Predicting the climatic distribution of the Colombian oak *Quercus humboldtii* Bonpl. (Fagaceae)

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Abstract

Spatial analyses of climate are important for understanding the potential adaptation of species to unstable environments. This paper reports on the potential climatic distribution of the Colombian oak or *Quercus humboldtii (Q. humboldtii)*. A predictive model was used to analyse data on the *Q. humboldtii*, calculating the habitat suitability on the basis of 36 climate variables using a Principal Component Analysis. Our analysis found that the *Q. humboldtii* is distributed through the west, central and eastern mountain ranges and some lowland inter-Andean regions. *Q. humboldtii* has a wide climatic adaptation, with a particular preference for environments that have a mean temperature between 9.3°C to 27.9°C and annual rainfall between 788mm/year and 2681mm/year. *Q. humboldtii* grows at elevations of 1.100 meters above the sea level and is well-adapted to wet and dry environments. There is however, no climatically unique and geographically succinct cluster of *Q. humboldtii* populations. The *Q. humboldtii* population is split into two climatic envelopes with a differing mean temperature for populations located in low and high elevations. A population of *Q. humboldtii* never collected prior to our study was reported at 1,100 m above sea level in the Serranía de San Lucas. This new record is relevant because it represent the lower elevation range of the species in the northern part of the country. Therefore, it is essential for future studies on conservation of the species because it suggest the possibility of finding new populations even further north of San Lucas. Our results prove to be useful for identifying potential climatic risk to the species and locating suitable environments in Colombia and some neighbouring countries where the *Q. humboldtii* could potentially grow.

Key words: *Q. humboldtii*, FloraMap, species distribution, Colombian oak

Resumen

Análisis espaciales de variables climáticas son importantes para entender la posible adaptación de las plantas a condiciones ambientales inestables. Este articulo presenta la distribución climática potencial de *Q. humboldtii* Bonpland en Colombia. Datos de colecciones de herbario fueron usados para generar el mapa de distribución. Los datos de distribución fueron cargados en el paquete de simulación FloraMap, el cual usó 36 variables climáticas para generar un mapa de predicción climática. La predicción está basada en análisis de componentes principales, los cuales interpolan la latitud y la longitud de cada uno de los registros de herbario con respecto a la elevación sobre el nivel del mar y cada una de las 36 variables de clima. Se reporta que *Q. humboldtii* se distribuye a lo largo de las tres cordilleras desde el sur de Panamá hasta el norte de Nariño. Se demostró que está adaptado a gran variedad de condiciones climáticas, con adaptación a rangos de temperatura que varían entre 9.3 y 27.9 grados centígrados y una cantidad de lluvia anual promedio entre 788 y 2.681 milímetros. Altitudinalmente, el Roble se distribuye desde 1.100 m sobre el nivel del mar hasta más o menos 3.000 m. Aunque no se identificó una condición ambiental específica, se detectaron dos tipos climáticos que están condicionados por la temperatura promedio: un clima seco de zonas bajas y otro húmedo de elevaciones altas. Como resultado de estas condiciones, es posible argumentar que la especie presenta una amplia adaptación climático-ambiental a lo largo y ancho de los Andes colombianos. Se reporta una nueva colección de la especie en el Departamento de Bolívar, Serranía de San Lucas a 1.100 m. Este registro de distribución es importante porque sugiere la posible existencia de más poblaciones en zonas aun más al norte. Esto es un incentivo para realizar más expediciones en las cuales se podría colectar la especie y así plantear estudios de conservación de poblaciones aisladas.

Palabras clave: *Q. humboldtii*, cambio del clima, Biogeografía, FloraMap, Colombia

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INTRODUCTION

Climate change poses a real threat to the natural distribution of species. Therefore it is crucial to characterise the climatic adaptability of trees and predict the climatic conditions that endemic and threatened species emblematic species such as the Colombian Oak require so that scientist can know the climate under which the species can survive and therefore adapt to a changing climate. Unfortunately, little information exists about the geographical regions in Colombia where the most suitable climatic for *Q. humboldtii* exists to make it able to grow. The purpose of this study is to predict the climatic distribution of the Q*uercus humboldtii* Bonpland (*Q. humboldtii*). In this paper, we specifically investigate the capabilities of using the software FloraMap to predict the potential climatic conditions that the Colombian oak relies on to exist. FloraMap has been used in different case studies (Upadhyay *et al.* 2011; Segura et al. 2003; Laderach *et al.* 2008; Jones and Gladkov 1999; Jones *et al*. 2002; Jarvis et al. 2002; Jones 1991; Jones *et al*. 1997). Theoretical background can be found in the FloraMap manual, which is available online at http://www.floramap-ciat.org http://www.floramap-ciat.org/.

The relationship between climate and geographical distribution of trees is an important aspect of forest ecology and habitat distribution models (Guisan and Zimmermann 2000). Biologists or ecologist are presented with two methods for assessing species distribution: point observations and predictive distribution models. Point observations can be used to examine the distribution of a species at the local scale but this method tends to underestimate the true distribution if observations are an incomplete representation of the geographic range of the species (Anderson *et al.* 2002). Spatial predictive modelling has received particular focus in ecology in recent years (Guisan y Zimmerman 2000) because it takes account of the environmental conditions surrounding the sampling point. Predictive distribution modelling uses occurrence observations of a species to understand the biophysical adaptation of the species in question and then extrapolate the potential distribution to larger regions.

Point and predictive methods are usually applied separately, in our study, we combine both methods using FloraMap. FloraMap is one of many climatic envelope models tools available that produces a predicted layer composed of grid cells with assigned high or low values of prediction. These prediction values are based on the interpolation of climatic variables. The output data are used to analyse the potential distribution of species based on their original spatial location. There are numerous statistical models that have been developed to analyse output data, including genetic algorithm (Anderson *et al.*2002) and logistic regression (Draper *et al.* 2003). FloraMap uses a Principal Component Analysis (Jarvis *et al.* 2003b; Robertson *et al.* 2001) commonly known as "PCA" as its main statistical method.

In our study, we focus on the use of FloraMap to investigate to what extent the variations in elevation, rainfall and temperature influence the potential spatial distribution of the population of *Q. humboldtii* in Colombia. Our specific objective is to predict the habitat suitability of such variables on the current distribution of *Q. humboldtii.*

MATERIALS AND METHODS

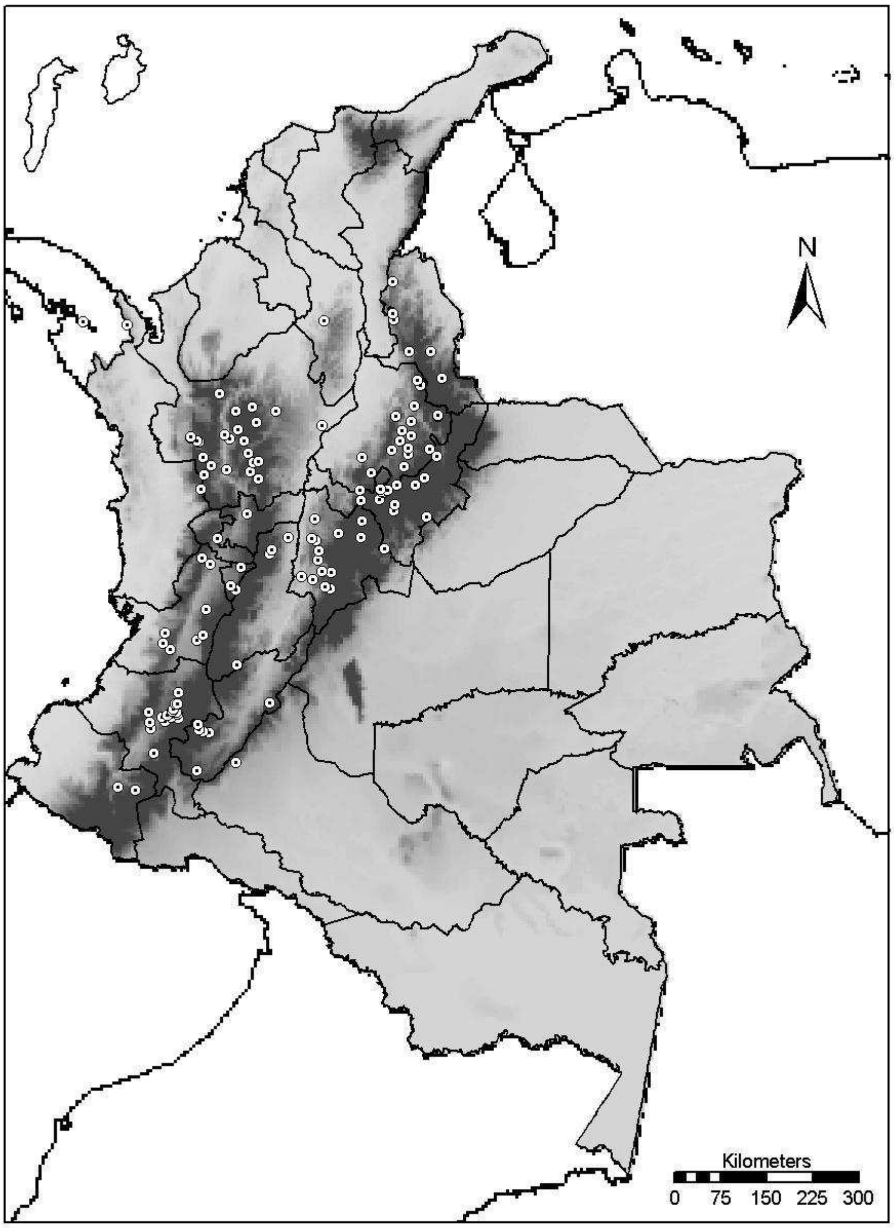
Studied taxa

The genus *Quercus* has 500 species distributed in the northern hemisphere with a mid- latitude holartic origin (Manos et al. 1999). It belongs to the Fagaceae family and has a Laurasian origen (Hernandez et al. 1980). The closest genus, *Trigonobalanus*, comes from the northern hemisphere of the new world (Palacio 2001). In Colombia, *Q. humboldtii* is widely distributed across the country with large populations found in specific areas of the Andean region forests. *Q. humboldtii* is a woody tree commonly known as "Roble". The species has other common names, including Roble Amarillo, Roble Negro, and Roble Blanco (Pacheco and Pinzon 1997). In previous studies by Lozano and Torres (1974), seven Colombian *Quercus* species were cited and found in Tolima, Cauca, Boyacá and Valle del Cauca provinces municipalities. They referred to different "roble" names or synonyms of *Q. humboldtii* including *Q. tolimensis, Q. almaguerensis, Q. lindenii, Q. colombiana, Q. boyacensis* and treated them as separate taxonomic species. In contrast, Cavelier et al. (1994) classified all robles in Colombia as a unique species. The question remains as to the true taxonomy of the species. *Q. humboldtii* has recently been classified by the International Union for Conservation of Nature (IUCN) as a tree species under "VU" vulnerable risk of endangerment (Salinas and Cardenas 2007).

Data set

Figure 1 shows the spatial distribution of the 132 accessions of *Q. humboldtii* used in this study. Each accession was georeferenced and any spatial errors were corrected. This dataset covers 95 percent of the species distribution range. The data set was compiled gathering information from different herbaria in Colombia and also online international databases. We visited herbariums at the national university of Colombia located in Bogota; the University of Antioquia in Medellin; the Humboldt Institute in Villa de Leyva; the University of Valle in Cali; the University of Cauca in Popayan and the University of Nariño in Pasto. Our main international sources were the online datasets of the Missouri Botanical Garden and the New York Botanical Garden (See Annex 2 for a list of the accessions).

Figure 1. Distribution of collection records (1940-2003) for *Q. humboldtii* in Colombia and Panama used in our study



Climatic prediction

The 132 accessions were imported into FloraMap, which is a predictive modelling tool that maps the potential distribution of species. The software FloraMap assumes that the climate at each of the 132 accessions represent a broad environmental range of the organism. FloraMap maps the potential distribution of the species, on the basis of climatic variables that are used to create climatic surfaces in a gridded format. The climatic surfaces were created by the FloraMap developers by using data from 2,167 weather stations distributed around Colombia, Ecuador and southern Panama. The main variables used are rainfall, mean temperature and diurnal temperature. FloraMap uses monthly values of thirty-six climate surfaces to generate the climatic predictive model.

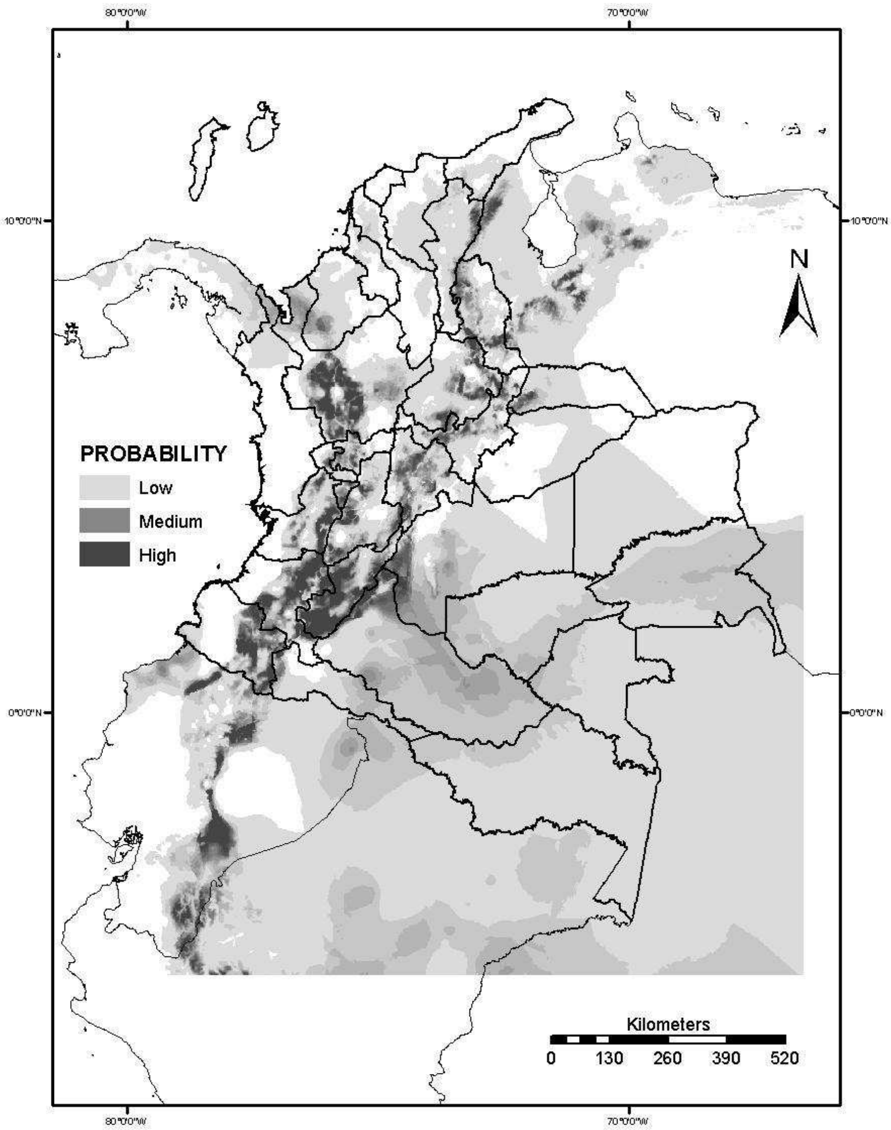
The steps that FloraMap follows to compute the climatic prediction are: (1) loading the accessions; (2) extracting climatic data for each accession; (3) running the PCA statistical analysis; (4) testing the multivariate normal distribution of the PCA scores; (5) calculating the probability value for each grid cell; and (6) mapping the probability surface of the study site.

Once the 132 herbarium accessions are loaded and displayed in FloraMap. The next step is to assign climatic values of rainfall, mean temperature and diurnal temperature to each of the 132 accessions. The climatic values for each of the 132 accessions were subjected to a Principal Component Analysis (PCA), which helps to select the best climatic predictors. The PCA data were then coupled with a probability model to map the potential distribution of the *Q. humboldtii* in areas where no accessions are reported. In other words, FloraMap was used to assign predicted values to the empty grid cells between the 132 accessions. Following this, a clustering analysis algorithm was applied using FloraMap to identify different climatic clusters within the species. Individual accessions in each cluster are identified, and also map the predicted distribution of that climatic cluster. The PCA scores and clustering analysis were analysed in order to ascertain the most important climatic factors in shaping the distribution of *Q. humboldtii*.

RESULTS

The predicted climatic distribution of *Q. humboldtii* in Colombia is fragmented across the three Andean ranges (Fig 2). Some regions in Ecuador and Venezuela are also climatically suitable. This result confirms that *Q. humboldtii* have a broad climatic adaptation. It is interesting to note that the regions with highly suitable climatic conditions do not always align with the historical distribution of the species. The spatial pattern of the predicted climate tends to be uneven suggesting that if climatic changes occurred, populations of *Q. humboldtii* located outside of the FloraMap predicted areas, could be under a chance to be climatically restricted leading to difficulties to adapt as mentioned by Calderon (1999).

Figure 2. Predicted climatic distribution for *Q. humboldtii* in Colombia and some neighboring countries with a spatial resolution of 2 × 2 kilometres gridded cells.



The areas that Floramap predicted as climatically suitable for *Q. humboldtii* are characterised by an average rainfall of 1,753 mm/year with a maximum of 2,681 mm/year and a minimum of 788 mm/year, a monthly mean temperature of 17.1 °C ranging from 9.3°C to 27.9°C and a diurnal temperature range of 10.6 °C ranging from 6.8°C to 13.7°C (Table 1).

	Precipitation	Temperature	Range
Correlation	-0.2754**	-0.0537***	0.291**
Mean	1753.11	17.08	10.57
Minimum	788	9.31	6.83
Maximum	2681	27.94	13.73
Lower Q	1470	14.81	9.04
Upper Q	2020	19.68	12.16
Std. Dev	409.20	4.05	1.77
Skewness	-0.13	0.50	-0.04
Kurtosis	-0.57	0.14	-0.99

Table 1. Pair wise correlations between elevation and total precipitation, mid temperature and mid range for all records of *Q humboldtii* included in our FloraMap model ($p < 0.05$*; $p < 0.001$**; $p < 0.0001$***)

Figure 3 reports two clusters of *Q. humboldtii*, cluster 1 (dark dots in Figure 3) and cluster 2 (white dots in Figure 3), which are defined mainly by elevation and to a lesser extent temperature. The clusters are groups of accessions that were statistically significant and therefore classified as climatically different from the others. Cluster 2 can be classified as containing accessions located on the high elevation (altitude average of 2,237 metres), and the accessions that composed cluster 1 come from environments located in lower elevations (altitude average of 1,574 metres).

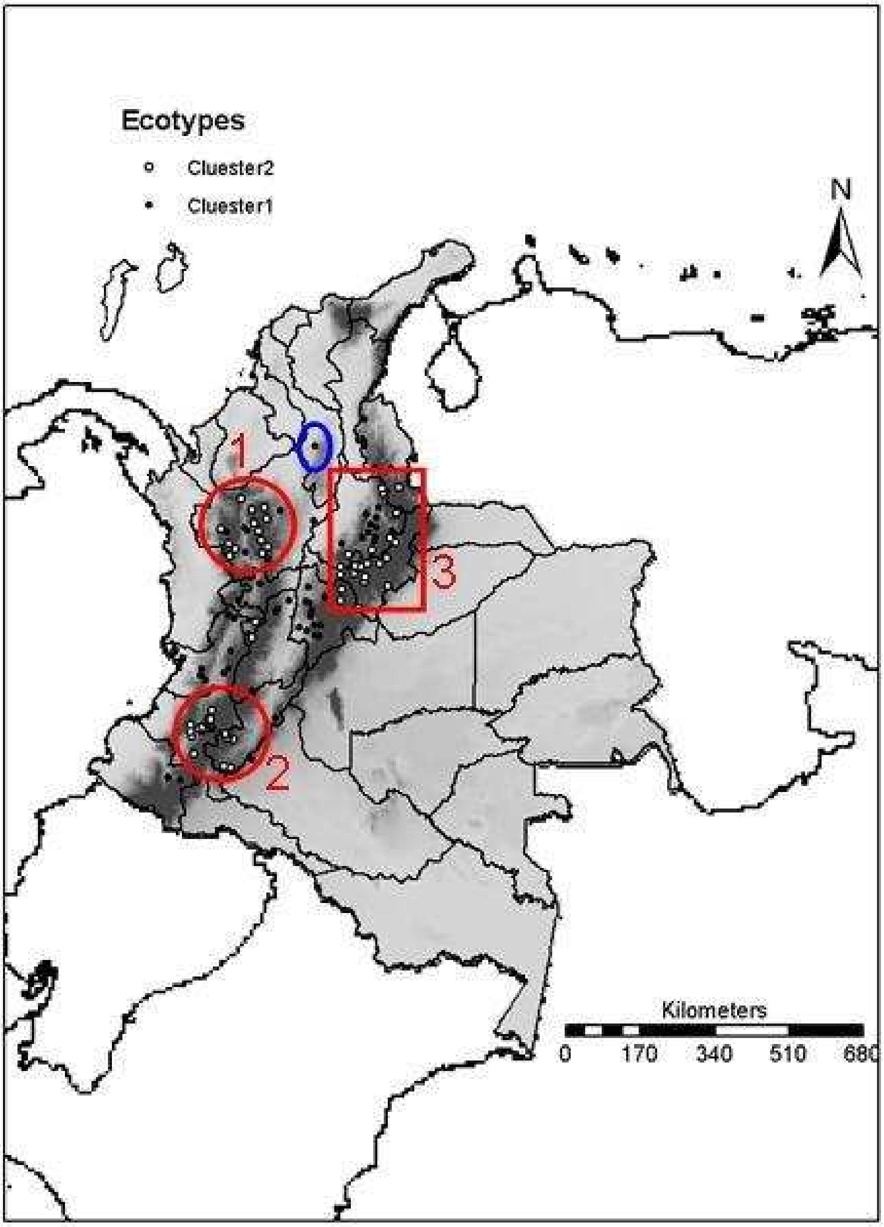
The purpose of the red circles and rectangle in Figure 3 is to point out the geographic location of areas where each of the clusters tend to distribute. The accessions corresponding to cluster 2 (white dots in fig 3) are mainly concentrated on three bio- geographical regions: central and south-west of Antioquia (red circle 1); the Popayan plateau and south-east part of

Cauca, southern part of Huila and north of Nariño (red Circle 2); Santander, Norte de Santander and Boyacá departments (red rectangle 3). Whereas, the dark dots corresponding to cluster 1 has a more even distribution pattern through the country with a lower degree of clustering. The Departments of Cauca, Antioquia and Boyacá have the greatest number of municipalities potentially containing the species. Finally, the blue circle shows the new extension record collected on the western slopes of the Serranía de San Lucas at 1,100 meters above sea level (See blue circle in Figure 3). The original collection is stored at the Natural History Museum, University of Cauca). Serranía de San Lucas is geographically isolated by Magdalena and Cauca river, this aspect and the high deforestation pressure in that regions suggest that conservation effort should be considered for the population of *Q. humboldii* in that particular region.

The geographical distribution of cluster 1 (dark dots in Figure 3, Table 2a) includes 60 accessions and stretches from the south to the north of Colombia mainly in corridors along the Cauca and Magdalena river catchments. Average altitude value was 1,574.8 meters above sea level. The annual average rainfall corresponding to this cluster was 1,892 mm/year, with a maximum of 2,692 mm and a minimum of 1,228 mm. The climatic pattern was characterized by rainfall concentrated during four months from December to March but with a drier season from June to September. The average annual temperature for this cluster was 22.5 °C. The western slopes of the eastern mountain ranges have the greatest potential coverage with more scattered regions on the eastern slope of the western range and the western side of the central range. The southern region contains less suitable environments than the northern part of the country for the population of *Q. humboldtii* contained in cluster 1. According to the first principal component that accounts for 54% of the variance, there is a negative correlation with all the monthly diurnal temperature range values and a positive correlation with rainfall values. The second principal component, which accounts for 25 %, reflects a slight negative correlation with rainfall for the three dry months (July-Sept). In general, *Q. humboldtii* appears to be most limited in distribution by rainfall, being best adapted to areas of high rainfall all year round.

The geographical distribution of cluster 2 (light dots in Figure 3, Table 2b) includes 71 accessions. The average in elevation for the accessions corresponding to cluster 2 was 2,237 meters above sea level. Climate patterns are dominated by a rainfall range influence with peaks in October-January and May-June. The monthly mean rainfall for the accessions corresponding to cluster 2 was 1,958 mm/year with a maximum of 2,866 mm/year and a minimum of 951 mm/year with a standard deviation of 74.3 mm/year and a diurnal temperature mean of 17°C and a diurnal mean monthly range value of 11.7°C. The geographical distribution is localized on the edges of the eastern, western and central ranges.

Figure 3. Patterns of distribution for the accessions of cluster 1 and 2 for *Q. humboldtii* in Colombia. The labels representing the clusters are at the top of the map, one with dark dots referring to Cluster 1, and cluster 2 with light dots.



The first principal component (54% variance) has a positive correlation with rainfall values for all months except August and September. The second component has a negative correlation with diurnal temperature for all months and a negative correlation with rainfall in May-June and November and December. The temperature is positively related to all months, indicating that for this cluster temperature may be a more limiting factor. The southern region of the distribution generally has wetter environments in comparison with the north which is drier.

(a)

	Mean	Minimum	Maximum	Lower Quartile	Upper Quartile	Std.Dev.	Skewness	Kurtosis
Precipitation	1891.77	1228.00	2692.00	1536.00	2202.00	433.65	0.21	-1.17
Temperature	22.51	13.66	30.58	20.95	24.47	3.63	0.12	0.28
Range	9.15	6.77	11.35	8.14	10.31	1.18	0.22	-1.12

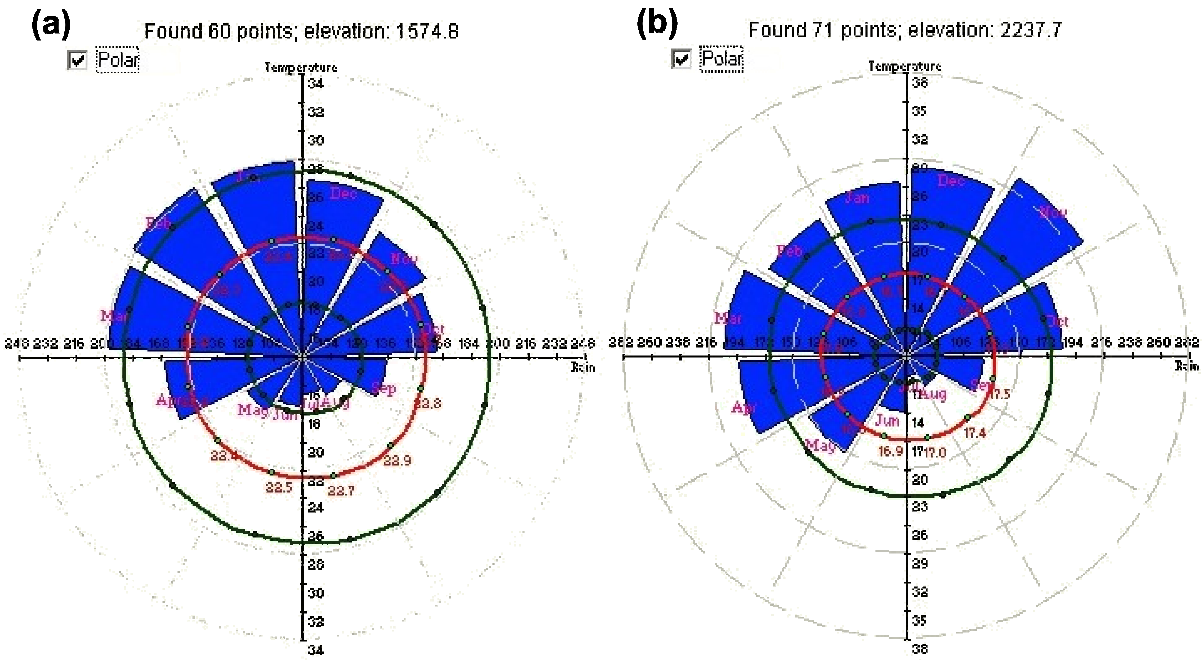
(b)

	Mean	Minimum	Maximum	Lower Quartile	Upper Quartile	Std.Dev.	Skewness	Kurtosis
Precipitation	1958.14	951.00	2866.00	1622.00	2203.00	395.61	-0.40	0.01
Temperature	16.99	12.31	20.38	15.34	18.78	2.22	-0.57	-0.90
Range	11.75	9.30	13.74	10.68	12.65	1.23	-0.16	-1.13

Table 2. Statistics summary for cluster 1(a) and cluster 2(b). Total precipitation, temperature range and range medium.

Both clusters are most markedly defined by mean temperature differences. Cluster 1 (Figure 4a) contains greater climatic seasonality than cluster 2 (Figure 4b). Cluster 1 is distributed continuously along the mid-elevation flanks of the Andes, in all three Andean mountain ranges; whilst cluster 2 has a more fragmented and localized distribution around the altitudinal maximal.

Figure 4. Principal Component Analysis displayed as a climate diagram for Cluster 1 (a) and Cluster 2(b)



DISCUSSION

The objective of our research was to predict the climatic distribution of *Q. humboldtii* in Colombia. The results of this study show that *Q. humboldtii* has a wide climatic adaptation ranging from low to high elevations and wet to dry environments (788mm/year – 2681mm/year) representing a mean temperature from 9.3^{o}C to 27.1 ^{o}C .

The predicted climatic distribution computed by FloraMap is not fully consistent with the records collected by other authors in the past decade (Lozano and Torres 1974; Rangel and Lozano 1986; Rangel and Lozano 1989). However, the species has been reported in 13 of the 33 Colombian departments (Annex 1 lists the localities of major climatic relevance).

Understanding the spatial distribution of a species is of most importance in assessing the conservation status and in suggesting possible conservation decisions that must be taken (Guarino *et al.* 2001). Despite of the wide distribution of *Q. humboldtii* across Colombia, conservation efforts must include measures to conserve the genetic diversity within the species, as well as populations. More evidence on the basis of genetic variation shown by Fernandez and Sork (2007) suggested that *Q. humboldtii* may have restricted gene flow, which in terms of habitat conservation, could it put at risk of "future genetic bottlenecks, if large tracts of forest disappear". Cavelier *et al.* (1995) explored systematic RAPDS techniques in *Q. humboldtii*. Fernández (2001) has also developed micro-satellite genetic techniques for Colombian Fagaceae species. It is believed that this predictive climatic method provides complementary information for planning and *ex situ* conservation. A similar methodological case study conducted by Jarvis *et al.* (2005), successfully implemented a predicting model for prioritizing areas within Paraguay for acquisition of germplasm of a crop gene pool for *ex-situ* conservation and other studies reported by Jarvis et al (2003a).

CONCLUSION

The results presented here offer relevant evidence on the climatic variables that may be relevant for the distribution of *Q. humblodtii* across Colombia. The two climatic clusters reported in our study suggest that the species is not found in separate geographic regions with vastly different environments. We demonstrated that some populations of *Q. humboldtii* such as Cluster 2 could be more vulnerable if the future climate continues to change. However, no conclusive evidence was found to support the thought that there are populations in unique geographic regions with exclusive climates. The only climatic clustering that was found separates high elevation populations from their lower elevation counterparts. This is not a separation of vastly different climates, but more a separation along a continuous elevation gradient.

For the future, there are a number of aspects, which could be further explored. The research topics could include: modelling distribution of pests or insects related to the natural distribution of *Q. humboldtii*, spatial analysis diversity based on genetic information, analyses of phylogenetic diversity, prioritizing *ex situ* conservation areas within Colombia, locating the suitable distribution habitats by applying the latest predictive models such as Maxent and Bioclim (Hernández *et al.* 2006), conducting *ex situ* molecular analysis and understanding *in situ* aspects based on climatologically variables that impact on *Q. humboldtii* conservation and preservation.

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Annex 1.

A list of provinces where the most suitable climate is reported for *Q. humboldtii*, and therefore where the species is likely to be found is presented below:

(1) Low-elevation climates (warmer temperatures): Nariño (south east of Ipiales, east of Funes, Puerres and Pasto, Santa Cruz, Samaniego, Los Andes, Cumbitará, east of Magui); Putumayo (nort west of Orito and Villa Garzón); Cauca (south of Santa Rosa); Huila (Pitalito, Isnos, south of San Agustín, center of Iquira and Teruel, north of Gigante); Caquetá (west of El Florencia, Puerto Rico, El Doncello); Meta (south central of La Uribe); Tolima (Alpujarra , Dolores, south of Roncesvalles, east of San Antonio and north of Chaparral, Venadillo, Alvarado, Líbano); Valle del Cauca (central east of Ginebra, Guacarí, west of Sevilla); Valle del Cauca (eastern part of Dagua and Buenaventura); Quindío (La Tebaida); Cundinamarca (Pacho, Vergara, El Peñón); Risaralda (Quinchía, Apía, Guatipa); Caldas (Aguadas, Ancerma); Antioquia (Jericó, Támesis, Santa Barbara, west of Buritica, center of Ituango, Betulia, east of Turbo); Cordoba (east of Tierralta); Bolivar (Morales), Norte de Santander (west of El Carmen, Toledo); Santander (El Playón, Bucaramanga, Lebrija); Casanare (Sácama and north west of Tacama); Boyacá (Socotá, Labranzagrande, Mongua); Magdalena (east of Santa Marta).

(2) High elevation climates (lower temperatures): Huila (east of Algeciras); Nariño (south of El Tablón); Putumayo (north of Colon); Cauca (north of Balboa and Argelia, east of La Sierra, central of Timbío, central eastern of Jambaló, Toribío and Corinto, north western and east of Paez, west of Suarez); Valle del Cauca (east of Praderas); Tolima (central of Planadas and Villa Rica); Antioquia (Andes, Cañasgordas, Liborina, Sabanalarga, San Vicente); Boyacá (Tinjacá, Moniquirá, San José de Pare, north of Chiscas); Santander (north east of Puente Nacional, central east of Carcasi, north of Piedecuesta); Norte de Santander (center of Cucutilla and Arboledas, south of Abrego, north of Villa Caro); Córdoba (east of Tierralta), Arauca (north of Tame); Cesar (across the Perijá range on the eastern of Chiriguaná, la Jagua de Iribico, Becerril, La Paz, Agustin Codazzi and north west of Valledupar), Guajira (east of Urumita); Magdalena (north east of Aracataca and central part of Ciénaga).