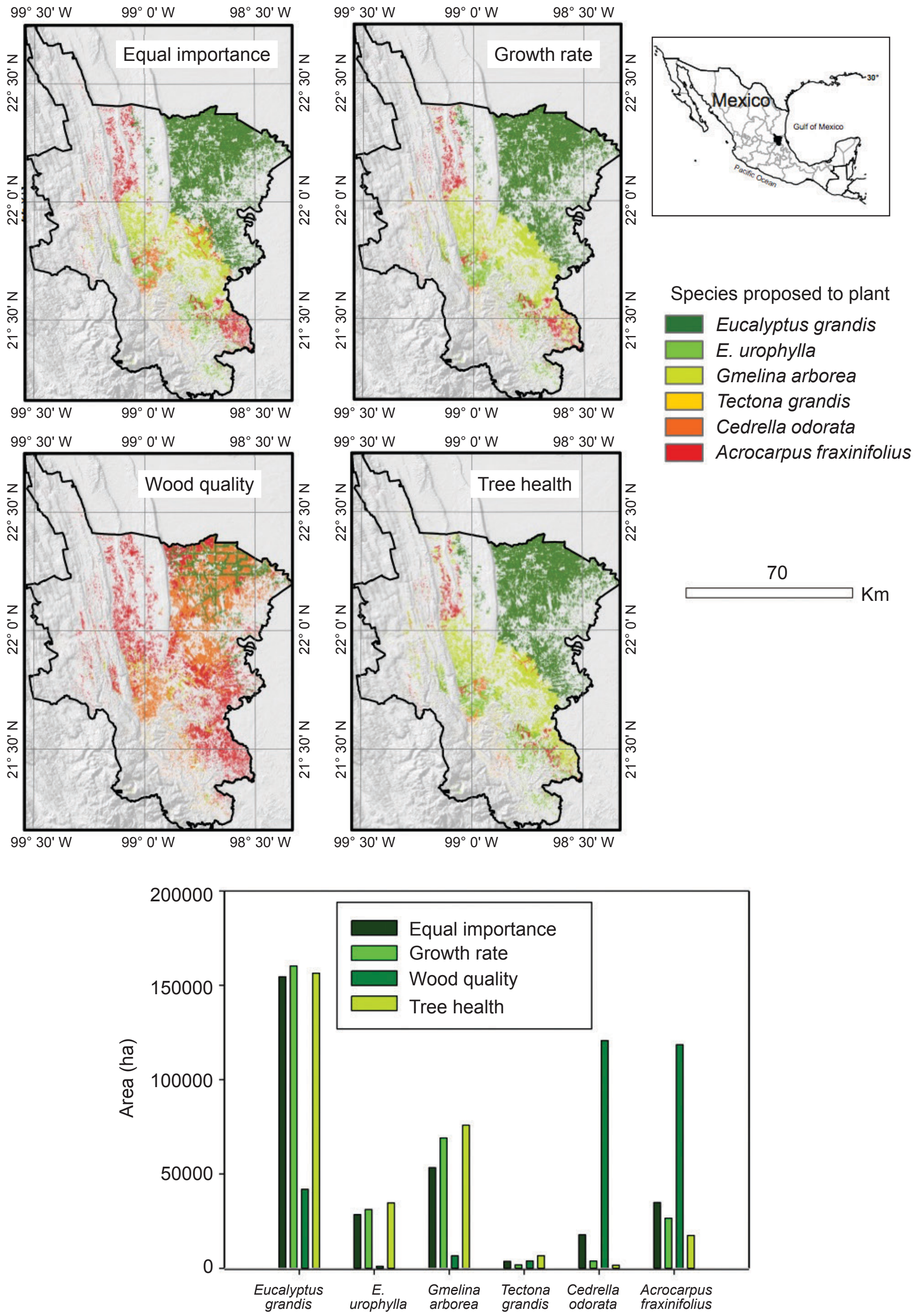

Figure 10 Spatial distribution of the most suitable areas for each tree species based on the search for the ideal point using multi-objective land allocation approach in Huasteca Potosina, Mexico

1,129,186 ha and had shown complications of acquiring a 1:50,000 scale soil map that completely covered the area of study. Such difficulties are frequent for areas larger than 500,000 ha. In Mexico, there were basically three sources of soil information that could be used in this study: (1) 1:250,000-scale soil map series I, made using data for the period 1980–1998, (2) 1:50,000-scale soil map with limited spatial coverage for the entire country and (3) 1:250,000-scale soil map series II, made by updating the series I soil map with information from the 1:50,000-scale soil map, and its reclassification of soil units based on the World Reference-Base system also known as WRB 2000. The third source was the best option available for documenting variation in soil characteristics (INEGI 2005).

Spatial variation of land suitability for each species revealed the effectiveness of using the weighted linear combination approach and standardised data with fuzzy membership functions to adequately zone land suitability (Figure 10). This paper represents an interesting complement that enriches the spatial information generated by FOA and INDUFOR (2009). They did not provide fuzzy land suitability scores for selected species probably due to their use of the Boolean approach for site selection. Their land suitability maps are too general to reflect both real estimates on available land and spatial variation for establishing new tree plantations, both of which are important to decide what and where to plant. The advantages of working with this methodology over Boolean logic or other methodology have been discussed (Delgado-Caballero et al. 2010). The authors compared fuzzy and Boolean approaches for mapping land suitability for two species of *Eucalyptus* spp. When using the Boolean method, the suitable area identified was reduced by 75.6% for *E. urophylla* and 97.5% for *E. grandis* compared with the area identified as suitable by the fuzzy method. Their findings revealed a dramatic loss of information through the Boolean approach. Another justification of using the weighted linear combination approach in this study was the need to generate species-specific land suitability maps that were later used as inputs in the MOLA approach to create different production scenarios.

A novel application in our study is the use of a pairwise-comparison matrix for weighting several preferences in order to obtain different MOLA maps describing specific scenarios. Other researchers have used other methods to generate multi-objective solutions that reconcile different potential landuses (Geneletti & Van Duren 2008, Alçada-Almeida et al. 2009, Tenerelli & Carver 2012). Six objectives (species) were modelled in this study, which to us was an optimal number. Seven objectives were reported as the maximum number of objectives in order to ensure meaningful judgments since using more could be confusing (Saaty & Ozdemir 2003).

An increasing demand for forest products such as logs, pulp, chips and resin as well as the importance of forests for providing environmental services such as carbon sequestration, biodiversity conservation, watershed protection, erosion control and regulation of the hydrological cycle, will continue to motivate the establishment of new forest plantations. In 2010, it was estimated that tree plantations accounted for 6% of the global forest area which was approximately 264 mil ha. At that time, the potential production of roundwood from plantations was estimated at 1.2 bil m^3, which accounted for a little over 60% of the industrial needs for roundwood worldwide (Evans 2009, FAO 2011).

This work presented an interesting contribution regarding current land allocation planning of the study area. During the last seven years, the policy of CONAFOR has been promoting the establishment of tree commercial plantations, particularly in three areas of Mexico, namely, Gulf of Mexico, North-East Mexico and Huasteca. Although this work was focused mainly on planning the use of land for timber production, there was a wide range of species that could be planted for industrial and commercial purposes including *Jatropha curcas*, *Azadiracta indica* and *Moringa citrifolia*.

CONCLUSIONS

Four conclusions can be drawn from this study. First, spatial modelling of land suitability for the establishment of commercial tree plantations in the Huasteca, Mexico with six species (*E. grandis*, *E. urophylla*, *G. arborea*, *T. grandis*, *Cedrela odorata* and *A. fraxinifolius)* was successfully carried out by combining geospatial and remotely-sensed data (30-m spatial resolution) in a multi-criteria/multi-objective approach. Second, the selection of species was appropriate because over 80% of the available area for establishment of tree plantations was classified as moderately, highly and very highly suitable. Third, calculated weights for each species were essential when allocating total area available using multi-objective land allocation, a procedure that took into account both on-site land suitability and preferences benchmarked by the different scenarios proposed. Finally, the proposed methodology can be used to generate valuable information in other geographical areas worldwide while assessing multi-objective land suitability for industrial tree plantations.

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