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Interactive comment on "Analysis and definition of potential new areas for viticulture in the Azores (Portugal)" *by* J. Madruga et al.

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Dear referee, thank you by your pertinent comments.

Besides the minor corrections that have been included, we believe that we have answer to your specific comments and substantive questions, namely:

1) We have performed the traditional Winkler scale index and "our" local scale index, both to the same period of April_October; Figures of both spatial distributions have been included;

2) We have included an ilustrative climatic-diagram in order to have some quantitative information about the climatic conditions of the litoral of the Islands, including precipi-

tation, temperature and water balances;

3) We have included as suplementary material (under consideration of the referees) two more indexes: Cool night index proposed by Tonieto and Carbonneau and growing season accumulated precipitation.

4) We have improved and expanded all the text and the results, including pertinent references, and some considerations about wine characteristics of these new potential zones for wine production in Azores.

So, as the comments from other referee intersect in some cases with yours, and we had to alter the structure of the text in order to accomodate the sugestions from both, I will submit below the full text and the new imagery.

*********************************** Abstract.

Vineyards in the Azores have been traditionally settled on lava field "terroirs" but the practical limitations of mechanization and high demand on man labor imposed by the typical micro parcel structure of these vineyards contradict the sustainability of these areas for wine production, except under government policies of heavy financial support. Besides the traditional vineyards there are significant areas in some of the islands whose soils, climate and physiographic characteristics suggest a potential for wine production that deserves to be object of an assessment, with a view to the development of new vineyard areas offering conditions for a better management and sustainability.

The landscape zoning approach for the present study was based in a Geographic Information System (GIS) analysis incorporating factors related to climate, topography and soils. Three thermal intervals referred to climate maturity groups were defined and combined with a single slope interval of 0–15% to exclude the landscape units above this limit. Over this resulting composite grid, the soils were than selectively cartographed through the exclusion of the soil units not fulfilling the suitability criteria.

The results show that the thermal interval of warmer conditions, well represented in

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the traditional “terroir” of Pico island, has practically no expression in the other islands. However, for the intermediate and the cooler classes, we could map areas of 5611 and 18115 ha respectively, fulfilling the defined soils and slope criteria, indicating thus the existence of some landscapes in the studied islands revealing adequate potential for future development of viticulture, although certainly demanding a good judgment on the better grape varieties to be adapted to those climatic conditions.

1 Introduction

Under the holistic concept of “terroir”, which deals with the influence of environmental factors on vine behavior and grape ripening, climate is recognized as the factor that exerts one of the most significant effect on the ability of a region to produce quality grapes (Jones, 2006).

It is also well accepted that geology and the particular soil conditions are of great importance in defining the characteristics and qualities of the wine as the final product (Mackenzie, 2005), in spite of the recognized difficulty of establishing and interpreting this relationship clearly.

Moreover, although it is known that the vine is adaptable to a wide diversity of soil types, it appears also that many of the world’s most famous vineyards are installed in poor, shallow or rocky terrain (Leeuween and Seguin, 2006) where no other crop would be grown in favorable conditions. Such is the case, almost extreme, of the vines implanted in the lands of “biscoito” and “lagido”, the traditional names in the archipelago of the Azores to the cracked surfaces of basaltic lava fields of heterogeneous size ranging from gravel to blocks, an harsh environment for all forms of agriculture except for grape vines where the plants still manage to survive and produce. This is mostly expressed in the landscape of the Pico island vineyard culture, recently classified as a UNESCO World Heritage Site (987 ha).

Due to the financial support measures implemented by the regional government of the Azores, the maintenance and recovery of abandoned areas of traditional vineyards within the limits of the classified area recently have gained a renewed interest by the land owners and wine producers. However, outside of these limits, there are vast areas with similar conditions where the ancient vineyards are abandoned since long time without any perspective of recovery, being presently colonized by invasive trees and shrubs species, predominantly the Pittosporum undulatum Vent. In fact, the practical limitations of mechanization and high demand on man labor imposed by the micro parcel structure of the vineyards aggravated by the absence of financial subsidies outside of the classified area make it impossible to admit the recovery of these areas for the wine production in present times.

Besides Pico island, where the costal landscape is dominated by lava fields of abandoned vineyards with the exception of the classified area, a few small spots also exist in some of the other islands of the archipelago, where in most cases the production has been partially abandoned as well.

Apart from this traditional Azorean model of "terroir" of recognized cultural value and where a few interesting wines have been produced, there are significant areas in some of the islands whose soils, climate and physiographic characteristics suggest a potential for wine production that deserves to be object of an assessment, with a view to the development of new vineyard areas offering conditions for a better management and sustainability. We refer specifically to landscape units of the lower area of some islands, in many cases presently devoted to pasture where productivity tends to be marginal because strongly affected by water stress during the summer. Such areas, presenting gentle to moderate slopes and providing conditions to the mechanization of farming operations, comprise some well drained soils of the Andisol Order (Soil Survey Staff, 2014).

In this preliminary study climatic, pedological and topographical characteristics of the landscape are considered based on GIS tools, in order to define the distribution of the most representative landscape units with the greatest apparent potential for wine production in some islands of the Azores. It is not our objective to produce a detailed cartographic definition of vineyard suitability classes but rather to establish some basic criteria for prediction and identification of new areas from which representative sites can be depicted for experimental studies in a subsequent phase.

2 Data and methodology

The landscape zoning approach for the present study was based on a Geographic Information System (GIS) analysis incorporating factors of climate and topography which was then combined with the soil mapping units fulfilling the suitable criteria concerning the soil properties taken as the most relevant for viticulture (Van Leeuwen et al., 2004; Deloire et al., 2005; Jones et al., 2006; Dutt et al., 1985).

In this work, the spatial climatic differentiation for viticulture is based on climate/maturity classes defined from the sum of the daily average temperatures that exceeds a base temperature of 10° C along the growing season, as expressed in growing degree-days (GrDDs) concept and representing the potential for the region to ripen given varieties based upon heat accumulation.

A first cartographic approach has been done using the full Winkler scale (Amerine and Winkler, 1944; Winkler et al., 1974; Fraga et al., 2013) for the traditional April-October period allowing for comparisons with other wine regions of the northern hemisphere (Fig. 1). However, those results when compared with the cartography of the geographic distribution of the traditional vineyards of the Azores Islands (Madruga et al., 2011), denoted an evident lack of resolution for the representation of such specific conditions observed at the lower altitudes of these small territories. From this evidence, the present work is based in only three thermal classes defined however for the same period as the Winkler index, April to October.

For the establishment of these three classes, the thermal conditions found in the traditional vineyards mainly of Pico and Terceira islands, were taken as the baseline reference and from those the accumulating growing degree-days were defined in the following intervals: I:1600-1800; II:1800-2000; III:2000-2200. These temperature intervals for the classes being narrower than those defined in the Winkler criteria, allow for a better discrimination of the thermal variability within short distances as it occurs in the Azores islands where cloudiness and humidity degree can show significant differences in relatively short distances affecting local energy balance, being the altitude the factor that mostly defines its differentiation.

The three thermal intervals referred to climate maturity groups were combined with a single slope interval of 0–15% to exclude the landscape units above this limit. The resulting composite grid for each island was finally combined with the respective soil map to incorporate the cartographic units of Hapludands and Udivitrands great groups, whose average parameters of drainage, water holding capacity, depth to bedrock and pH fall within the adequacy limits for grapevine growth and production.

2.1 Climate

The Azores Archipelago, located in the middle of the Atlantic Ocean basin, north of the predominant influence of the trade winds and on the influence of the subtropical high-pressure belt, sits in an area of transition and confrontation between air masses from the tropics and colder air masses coming from north. Sufficiently far apart from the continental coasts, the air masses that hit it reveal a strong increment in properties associated with their maritime route. In this geographic context, the climate of the Islands of the Azores depends, quite evidently, of their geographic setting and their relationship with the surrounding sea, but also of particular aspects that set them apart from each other. Normal climatology and sequential water balance for lower altitudes (<100m) of the Azorean Islands can be observed in Fig. 2.

A strong climatic differentiation can be observed in altitude, as well as significant climatic asymmetries inland of each island. The spatial expression of the climatic elements is related in each island to its dimension and orography, the topographical orientation, the superficial geologic structure, the top soils and the vegetation. In some cases the climate of one island is affected by the “shadow” effect from its neighboring

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islands (Azevedo, 1996).

Locally, important subscale characteristics and mechanisms have a prominent role in the climatic spatial differentiation. Advective transport of air and the consequent adiabatic cooling due to the orographic obstacle is determinant in the configuration of the temperature and humidity fields. The same mechanism is in the origin of the orographic clouds cover that, besides the reinforcement of precipitation, have an indirect but important interference on the local water balance since they act as a filter to the solar radiation and as a source of long-wave radiation to the local balance of energy. Also, the saturation (or near saturation) conditions that they provide constitute a barrier to water vapour diffusion in the mechanisms of evapotranspiration (Azevedo et al.,1998). Diversity of soils and geology, typical of volcanic environments leads to a diversification of heat capacity and heat fluxes, affecting strongly the climate of the parcels, playing a strong influence on the properties of the “terroirs”.

According to the Köppen-Geiger climate classification (Essenwanger, 2001; Peel et al. 2007), the littoral climate of the Azores Archipelago islands is included in the temperate climates category (group C), characterized by having a summer and a winter and an average temperature of the colder month below 18 °C but above −3 °C. However, the diagonal distribution of the islands across of about 700 km, leads to its climate being classified from east to west as a transition between the Cs and Cf subgroups, respectively, transitioning from temperate rainy climate with dry summer to temperate rainy climate, humid on all seasons. Still according to the same classification system, the mildness of the island’s climate can be emphasized by combining the letter b with these two codes, becoming, both of them, Csb and Cfb, meaning that the average temperature of the warmest month is, on average, below 22 °C. The oceanic characteristics are accentuated from the East to the West, with the islands of Flores and Corvo having the most oceanic properties.

The characteristic factors of each island overlaps to this regional scale climatic frame, giving them climatic specificities at local and microclimatic scales. The annual average air temperature on the coast of Pico Island (the one that presents the greatest climatic diversity of the whole archipelago of the Azores) is located around 18.0 °C, with average minima of 10.5 °C felt on February and maxima going over 26.0 °C in August. The annual average diurnal amplitude is low, around 6.0 °C.

As the altitude increases, the temperature decreases regularly; on a ratio of 0.9 °C per 100m (dry adiabatic lapse rate) until the dew point temperature is reached at an average altitude of about 600 m. From there, until the top of the islands, the temperature decreases at a lower rate (wet adiabatic lapse rate) as result of the thermal energy released by the water condensation process.

In this work CIELO model (Azevedo, 1996; Azevedo et al., 1998, 1999), acronym for "Clima Insular à Escala Local" has been used to set up spatial climatic differentiation based on climate/maturity classes.

The CIELO is a physically based model that simulates the transformations of the climatic variables in an island using data from a synoptic reference weather station or downscaling from a lower resolution climatic model. The model reproduces the thermodynamic transformations experienced by an air mass crossing the island, and simulates the evolution of the air parcel's properties starting from the sea level. The domain of computation is based on the digital elevation models of the islands (DEM).

The model consists of two main sub-models. One, relative to the advective component simulation, assumes the Foehn effect to reproduce the dynamic and thermodynamic processes. This makes possible to simulate the air temperature, air humidity, cloudiness and precipitation as influenced by the orography along its trajectory. The second concerns the radiative component as affected by the clouds of orographic origin and by the shadow produced by the relief.

The application of the CIELO model has been successful for modeling species distributions (e.g. Hortal et al., 2010; Jiménez-Valverde et al., 2009; Aranda et al., 2011; Boieiro et al., 2013; Florencio et al., 2013; Guerreiro et al., 2014) and patterns of species richness (e.g. Borges et al., 2006) in the Macaronesian Islands.

2.2 Topography

The topography influences grapevine growth and quality thru elevation, slope, exposure and morphology of the proximate landscape which may also define the occurrence of microclimatic zones (Leeuween and Seguin, 2006).

In this work the topography was analyzed based on the tridimensional models of the islands in GIS. Instead of various slope classes we considered only one global interval in the 0–15% range as the suitability limit to include the best slopes for the mechanization of the vineyard cultural operations (Jones et al., 2004).

2.3 Soils

Soils of the Azores archipelago are originated from modern volcanic materials that have evolved under humid and moderate Atlantic climate. In general they accomplish the criteria to be classified in the the Andisol Order (Soil Survey Staff, 2014).

The typical parent material of Andisols is tephra, a general term for all airborne volcanic ejecta, regardless of morphology, size, and composition, being often quite porous with a large active specific surface. It is also difficult to determine the mineralogy of tephra because of microcrystallinity and/or non-crystalline nature of the materials (Dahlgren et al., 1993).

Andisols present unique soil properties resulting from the weathering of volcanic materials and in particular of their tephra glassy products which show a very low resistance to chemical weathering, suffering a rapid evolution to the formation of large amounts of non-crystalline products, usually referred in literature as "short range-order materials" (SROM). The noncrystalline materials consist primarily of allophane, imogolite and ferryhidrite (Parfitt and Kimble, 1989). In the Azores, at the lower altitudes where climatic conditions can be marked by a dry spell in the summer, the Andisols show an evolutionary tendency to other soil categories mainly of the Inceptisol Order, especially in the more stable and older geological areas of the islands (Pinheiro, 1990). Andisols may have AC, ABC, or multisequa of these horizon sequences, as the soil environment is characterized by deposition of parent materials, gradually or repeatedly being buried under new fresh vitric materials. Vitrudands formed from thick pumice or scoria tephras show the AC profile while intermittent tephra deposition and subsequent soil formation result in the development of other Andisols with a multisequum profile (Shoji et al., 1993).

Soils of the Azores Archipelago have been studied in detail, and their characteristics and classification have been discussed in several papers (Auxtero et al., 2004; Pinheiro et al., 2004, 2001; Madeira et al., 2003, 2002, 1980; Pinheiro, 1999, 1990; Madruga, 1995; Medina and Grilo, 1981; Ricardo et al., 1977).

For the present study soils were analyzed based on data and soil map units as defined in the soil surveys of the Azores archipelago (ongoing project by the soils group of the University of the Azores). Hapludands and Udivitrands great groups were selected as the taxonomic soil categories mostly represented in the lower surfaces of the islands and where grapevine growth can be admitted. As the present study attempts to define and map landscape units in alternative to the traditional lava field based "terroir", this one was not included in the selected areas with apparent potential for viticulture in the Azores.

The soil properties taken as the most relevant for this analysis where: drainage, water holding capacity, depth to bed-rock and pH. Soil drainage, being dependent on various soil characteristics such as texture, structure depth and slope, affects crop health and management conditions.

Soil depth, not only defines the soil volume for root development and mineral nutrition as it defines and limits the available soil water capacity. Soil pH, being a regulator of chemical and biological processes, gives an indication of the potential for nutrient availability. The neutral to slightly acid reaction is the best pH condition for nutrient

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fertility and balance in the soil. However, it is well recognized that the nutritive fertility for grapevines should be only moderate, as an high nutritional condition leads to excessive vegetative growth and induces in the wine an overall lowering of the quality parameters.

Different water level in the soil affects grape quality and reflects in wine quality (Conradie et al., 2002). Andisols can retain a large amount of water primary due to their large volume of mesopores and micropores produced within the stable soil aggregates. Formation of these aggregates is greatly enhanced by noncrystalline materials and soil organic matter (Maeda et al., 1977).

High water permeability is a distinctive physical property of volcanic ash soils under both saturated and unsaturated conditions. Under unsaturated conditions, Andisols have greater hydraulic conductivity than other mineral soils such as clayed alluvial soils (Nanzyo et al., 1993). Both, Hapludands and Udivitrands of the considered areas generally present average to good drainage conditions without impeding layers. Even the finer textured Hapludands, found in the older geological areas of the islands Terceira (Pinheiro, 1999) and Graciosa (Medina and Grilo, 1981) showing an eutric character, have no drainage constrains.

In these soils the available water-holding capacity (AWC) is relatively high, varying between 0.20 and 0.25 cm3 of water per 1cm3 of soil. The Udivitrands, which predominate in the islands of S. Miguel (Ricardo et al., 1977) and Faial (Madeira et al., 2002), have in general coarse textures with significant fractions of pomice and cinders fragments from sand to gravel dimensions. Under these textural conditions the water-holding capacity may be somewhat limited. As in these soils the internal drainage is frequently very high, these combined factors may increase the risk of draught periods during the growing season and the average interval of AWC variation lowers to 0.10–0.15 cm3 of water per cubic centimeter of soil in the Udivitrands. Nevertheless, it has been observed that a certain lack of water during the ripening period is favorable to the organoleptic wine quality (Galet, 1993; Riou et al., 1994; Huglin and Schneider, 1998).

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In volcanic landscapes the profile characteristics concerning horizon sequence and thickness can be quite variable even within short distances. Depth to bed rock of the Hapludands in the selected areas averages 60 cm with no less than 40 cm and the Udivitrands are in general more than 1m deep.

The soil reaction found in the considered altitudes for both soil categories is in general slightly acid to neutral, being the pH range of 5.6 to 6.5. From a soil standpoint, high-quality wines are made from grapes grown in many different types of soils with no single type considered ideal (Wilson, 1998). Grapevines will tolerate a wide range of soils, but yield and variation in vine vigour commonly match changes in local soil properties, which in turn can influence grape characteristics (Bramley 2001, 2005; Reynolds et al. 2007). In spite of the relative variability in both physical and chemical parameters as generally described above, the soils here considered reflect an overall suitability for the viticulture expansion in the Azores.

3 Results and conclusions

In this study we attempt to define and map landscape areas with apparent potential for grapevine growing in the Azores islands of S. Miguel, Terceira, Faial and Graciosa, as an alternative to the traditional “terroir”. The lava field “terroir” was not included in the potential areas here defined because the management costs imposed by the peculiarities of these vineyards, established over a micro parcel and stony structure, deny their economical sustainability and maintenance in the Azores, except under significant government funding as it is the case of the UNESCO protected vineyard area in Pico island.

Under the specificity of the Azorean environmental conditions, white wines produced from several adapted winegrape varieties (e.g.,Verdelho, Arinto and Terrantês), which started to be introduced in the Archipelago since the fifteenth century in the advent of the colonization of the islands and probably originated from Cyprus and Madeira islands (Duarte Jr., 2001), have been more successful then red wines most probably

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due the generally lower heat demand for maturation of the white grape varieties. The more recognized and typical white wines of the Azores have been produced in the lavafield terroirs of Pico, both table and licourous wines. Biscoitos, a small village of stony volcanic cover in Terceira island, is also recognized by its white wines in spite of the reduced overall production. There are very few studies of chemical characterization of wines from the Azores. Lima et al. (2004) found that the concentrations of iron, copper manganese and zinc in Azorean wines correspond with the mean values observed for other regions in Europe. Batista et al (2001) presented a comparison study of polyphenols and aroma in red wines from Portuguese mainland versus Azores islands.

The spatial potential for viticulture of each island is presented in the maps of Fig. 3, with the area distribution depicted by climate maturity groups. The cartographic representation of these landscape areas resulted from a GIS supported spatial analysis of climate, soils and topography based on the combination of the selected criteria for each of these three factors. Three thermal classes defined as climate/maturity groupings were established from a baseline reference (vineyards area of Pico island), and then combined with the soils fulfilling the most advantageous characteristics of moderate to good drainage, adequate soil depth, fair to good water-holding capacity and near neutral pH, and being distributed within a slope interval of 0 to 15% taken as the most adequate to the vineyard cultural operations.

The calculated surfaces (ha) of the cartographic areas with potential for grapevine production, as defined for each island and thermal class are presented in Table 1. The warmer conditions of thermal class III, well represented in the traditional "terroir" of Pico island, has practically no expression in the other islands. However, for the intermediate class II and the cooler class I, we could map significant areas – 5611 and 18115 ha respectively – fulfilling the defined soils and slope criteria. These results indicate that landscape units exist across the climate maturity classes II and I of the studied islands revealing adequate potential for future development of viticulture, although cer-

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tainly demanding a good judgment on the better grape varieties to be adapted to those climatic conditions.

The defined thermal classes, based in the degree-day concept for a base temperature of 10° C (Amerine and Winkler 1944), that we used as climatic indicators for viticultural zoning in the Azores, may be broadly compared to the bioclimatic index (CatI) which incorporates the most relevant characteristics of a given region, as defined for Portugal mainland (Fraga et al, 2013). The Azores climate has been characterized as humid and the average daily temperatures in the lower areas are moderate with low thermal amplitudes and warm nights (above 14°C) along the growing season, due to the maritime regulatory influence. The littoral of the Islands covered by the three considered classes falls in the categories of "temperate nights" (September average Tmin>14°C-18°C<) and "warm nights" (September average Tmin > 18°C) as it is defined by the Cool Night Index (CI) (Tonietto and Carbonneau, 2004), Fig. S1. The Growing season accumulated precipitation varies from 400 mm to 800 mm, Figure S2. Consequently, the thermal classes I and II defined in this study can be broadly compared to the category 8 of the CatI bioclimatic index which is described as temperate, humid with warm nights, while the thermal class III would be better comparable to the category 12 which represent the warmer conditions found in the lavafield grapevines of Pico island, where average temperatures are amplified by the heat capacity of the basaltic stones where the grapevines are laying.

The present study, through the use of spatial analysis based on climate, soils and slope, conducted at an intermediate scale level, provides an overall perspective and understanding of the potential for expansion of viticulture in the Azores. Additionally, the results presented should serve as a decision support tool in the site selection process for new vineyards establishment. However, there are limitations and further issues to be addressed before developing any individual site. In fact, the resolution limits of the landscape analysis, related to elevation and slope data as well as to soils variability, request a detailed site specific assessment to be conducted prior to any final decision

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on a new vineyard establishment.

Author contributions.

E. B. Azevedo developed the climatic analysis and with F. Reis and F. Fernandes they adapted the GIS model. J. Madruga and J. Sampaio selected the background soils data and analysis. J. Pinheiro participated in soil analysis and prepared the manuscript with contributions from all co-authors. Acknowledgements. The climatic CIELO model simulations for this work were done under the framework of the project ESTRAMAR (FEDER – MAC/3/C177) from the Program MAC 2007– 2013, Transnational Cooperation.

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Table 1. Areas (ha) with potential for grapevine production for each island and thermal class.

Figure 1. Winkler scale distribution for S. Miguel, Terceira, Faial and Graciosa islands of the Azores.

Figure 2. Normal climate and a typical sequential water balance at the littoral of the Azorean Islands.

Figure 3. Composite landscape units with potential for viticulture in each island with distribution depicted by climate maturity groups.

Aditional material (if acepted!)

Figure S1 – Cool Night Index (September average minimum temperature) Figure S2 – Growing season accumulated precipitation (April-October)

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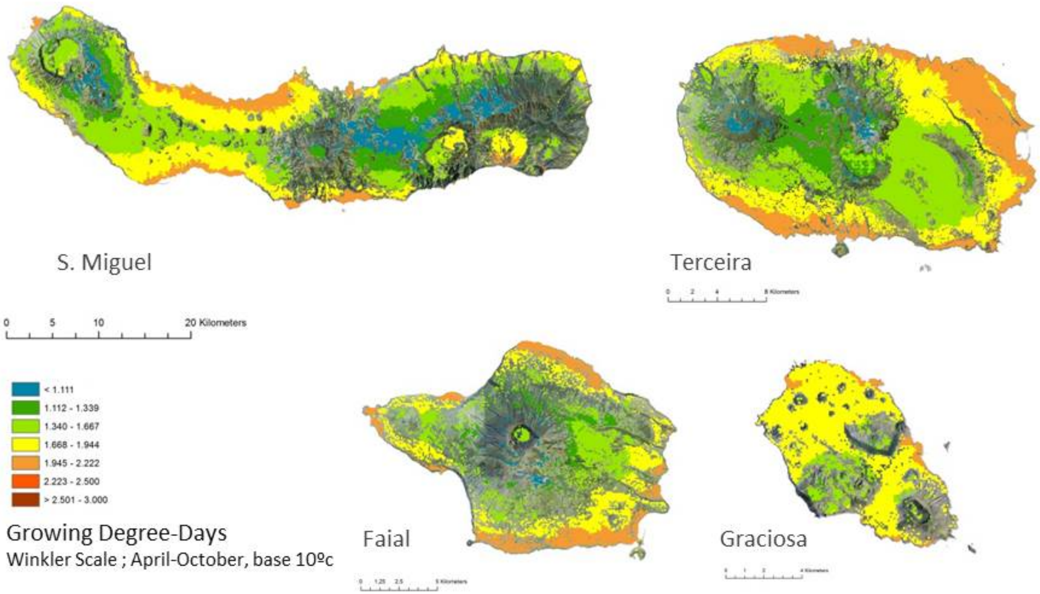

Fig. 1.

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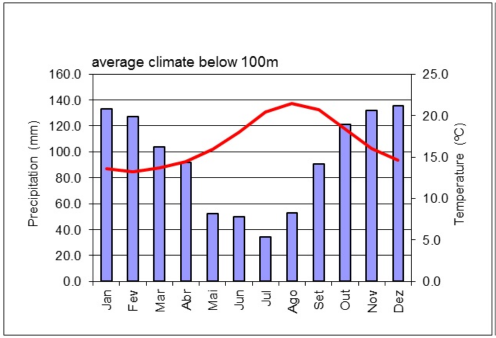

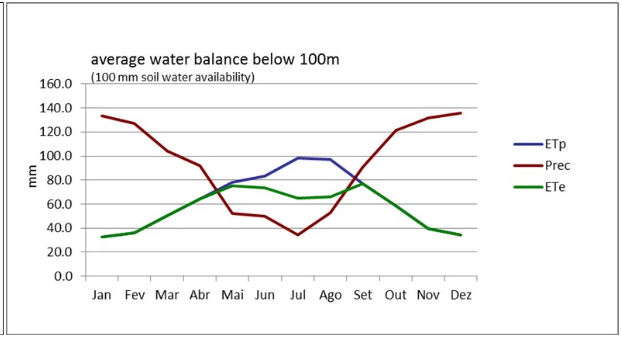

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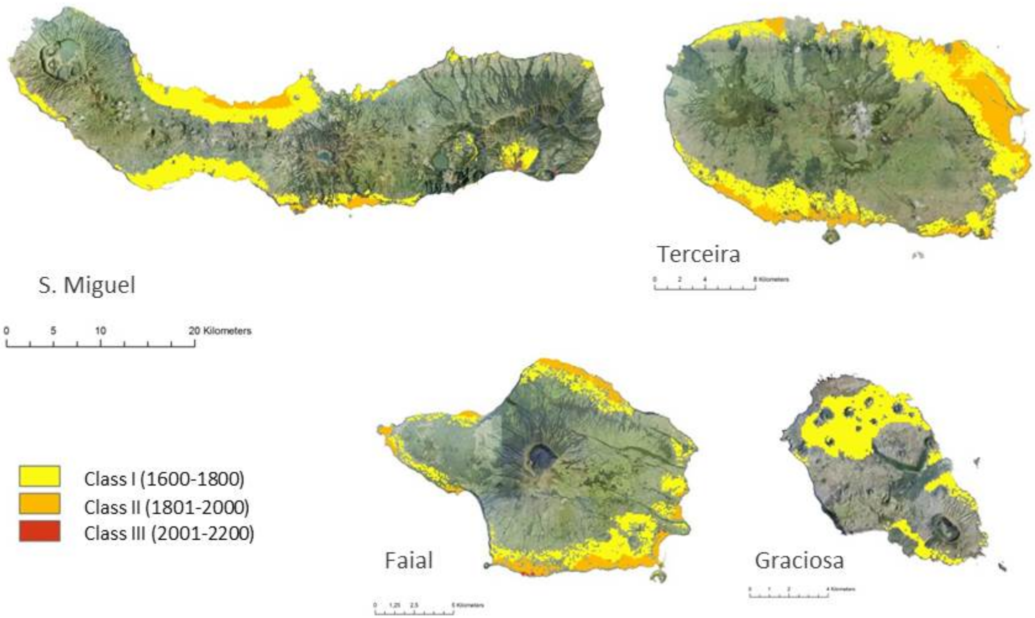

Fig. 3.

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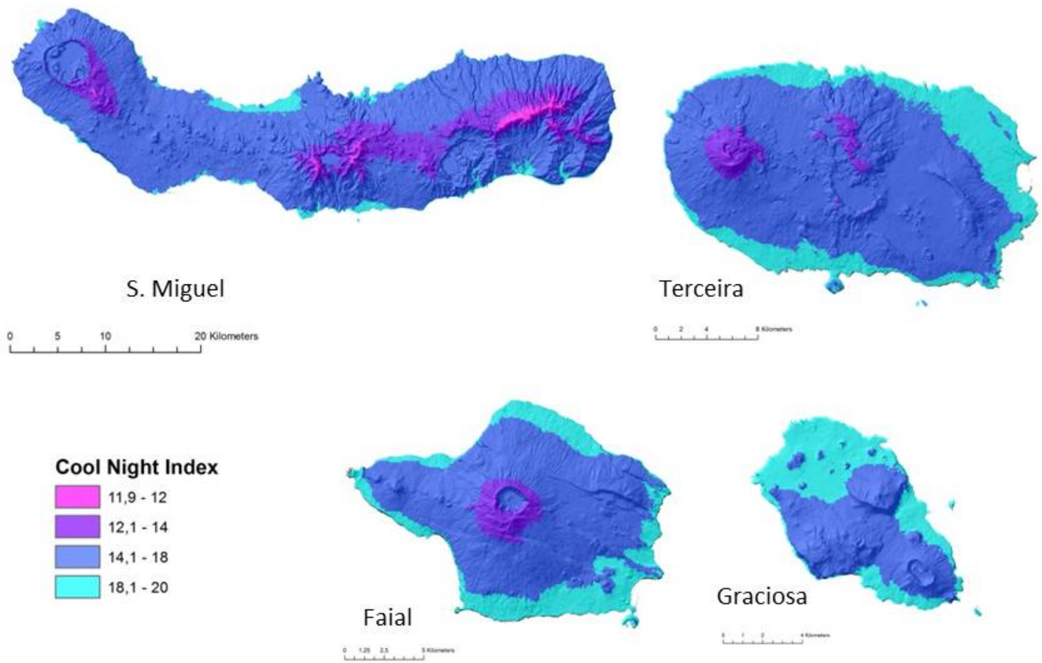

Fig. 4.

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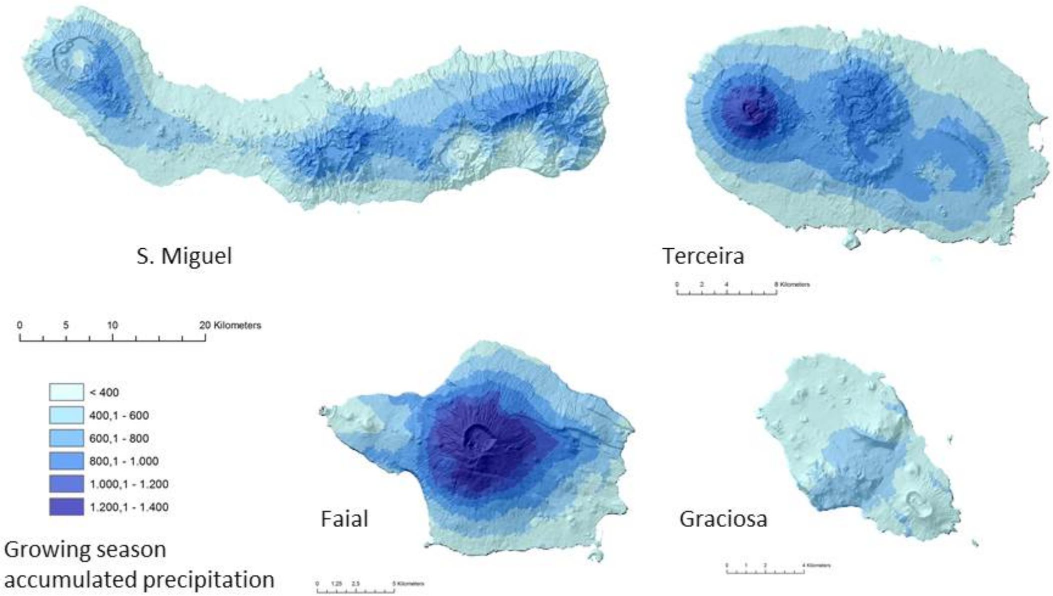

Fig. 5.

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	Area (ha)		
	climate maturity class		
Island	**I**	**II**	**III**
São Miguel	8696	1541	30
Terceira	6088	3028	0
Faial	1848	1042	13
Graciosa	1483	0	0
Total	18115	5611	43

Fig. 6.

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