CLIMATE CHANGE PERSPECTIVES FROM THE ATLANTIC:
PAST, PRESENT AND FUTURE

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PAST VEGETATION DYNAMICS TO INFER HOLOCENE CLIMATE CHANGES IN TENERIFE AND LA GOMERA, CANARY ISLANDS

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ABSTRACT

Oceanic islands in the low latitudes, as the Canary Islands, are generally considered to have been well buffered from the climate change of the Quaternary period. However, questions remain about whether past climatic changes on Atlantic islands are synchronic with those occurring in Africa and the Mediterranean coast or if the climate remained stable during the Holocene. Here we used fossil pollen and charcoal time series on Tenerife and La Gomera in order to: 1) provide the first inter-island picture of vegetation dynamics through the last 9600 years of this important biodiverse region of Europe; 2) detect the vegetation sensitivity, mainly tree communities, to past climatic changes; and, 3) provide evidences for human-induced changes at this potentially highly informative point. Preliminary analyses suggest very little climate change for the period 4000 years to present, but this requires confirmation by reference to additional coring sites. In La Gomera, we found strong evidences of a shift towards drier conditions at around 5500 years ago. The general vegetation pattern observed was a decrease in hygrophilous trees (Canarian palm and willow) and an expansion of *Morella-Erica* woody heath. Our results provide the first evidence to suggest that the general Northern Africa and Mediterranean shift towards drier conditions may be traced in the Canary Islands.

KEYWORDS: fire, island ecology, key species, palaeoecology, palaeoclimate, pollen fossil.

INTRODUCTION

Currently, a high number of environmental assessments (e.g. Millennium Ecosystem Assessment, 2003; IPCC report, 2007) have been highlighting the importance of understanding the sensitivity of vegetation to changes in the environment. In this context, oceanic islands are of particular interest as some of them (mainly small islands) have been identified as vulnerable to the adverse impacts of climate change (e.g. Pacific Islands) (Mimura *et al.*, 2007).

In general, islands offer the opportunity to detect major past climatic changes, without accounting for anthropogenic impacts as they are considered to be among the latest regions which have been colonized by humans. For instance, according to palaeoclimatic results, high-latitude islands (e.g. Arctic islands) have been the most affected by climatic oscillations while low-latitude oceanic islands (e.g. Eastern Island, Galápagos) have been considered well buffered from past climate changes. This is being challenged by fossil pollen time-series in tropical and subtropical islands which have shown evidences of the effects of past global climate changes upon the local (isolated) vegetation (Whittaker and Fernández-Palacios, 2007).

The Macaronesian archipelagos (Azores, Madeira, Selvagens, Canary Islands, and Cape Verde) stand out as an interesting biogeographical region to study the climatic history and vegetation sensitivity to the changing environment. In the Canary Islands, palaeoecological reconstructions based on pollen fossil are scarce (but see de Nascimento *et al.*, 2009; Nogué *et al.*, 2013) in comparison to the nearby continental regions (Carrión *et al.*, 2010 and references therein). This is because the limited availability of sites, mainly due to the volcanic nature of the sediments and the lack of permanent water bodies. Moreover, eastern islands (Lanzarote, Fuerteventura, and Gran Canaria) have been more frequently studied than the western islands (Tenerife, La Gomera, La Palma, and El Hierro) thanks to the existence of Quaternary deposits with good profiles for fossil and sediment analysis (Damnati, 1996; Lomoschitz *et al.*, 2002; Meco *et al.*, 2010; Suchodoletz *et al.*, 2010; Yanes *et al.*, 2011).

Main plant communities in the Canaries are distributed along an altitudinal gradient associated with different climatic zones (Fernández-Palacios and de Nicolás, 1995; del Arco *et al.*, 2010). Vegetation units from coast to peak are: coastal shrubland, thermophilous woodland, evergreen laurel forest, pine forest and summit scrub. Depending on the island elevation and aspect (windward and leeward) some communities might be absent. The incidence of trade winds, on those windward slopes which are high enough for cloud banks formation (usually around 800–1500 m above sea level – a.s.l.), is considered to be a key element for the existence of the evergreen laurel forest (Höllermann, 1981; Ritter *et al.*, 2009). Therefore, changes in distribution and intensity of the cloud belt due to future changes in climate may compromise the future of the laurel forest (Sperling *et al.*, 2004; Martín *et al.*, 2012).

In this study we reviewed the fossil pollen and microscopic charcoal of two sites in La Gomera and Tenerife, to determine the long-term vegetation and fire history of western Canary Islands. We also analyse the sensitivity of four key taxa from different Canarian forests: hygrophilous (*Phoenix canariensis* and *Salix canariensis*), *Carpinus*, *Quercus*, and the *Morella-Erica* heath (*Morella faya* and *Erica sp.*). We aim to provide the first inter-island review of the past vegetation dynamics and climatic history of this important biodiverse region of Europe and to detect the vegetation sensitivity, mainly tree communities, to past climatic changes.

MATERIAL AND METHODS

Two former lagoons in the Canary Islands

In this chapter, we describe the results of two former lakes in the Islands of Tenerife and La Gomera (Table 1).

TABLE 1. INFORMATION OF THE MAIN CHARACTERISTICS OF THE STUDIED SITES.

	LA LAGUNA	LAGUNA GRANDE
Island	Tenerife	La Gomera
Coordinates	28˚ 29´ N, 16˚ 19´ W	28° 07´ N, 17° 15´ W
Height (m a.s.l.)	560	1250
Mean annual precipitation (mm)	550	650
Mean annual temperature (ºC)	16	13.5
Main vegetation type	Cultivated lands	*Morella-Erica* woody heath with *Ilex canariensis*
Maximum age (cal. years BP)	4700	9600
Number of zones (zonation method)	3	2
Significant vegetation transitions (cal. years BP)	2900; 2000	5500
Reference	de Nascimento *et al.*, 2009	Nogué *et al.*, 2013

The former lagoon of La Laguna (Fig.1), in Tenerife (28˚ 29´ N, 16˚ 19´ W; 560 m a.s.l.) was mapped by Torriani in the XVI century and was calculated to cover a surface 27 ha (Criado, 2002). The mean annual precipitation is about 550 mm and the mean annual temperature is 16º C. Due to intensive land use over the last centuries the vegetation of the basin is largely agricultural being the monteverde from the Anaga massif, at 3 km to the northeast, the closest natural forest. This forest is mainly composed by *Morella-Erica* woody heath; although some well-preserved stands of laurel forest are also present (del Arco *et al.*, 2006).

Laguna Grande (28° 07´ N, 17° 15´ W; 1250 m a.s.l.), located in the National Park of Garajonay in La Gomera (Fig. 1), is originated in the basin of an old crater with a total surface of 3 ha (Rodríguez-Rodríguez *et al.*, 2009). Mean annual precipitation is 625 mm, although it can be doubled by water condensation, and mean annual temperature is 13.5º C (Marzol and Sánchez, 2009). Its position in the upper boundary of the sea cloud belt determines the presence of different forest types around the basin. Above 1300 m a.s.l. the forest is dominated by *Morella faya* typically found in cooler summit and surpassing towards southern slopes where the effect of trade winds stops during the summer. Below this altitude on windward humid slopes is located the laurel forest where the most common trees are Lauraceae species (del Arco *et al.*, 2006). Laguna Grande was used in the past as a crossroads and there is no evidence of agricultural uses in the area (Navarro, 2009).

Both lagoons are nowadays subjected to temporal flooding during rainy season, although La Laguna was artificially channelled 240 years ago (Table 1).

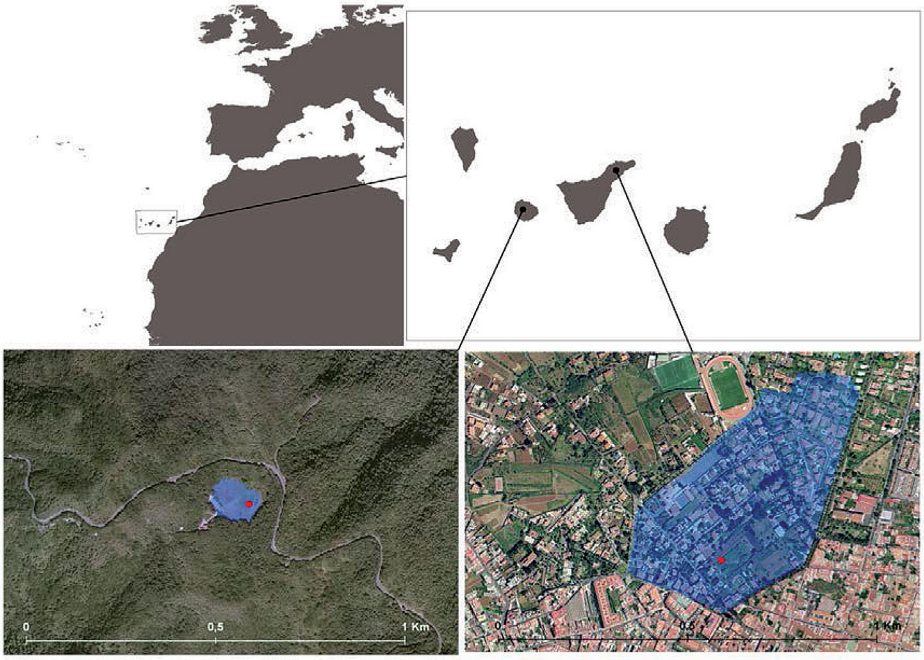

Figure 1. Study sites

PALAEOECOLOGICAL METHODS

The sedimentary sequences were taken using a modified Livingstone piston corer and wireline drilling technology and transported and stored at the Long-term Ecology Laboratory at the University of Oxford (UK), and the «Instituto Universitario de Enfermedades Tropicales y Salud Pública de Canarias» at the University of La Laguna (Spain). To reconstruct the vegetation dynamics of both sequences we followed the standard procedure, involving sub-sampling and processing the samples (Bennett and Willis, 2001). We then, identified pollen and spores using Reille (1992; 1995; 1998) and the reference collection of the Long-term Ecology Laboratory. We also reconstructed regional fire through the measurement of micro-charcoal (<150 µm; cm^2/cm^3) following standard procedures (Clark, 1982; Whitlock and Larsen, 2001). Three and six samples from La Laguna and Laguna Grande respectively, were dated using ^{14}C Accelerator Mass Spectrometry carried out at different laboratories.

In this chapter we summarized the pollen time-series for four key taxa: hygrophilous (*Phoenix canariensis* and *Salix canariensis*), *Carpinus*, *Quercus*, and the *Morella-Erica* heath (*Morella faya* and *Erica sp.*). Details of other vegetation types and the depth-age model can be found in de Nascimento *et al.* (2009), and Nogué *et al.* (2013).

MULTIVARIATE ECOLOGICAL METHODS

Results from the pollen percentage data and zonation analyses, through numerical zonation of the pollen data using optimal splitting based on information content (Bennett *et al.,* 1996), were described by de Nascimento *et al.* (2009) and Nogué *et al.* (2013). In this chapter we use these zones (Phase 1, 2, 3, and 4) and the significant vegetation transitions (I, II, III) for further analyses (Table 1, Fig. 2). We followed the methodology applied by Nogué *et al.* (2013) in La Gomera, for the Tenerife pollen data. Thus, we interpolated pollen data from La Laguna sequence at a constant time-step of 20 years and opened a time window of 200 years before and after the previously identified vegetation transition (II, III) (de Nascimento *et al.*, 2009). A window of this size should be large enough to detect any significant response to climate and fire events. Significant changes in vegetation composition and abundance of taxa in this time-window were quantified using one-way permutational ANOVA (Anderson *et al.*, 2008) obtaining a *Pseudo-F* from Bray-Curtis distances and a *P*-value from a Monte Carlo test using 9999 permutations. Similarity percentages procedure (SIMPER) was used to determine the dissimilarity before and after each vegetation transition and to identify those taxa that contributed to the dissimilarity. PRIMER 6 with PERMANOVA+ software was used to perform both analyses. For more details see Nogué *et al.* (2013).

RESULTS

WHAT THE FOSSIL POLLEN DATA EXPLAIN: VEGETATION CHANGES OVER THE LAST 9600 YEARS

The long-term vegetation data presented here represented the pollen data from La Laguna Grande (La Gomera) which expanded the last 9600 years and from La Laguna (Tenerife) which covers the last 4700 years. Thus the results of the first 4900 cal. years BP (9600 to 4700) are inferred from La Gomera data alone.

In Phase 1 (9600 to 5500) hygrophilous taxa predominated (*Phoenix canariensis* and *Salix canariensis*) although decreasing towards the end of the zone. On the contrary, low values for *Morella-Erica* heath can be observed at the beginning of the sequence, followed by an increasing trend at the end of the zone (Fig. 2a). Thus, a shift from evergreen forest with presence of hygrophilous trees to an evergreen forest with *Morella faya* and *Erica sp.* occurred around 5500 years ago. During this phase there were no evidences of intense fire occurring in Garajonay (Fig. 2c). The period from 5500 to 2900 cal. years BP (Phase 2) was a flourishing

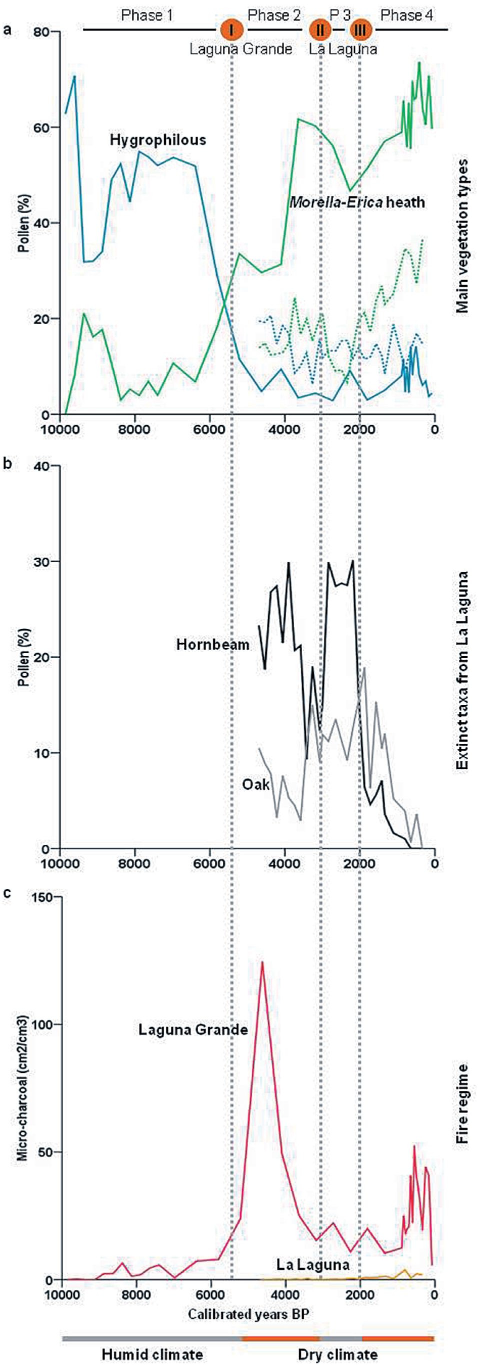

Figure 2. Pollen percentages for selected vegetation types for Laguna Grande (La Gomera) and La Laguna (Tenerife). a) *Morella-Erica* heath (green lines) and hygrophilous taxa (blue lines) for Laguna Grande (solid lines) and La Laguna (dotted lines); b) *Carpinus* (black line) and *Quercus* (grey line) for La Laguna; c) Micro-charcoal concentration (cm^2/cm^3) for Laguna Grande (red line) and La Laguna (orange line). Vertical dotted lines indicate vegetation transitions I, II, and III.

stage for the *Morella-Erica* heath in both sites although displaying different abundances. While in Laguna Grande (La Gomera) *Erica* sp. is very abundant, in La Laguna, the most abundant taxa are *Quercus* and *Carpinus* (taxa absent in Laguna Grande). Moreover, *Carpinus* experienced a decrease at the end of the zone and *Quercus* an increase (Fig. 2b). At the same time, hygrophilous taxa showed the minimum abundance of the entire sequence in both sites (Fig. 2a). There was a low micro-charcoal concentration for both islands with the exception of a peak in La Gomera, at 4800 cal. years BP (Fig. 2c). The next phase (Phase 3; 2900–2000 cal. years BP) is a transition zone where the *Morella-Erica* heath decreased while hygrophilous experienced a small increase (Fig. 2a). In La Laguna, *Carpinus* increased and *Quercus* remained constant (Fig. 2b). Microfossil charcoal remained low during all this phase (Fig. 2c). Finally, the last phase (Phase 4; 2000 cal. years BP to present) was characterized by a steep decrease of *Carpinus* and *Quercus* and an increase in *Morella-Erica* heath (Fig. 2a, 2b). During this period there is a noteworthy increase in micro-charcoal concentration in La Laguna sequence (Fig. 2c).

VEGETATION TRANSITIONS AND VEGETATION SENSITIVITY

In previous publications (de Nascimento *et al.*, 2009; Nogué *et al.*, 2013), three significant vegetation transition boundaries were identified. One in Laguna Grande (La Gomera) at 5500 cal. years BP (I), and two in La Laguna (Tenerife) at 2900 (II) and 2000 (III) cal. years BP, respectively (Table 1).

In La Laguna, the average dissimilarity for the vegetation transition II (2900 cal. years BP), is 15% (*Pseudo-F* = 18, *P* (MC) < 0.01). The vegetation differentiation was driven primarily by an increase of *Carpinus* (21.11%), *Quercus* (2.25%), and *Salix canariensis* (6.13%) and a decrease of *Morella faya* (8.73%) and *Phoenix canariensis* (5.73%) (Table 2). The average dissimilarity for the vegetation transition III (2000 cal. years BP) for La Laguna showed a significant average dissimilarity for +/- 200 years of 21% (*Pseudo-F* = 42, *P* (MC) < 0.01). Vegetation differentiation either side of the boundary was driven mainly by a decrease in *Carpinus* (24.19%) and an increase of *Quercus* (5.98%) and *Morella faya* (9.20%) (Table 2). See Nogué *et al.* (2013) and Table 2 for SIMPER results for La Gomera.

DISCUSSION

INTER-ISLAND VEGETATION DYNAMICS THROUGH THE LAST 9600 YEARS: TRACKING CLIMATE AND HUMAN CHANGES

Although traditionally, the oceanic islands have been considered well-buffered from past climate changes (Whittaker and Fernández-Palacios, 2007), recent data for the Canary Islands indicates a synchronicity with the palaeoclimate

TABLE 2. SIMPER RESULTS (PERCENTAGE OF CONTRIBUTION) FOR A TIME WINDOW OF +/- 200 YEARS EITHER SITE OF THE VEGETATION TRANSITION (5500, 2900 AND 2000 CAL. YEAS BP) FOR SIX TAXA. PERMANOVA PSEUDO-F VALUES, SIGNIFICANCE AND PERCENTAGE OF DISSIMILARITY ARE GIVEN. ARROWS SHOW THE DIRECTION OF CHANGE FROM THE SIMPER ANALYSIS. *DATA FROM NOGUÉ ET AL. (2013), **P (MC) < 0.01.

Taxa	I Laguna Grande*		II La Laguna		III La Laguna	
Carpinus	-	-	21.00	†	21.19	†
Erica	11.30	†	-	-	-	-
Morella faya	5.57	†	8.73	†	9.20	†
Phoenix canariensis	20.98	†	5.73	†	1.41	†
Quercus	-	-	2.25	†	5.98	†
Salix canariensis	-	-	6.13	↑	-	-
	(*Pseudo F*=75.2)** 15%		(*Pseudo F*=18.0)** 15%		(*Pseudo F*=42.2)** 21%	

of North Africa (Meco *et al.*, 2002; Ortiz *et al.*, 2006; Meco *et al.*, 2010; Suchodoletz *et al.*, 2010; Yanes *et al.*, 2011). These results suggest a more complex climatic frame, where not only the position of the islands (close to the African continent), but also the topography complexity may have played an important role to detect past climate changes. For instance, within Macaronesia, the Canary Islands display a significant elevation gradient which encompasses high ecosystem diversity (Fernández-Palacios and de Nicolás, 1995; Whittaker *et al.*, 2008).

In this context, in the eastern islands, it has been described frequent and abrupt transitions between humid and arid conditions during the last glacial-interglacial cycle. These humid/arid phases are thought to reflect changes in the strength of palaeomonsoon activity in North Africa, the enhancement in westerly cyclonic activity, and/or variations in sea surface and air temperatures (Ortiz *et al.*, 2006; Suchodoletz *et al.*, 2010). In a smaller time frame, our results also suggest a climatic-induced shift towards drier conditions, in La Gomera (Nogué *et al.*, 2013). Starting 9600 years ago, the landscape around Laguna Grande (1250 m a.s.l.) was dominated by monteverde forest complemented with high abundance of *Salix canariensis* and *Phoenix canariensis*. The latter, considered hygrophilous species indicative of wet conditions or permanently flooded lake. This landscape dramatically changed with a sharp vegetation transition 5500 years ago where the hygrophilous species displayed a decreasing trend and the *Morella-Erica* heath expanded. Another indication of a climatic shift is the increase in regional burning (micro-charcoal) at 4800 years ago.

These results indicate that the climate could have been very similar to that obtained in Northern Africa (Hooghiemstra *et al.*, 1992; deMenocal *et al.*, 2000; Kröpelin *et al.*, 2008) where it was suggested a shift from humid to a drier climate (e.g. end of the African Humid Period). For instance, pollen records and variation in water levels from different lakes covering the African Humid Period in Northern Africa have shown a progressive desiccation of the region during the Holocene (Damnati, 2000; deMenocal *et al.*, 2000; Kröpelin *et al.*, 2008). Thus, at the beginning of the African Humid Period, the Sahara was vegetated with a combination of trees and shrubs and tropical species adapted to humid conditions with no current modern analogue (Watrin *et al.*, 2009). Towards the end of the period (between 7000–5000 years ago) a «desert» state covered the area. Our pollen data clearly showed a climatic signal in both islands, although in La Laguna, the vegetation shift occurs later in time (approximately 2900 years ago). We interpret this delay, as the influence of different environmental conditions including climate, local vegetation composition, and topography (Table 1). Moreover, in La Laguna, during the period 2900 to 2000 cal. years ago, there is an increase of hygrophilous taxa which suggest a deviation from the general climatic trend (drier climate) described in many Mediterranean and Northern African regions. Here, the constant influence of humidity potentially brought by the trade winds may be the reason for this trend, whereas the vegetation in Laguna Grande (700 m higher) was in the upper limit of the sea cloud influence, there climate appears to be more sensitive to major global trends.

According to archaeological studies, the first human settlement occurred approximately 3000–2500 years ago by pastoralists of full Neolithic culture, who brought with them goats, sheep and pigs (Rando *et al.*, 1999) and have triggered the extinction of several animal species (Bocherens *et al.*, 2006; Rando and Alcover, 2008). It is unclear how many influxes occurred after initial settlement and prior to the Hispanic contact in the 15th Century. Thus, from approximately 2500 cal. year BP to present, potential climatic changes cannot be interpreted from the pollen record without taking into account the role of human impacts.

What it was unknown until de Nascimento *et al.* (2009) and Nogué *et al.* (2013) was the extent of the human impact on vegetation. While in Garajonay forests, we have not found strong human impacts, in La Laguna, there are several evidences of this impact. First, the former presence of two taxa, *Quercus* and *Carpinus*, which likely formed a dominant part of the lost woodland zone totally disappearing by 700 cal. years BP. Second, a substantial increase in charcoal approximately 2000 years ago is coinciding approximately in time with the first wave of human colonization 2000 cal. years BP. From a climatic perspective, the relevance of the presence of *Quercus* and *Carpinus* is difficult to interpret.

VEGETATION SENSITIVITY TO PAST CLIMATIC CHANGES

Understanding the feedbacks associated with this climatic transition is an active area of research and the SIMPER analysis might provide a comprehensive scenario of how different species might rapidly respond to climate and human impacts.

There is not a definitive future climatic prediction for the Canaries (but see Sperling *et al.*, 2004; Martín *et al.* 2012), but what it is recognized is a climate-related zonation of vegetation types. Thus, if climate changes significantly, vegetation responses are likely to follow. One of the main contributions of this analysis is identifying which species are more sensitive to changes in climate. Our results show that the decline of humidity (e.g. 5500 cal. years ago) was followed by a decrease of *Phoenix canariensis*, and an increase of *Morella-Erica* heath. On the other hand, a potential increase of humidity (e.g. 2900 cal. years BP) is followed by a decrease of *Morella-Erica* heath and an increase in pollen grains of *Carpinus*, *Quercus,* and *Salix canariensis. Phoenix canariensis* is a hygrophilous species but also a thermophilous element, thus a decrease of this species under humid conditions, as occurred in the transition II in La Laguna, is also pointing to some temperature cooling. For the last vegetation transition occurring 2000 cal. years BP the role of human impact on the vegetation prevents us to link any change solely to natural forcing

Based on this, it is clear that future changes in climate are likely to affect the species compositions. In general, there are two possible scenarios associated with the expected increase in temperature (IPCC, 2007): 1) increase in humidity, and 2) a drying trend. If humidity conditions prevail, taxa sensitive to moisture-balance variability would be expected to have a rapid response. If this is the case, our results suggest that *Phoenix canariensis* and *Salix canariensis* will expand. On the other hand, if drier conditions become established our results indicate that an increase of the *Morella-Erica* heath may be expected.

CONCLUSIONS

These two long-term vegetation sequences have provided the first opportunity to compare and describe a general climatic pattern for the western Canary Islands Holocene. Although the sites are located in different elevations and surrounded by different vegetation types, we conclude that:

1) There are no strong evidences of human impact in Garajonay forests. On the contrary, La Laguna study revealed the extent to which prehistoric human impact has altered the natural vegetation of Tenerife (de Nascimento *et al.*, 2009). Thus, we suggest that high elevation forests may be the last areas settled by humans (Nogué *et al.*, 2013) owing to their preference of certain habitats, climatic condition, and vegetation structure.
2) The absence of human impact signal in La Gomera, allows us to suggest that global climate changes (e.g. the end of the African Humid period) may be traced in the Canaries (Nogué *et al.*, 2013). Moreover, there is a general trend in both islands: an increase of *Morella-Erica* heath and a decrease of hygrophilous species, suggesting the establishment of drier conditions at approximately 5500 cal. years BP (Fig. 2a).

3) One of the main contributions of this analysis is the identification of sensitive taxa to changes in climate. *Phoenix canariensis* and *Salix canariensis* stand out as the most sensitive taxa to a drier climate while *Erica* and *Morella* are favoured by these climatic conditions.
4) A practical conclusion is that high elevation areas, as Laguna Grande (1250 m a.s.l.) in La Gomera, are one of the best palaeoecological sites to detect the effect of major global climatic events in oceanic islands. On the other hand, the consequences of past climatic changes at lower elevations might be hidden by the buffering effect of the Ocean.

This chapter provides an example of how palaeoecological results in the Canary Islands offer a wonderful opportunity to study past climate changes, vegetation transitions, and extinctions not only local but at a regional scale. Future work will focus on new sites in order to better understand the vegetation changes in this archipelago.

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