

1   **Analysis and definition of potential new areas for viticulture in the Azores**  
2   **(Portugal)**

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8   **Abstract**

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

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

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

29   **1 Introduction**

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

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

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

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

53 classified area make it impossible to admit the recovery of these areas for the wine production in  
54 present times.

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

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

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

## 73 **2 Data and methodology**

74 The landscape zoning approach for the present study [is that of the so-called “natural terroir units”](#)  
75 ([Laville, 1993](#); [Priori et al, 2014](#)) and was based on a Geographic Information System (GIS) analysis  
76 incorporating factors of climate and topography which was then combined with the soil mapping units  
77 fulfilling the suitable criteria concerning the soil properties taken as the most relevant for viticulture  
78 ([Van Leeuwen et al., 2004](#); [Deloire et al., 2005](#); [Jones et al., 2006](#); [Dutt et al., 1985](#)).

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

83 A first cartographic approach has been attempted (Fig. 1) using the full Winkler scale (Amerine and  
84 Winkler, 1944; Winkler et al., 1974) for the traditional April-October Period, allowing for comparisons  
85 with other wine regions of the northern hemisphere. However, those results when compared with the  
86 cartography of the geographical distribution of the traditional vineyards of the Azores Islands  
87 ([Madruga et al., 2011](#)), denoted an evident lack of resolution. The temperature range of 278°C in  
88 each maturity grouping of the Winkler index was apparently excessive for the representation of the  
89 variability degree observed in the field at the lower altitudes of the islands where grapevines can be  
90 grown in the Azores. Additionally, in the cartographic output of Fig. 1 the lower GDD maturity  
91 groupings of the Winkler scale (cool and temperate) were represented at altitudes where the general  
92 climatic conditions other than temperature, such as relative humidity, winds and cloudiness, are  
93 globally adverse to the grapevine growth and fruit maturation.

94 From this evidences, we implemented an alternative GDD criteria based in only three thermal  
95 classes, being the temperature range of the maturity groupings narrowed to 200°C, defined however  
96 for the same April-October period as the Winkler index.

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

105 The three thermal intervals referred to climate maturity groupings were combined with a single slope  
106 interval of 0–15% to exclude the landscape units above this limit. The resulting composite grid for

107 each island was finally combined with the respective digitized soil map to select and incorporate the  
108 cartographic units of Hapludands, Udivitrands **and Eutrudepts**, whose average parameters of drainage,  
109 water holding capacity, depth to bedrock and pH, fall within the adequacy limits for grapevine growth  
110 and production, as depicted from the soil survey database and reports.

111 **2.1 Climate**

112 The Azores Archipelago, located in the middle of the Atlantic Ocean basin, north of the predominant  
113 influence of the trade winds and on the influence of the subtropical high-pressure belt, sits in an area  
114 of transition and confrontation between air masses from the tropics and colder air masses coming  
115 from North. Sufficiently far apart from the continental coasts, the air masses that hit the Azores  
116 islands reveal a strong increment in properties associated with their maritime route. In this  
117 geographic context, the climate of the Azores islands depends, quite evidently, on their geographical  
118 setting and relationship with the surrounding sea. Normal climatology and sequential water balance  
119 for the lower altitudes (<100m) of the Azorean islands is presented in Fig. 2.

120 A strong climatic differentiation can be observed in altitude, as well as significant climatic  
121 asymmetries inland of each island. The spatial expression of the climatic elements is related in each  
122 island with its dimension and orography, the topographical orientation, the superficial geologic  
123 structure, the top soils and the vegetation. In some cases the climate of one island is affected by the  
124 "shadow" effect from its neighboring islands (Azevedo, 1996).

125 Locally, important subscale characteristics and mechanisms have a prominent role in the climatic  
126 spatial differentiation. Advectional transport of air and the consequent adiabatic cooling due to the  
127 orographic obstacle is determinant in the configuration of the temperature and humidity fields. The  
128 same mechanism is in the origin of the orographic clouds generation that, besides the direct role as  
129 water source by the reinforcement of precipitation, have an indirect but important interference on the  
130 local water balance since they act like a filter to direct solar radiation and as a source of long-wave  
131 radiation affecting the local balance of energy. Also, the saturation (or near saturation) conditions that  
132 they provide constitute a barrier to water vapor diffusion in the mechanisms of evapotranspiration  
133 (Azevedo et al., 1998).

134 The annual average air temperature on the coast of Pico Island (the one that presents the greatest  
135 climatic diversity of the whole archipelago) is around 18.0 °C, with average minima of 10.5 °C in  
136 February and maxima over 26.0 °C in August. The annual average diurnal amplitude is low, around  
137 6.0 °C. As the altitude increases, the temperature decreases regularly approximately at a ratio of 0.9  
138 °C per 100m (dry adiabatic lapse rate) until the dew point temperature is reached at an average  
139 altitude of about 600m. From that point on, until the top of islands under the orographic cloud cover,  
140 the temperature decreases at a slower rate, at an average of 0.5°C per 100 meters, due to the effect  
141 of energy transfer to the atmosphere by the condensation process.

142 Particular aspects of the climate of the islands can also be explained locally by its singular geology  
143 as is the case of the unevolved lava fields in many cases traditionally occupied by vineyards. In these  
144 situations, the mild climate felt on the littoral of the islands is now a result of the conjugated effect of  
145 the ocean's proximity and the high thermal accumulation capacity of the black basalt lava flows,  
146 situation that also affects inversely the relative humidity of the air (Azevedo, 2014).

147 The wind is a constant of the Azorean climate. Throughout the year the wind blows regularly, more  
148 moderately in the summer months, and more vigorously in the winter. The wind speed increases  
149 from Islands of the Oriental Group to the ones on the Occidental Group. Generally, in winter, the  
150 syncopated evolution of the low pressure systems north of the Archipelago leads to the winds  
151 circumventing the islands by north and from the west to the east. During the summer, with the rise in  
152 latitude of the high pressure systems, the islands are besieged by winds from the southwest. The  
153 wind speed increases with altitude and as the atmospheric circulation releases itself gradually from  
154 the friction of the planetary boundary layer, all the while assuming greater regularity on its orientation.  
155 On the coast of the islands the annual average wind speed is around 17 km/h. In the winter months  
156 the average velocity approaches 20 km/h, although gusts reaching 100 km/h are felt almost every  
157 year. In the summer months, on the contrary, the wind velocity decrease to values under 10 km/h. It  
158 is also in this period that, due to the diminishing influence of the higher predominance systems, we  
159 can observe the formation of coastal breezes on the larger Islands of the Azores (Azevedo, 2014).

160

161 According to the Köppen-Geiger climate classification (Essenwanger, 2001; Peel *et al.* 2007), the  
162 littoral climate of the Azores archipelago is included in the temperate climates category (group C),  
163 characterized by having a summer and a winter and an average temperature of the colder month  
164 below 18 °C but above -3 °C. However, the diagonal distribution of the islands across **an extension** of  
165 about 700 km, leads to its climate being classified from east to west as a transition between the Cs  
166 and Cf subgroups, respectively, **evolving** from temperate rainy climate with dry summer (eastern  
167 islands) to temperate rainy climate, humid on all seasons (western islands). Still according to the  
168 same classification system, the mildness of the island's climate can be emphasized by combining the  
169 letter *b* with these two codes, becoming, both of them, Csb and Cfb, meaning that the average  
170 temperature of the warmest month is on average below 22 °C. The oceanic characteristics of the  
171 archipelago **is stressed in the western islands of Flores and Corvo where the oceanic conditions are**  
172 **mostly accentuated.**

173 In this work CIELO model (Azevedo, 1996; Azevedo *et al.*, 1998, 1999), acronym for "*Clima Insular à*  
174 *Escala Local*" has been used to set up spatial climatic differentiation based on climate/maturity  
175 classes. The CIELO is a physically based model that simulates **numerically** the transformations of the  
176 climatic variables in an island using data from a synoptic reference weather station or downscaling  
177 from a lower resolution climatic model. The model reproduces **through finite difference methods** the  
178 thermodynamic transformations experienced by an air mass crossing the island, and simulates the  
179 evolution of the air parcel's properties starting from the sea level **that justify the values observed in**  
180 **the reference weather station.** The domain of computation is based on the digital elevation models of  
181 the islands (DEM).

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

187 The CIELO model has been successfully applied for modeling species distributions (e.g. Hortal *et al.*,  
188 2010; Jiménez-Valverde *et al.*, 2009; Aranda *et al.*, 2011; Boieiro *et al.*, 2013; Florencio *et al.*, 2013;  
189 Guerreiro *et al.*, 2014) and patterns of species richness (e.g. Borges *et al.*, 2006) in the  
190 Macaronesian Islands.

## 191 **2.2 Topography**

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

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

## 199 **2.3 Soils**

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

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

207 Andisols present unique soil properties resulting from the weathering of volcanic materials and in  
208 particular of their tephra glassy products which show a very low resistance to chemical weathering,  
209 suffering a rapid evolution to the formation of large amounts of non-crystalline products, usually  
210 referred in literature as "short range-order materials" (SROM). The noncrystalline materials consist  
211 primarily of allophane, imogolite and ferrhydrite (Parfitt and Kimble, 1989). In the Azores, at the  
212 lower altitudes where climatic conditions can be marked by a dry spell in the summer, the Andisols  
213 show an evolutionary tendency to other soil categories mainly of the Inceptisol Order, especially in  
214 the more stable and older geological areas of the islands (Pinheiro, 1990). Andisols may have AC,

215 ABC, or multisequa of these horizon sequences, as the soil environment is characterized by  
216 deposition of parent materials, gradually or repeatedly being buried under new fresh vitric materials.  
217 **Vitrands** formed from thick pumice or scoria tephras show the AC profile while intermittent tephra  
218 deposition and subsequent soil formation result in the development of other Andisols with a  
219 multisequum profile (Shoji *et al.*, 1993).

220 Soils of the Azores Archipelago have been studied in detail, and their characteristics and  
221 classification have been discussed in several papers (Auxtero *et al.*, 2004; Pinheiro *et al.*, 2004,  
222 2001; Madeira *et al.*, 2003, 2002, 1980; Pinheiro, 1999, 1990; Madruga, 1995; Medina and Grilo,  
223 1981; Ricardo *et al.*, 1977).

224 For the present study soils were analyzed based on data and soil map units as defined in the soil  
225 surveys of the Azores archipelago (ongoing project by the soils group of the University of the  
226 Azores). **As presented in the maps of Figure 3, Hapludands and Udivitrands great groups of the  
227 Andisol as well as Eutrudepts (Inceptisols) (Soil Survey Staff, 2014) where the andic character is only  
228 weakly expressed, were selected as the taxonomic soil categories mostly represented in the lower  
229 surfaces of the islands and where grapevine growth can be admitted. Table 1 shows some analytical  
230 data of representative pedons of the major cartographed soil units, mostly selected as significant soil  
231 properties for viticulture. As the present study attempts to define and map landscape units in  
232 alternative to the traditional lava field based “terroir”, this one was not included in the selected areas  
233 with apparent potential for viticulture in the Azores.**

234 The soil conditions of the delineated new areas are hardly comparable to the traditional vineyards of  
235 the Azores since these ones have been settled over cracked lava fields where even the hydric and  
236 nutrient plant nourishment processes are frequently difficult to access and to explain. Additionally to  
237 the stony condition of the terrain, the micro parcel structure of the vineyards drastically limits the  
238 workability and trafficability of the traditional vineyards, making them highly costly and dependent on  
239 man labor for almost every management practices. Figure 4 show the distribution of the existing  
240 traditional vineyard areas and DOC limits.

241 The soil properties taken as the most relevant for **the analysis and definition of the potential vineyard  
242 areas** where: drainage, water holding capacity, depth to bed-rock and pH. **From these parameters, soil  
243 suitability classes were defined (Table 2) based on the concept and criteria as adapted from Bucelli and  
244 Costantini (2009). Table 3 show the areas of the soil suitability classes for each island, based on the  
245 soil parameters as established in Table 2.**

246 Soil drainage, being dependent on various soil characteristics such as texture, structure depth and  
247 slope, affects crop health and management conditions. Soil depth, not only defines the soil volume  
248 for root development and mineral nutrition as it defines and limits the available soil water capacity.  
249 Soil pH, being a regulator of chemical and biological processes, gives an indication of the potential  
250 for nutrient availability. The neutral to slightly acid reaction is the best pH condition for nutrient fertility  
251 and balance in the soil. However, it is well recognized that the nutritive fertility for grapevines should  
252 be only moderate, as an high nutritional condition leads to excessive vegetative growth and induces  
253 in the wine an overall lowering of the quality parameters.

254 Different water level in the soil affects grape quality and reflects in wine quality (Conradie *et al.*,  
255 2002). Andisols can retain a large amount of water primary due to their large volume of mesopores  
256 and micropores produced within the stable soil aggregates.

257 Formation of these aggregates is greatly enhanced by noncrystalline materials and soil organic  
258 matter (Maeda *et al.*, 1977).

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

266 In these soils the available water-holding capacity (AWC) is relatively high, varying between 0.20 and  
267 0.25 cm<sup>3</sup> of water per 1cm<sup>3</sup> of soil. The Udivitrands, which predominate in the islands of S. Miguel  
268 (Ricardo *et al.*, 1977) and Faial (Madeira *et al.*, 2002), have in general coarse textures with  
269 significant fractions of pomice and cinders fragments from sand to gravel dimensions. Under these

270 textural conditions the waterholding capacity may be somewhat limited. As in these soils the internal  
271 drainage is frequently very high, these combined factors may increase the risk of draught periods  
272 during the growing season and the average interval of AWC variation lowers to 0.10–0.15 cm<sup>3</sup> of  
273 water per cubic centimeter of soil in the Udivitrand. Nevertheless, it has been observed that a  
274 certain lack of water during the ripening period is favorable to the organoleptic wine quality (Galet,  
275 1993; Riou *et al.*, 1994; Huglin and Schneider, 1998).

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

279 The soil reaction found in the considered altitudes for both soil categories is in general slightly acid to  
280 neutral, being the *pH* range of 5.6 to 6.5. From a soil standpoint, highquality wines are made from  
281 grapes grown in many different types of soils with no single type considered ideal (Wilson, 1998).  
282 Grapevines will tolerate a wide range of soils, but yield and variation in vine vigour commonly match  
283 changes in local soil properties, which in turn can influence grape characteristics (Bramley 2001,  
284 2005; Reynolds *et al.* 2007). In spite of the relative variability in both physical and chemical  
285 parameters as generally described above, the soils here considered reflect an overall suitability for  
286 the viticulture expansion in the Azores.

### 287 **3 Results and conclusions**

288 Along the last half-century the agricultural activity in the Azores has been progressively concentrated to  
289 the milk industry, representing the wine production presently a very small part of the economy, around  
290 0.3% of the agricultural product as referred in the new program of rural development of the Azores -  
291 Prorural 2014-2020. However, the ongoing abolishment of milk quotas in EU and the increased risk on  
292 milk price volatility is expected to affect negatively the economical behavior of the dairy industry in the  
293 Azores.

294 This research provides a definition of the environmental characteristics of potential new areas of higher  
295 yielding vineyards under technically adequate mechanization conditions, allowing an efficient management  
296 of the crop and improvement of the wine industry in the Azores, contributing thus to the diversification and  
297 development of the agricultural sector as a whole.

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

305 Under the specificity of the Azorean environmental conditions, white wines produced from several  
306 adapted winegrape varieties (e.g., Verdelho, Arinto and Terrantês), which started to be introduced in  
307 the Archipelago since the fifteenth century in the advent of the colonization of the islands and  
308 probably originated from Cyprus and Madeira islands (Duarte Jr., 2001), have been more successful  
309 than red wines most probably due the generally lower heat demand for maturation of the white grape  
310 varieties. The more recognized and typical white wines of the Azores have been produced in the  
311 lavafield terroirs of Pico, both table and licourous wines. Biscoitos, a small village of stony volcanic  
312 cover in Terceira island, is also recognized by its white wines in spite of the reduced overall  
313 production. There are very few studies of chemical characterization of wines from the Azores. Lima  
314 *et al.* (2004) found that the concentrations of iron, copper manganese and zinc in Azorean wines  
315 correspond with the mean values observed for other regions in Europe. Batista *et al.* (2001)  
316 presented a comparison study of polyphenols and aroma in red wines from Portuguese mainland  
317 versus Azores islands.

318 The spatial potential for viticulture of each island is presented in the maps of **Fig. 5**, with the area  
319 distribution depicted by climate maturity groups. The cartographic representation of these landscape  
320 areas resulted from a GIS supported spatial analysis of climate, soils and topography based on the  
321 combination of the selected criteria for each of these three factors. Three thermal classes defined as  
322 climate/maturity groupings were established from a baseline reference (vineyards area of Pico  
323 island), and then combined with the soils fulfilling the most advantageous characteristics of moderate  
324 to good drainage, adequate soil depth, fair to good water-holding capacity and near neutral *pH*, and  
325 being distributed within a slope interval of 0 to 15% taken as the most adequate to the vineyard  
326 cultural operations.

327 The calculated surfaces (ha) of the cartographic areas with potential for grapevine production, as  
328 defined for each island and thermal class are presented in [Table 4](#). The warmer conditions of thermal  
329 class III, well represented in the traditional “terroir” of Pico island, has practically no expression in the  
330 other islands. However, for the intermediate class II and the cooler class I, we could map significant  
331 areas – 5611 and 18115 ha respectively – fulfilling the defined soils and slope criteria. These results  
332 indicate that landscape units exist across the climate maturity classes II and I of the studied islands  
333 revealing adequate potential for future development of viticulture, although certainly demanding a  
334 good judgment on the better grape varieties to be adapted to those climatic conditions.

335 The defined thermal classes, based in the degree-day concept for a base temperature of 10 °C  
336 (Amerine and Winkler 1944), that we used as climatic indicators for viticultural zoning in the Azores,  
337 may be broadly compared to the bioclimatic index (Catl) which incorporates the most relevant  
338 characteristics of a given region, as defined for Portugal mainland (Fraga *et al.*, 2013). The Azores  
339 climate has been characterized as humid and the average daily temperatures in the lower areas are  
340 moderate with low thermal amplitudes and warm nights (above 14 °C) along the growing season, due  
341 to the maritime regulatory influence. The littoral of the islands covered by the three considered  
342 classes falls in the categories of “temperate nights” (September average  $T_{min} > 14^{\circ}\text{C} - 18^{\circ}\text{C} <$ ) and  
343 “warm nights” (September average  $T_{min} > 18^{\circ}\text{C}$ ) as it is defined by the Cool Night Index (CI)  
344 (Tonietto and Carboneau, 2004), [Figure 6](#). The Growing season accumulated precipitation varies  
345 from 400 mm to 800 mm, [Figure 7](#). Consequently, the thermal classes I and II defined in this study  
346 can be broadly compared to the category 8 of the Catl bioclimatic index which is described as  
347 temperate, humid with warm nights, while the thermal class III would be better comparable to the  
348 category 12 which represent the warmer conditions found in the lava field grapevines of Pico island,  
349 where average temperatures are amplified by the heat capacity of the basaltic stones where the  
350 grapevines are laying.

351 The present study, through the use of [overlay GIS](#) spatial analysis based on climate, soils and slope,  
352 conducted at an intermediate scale level, provides an overall perspective and understanding of the  
353 potential for expansion of viticulture in the Azores. Additionally, the results presented should serve as  
354 a decision support tool in the site selection process for new vineyards establishment. However, there  
355 are limitations and further issues to be addressed before developing any individual site. In fact, the  
356 resolution limits of the landscape analysis, related to elevation and slope data as well as to soils  
357 variability, request a detailed site specific assessment to be conducted prior to any final decision on a  
358 new vineyard establishment. The expansion of the viticulture onto new soil types will also affect resulting  
359 grape and wine characteristics and will imply an additional effort of experimental study and research on the  
360 adaptation of traditional and new varietals to the alternative environmental conditions here defined.  
361 Furthermore, future research activities on viticultural and oenological results are needed to check the  
362 wine suitability of the delineated new areas of potential natural terroir units.

363

364 Author contributions:

365 E. B. Azevedo developed the climatic analysis and with F. Reis and F. Fernandes they adapted the GIS  
366 model. J. Madruga and J. Sampaio selected the background soils data and analysis. J. Pinheiro  
367 participated in soil analysis and prepared the manuscript with contributions from all co-authors.

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Table 1. Pedological properties of three soils representative of the potential new areas for viticulture in the Azores.

Soil horizons	Depth <sup>a</sup> (cm)	Bulk density (g cm <sup>-3</sup> )	Water retention		pH (H <sub>2</sub> O)	Organic carbon (g.kg <sup>-1</sup> )	Exchangeable bases <sup>b</sup> (cmol(+) kg <sup>-1</sup> )					Allophane <sup>c</sup> (%)	Textural class <sup>d</sup>	Coarse fraction >2mm (vol. %)
			300 kPa cm <sup>3</sup> cm <sup>-3</sup>	1500 kPa (H <sub>2</sub> O)			Ca <sup>2+</sup>	Mg <sup>2+</sup>	K <sup>+</sup>	Na <sup>+</sup>	Σ			
<i>Andic Eutrudepts (pedon Vila-Nova)</i>														
Ap	0-27	1.1	0.27	0.15	5.8	24	2.7	0.8	0.9	0.7	5.1	nd	L	6.8
Bw 1	27-60	1.0	0.35	0.17	6.0	19	3.6	0.7	0.6	0.5	5.4	nd	SCL	4.3
Bw 2	60-76	0.9	0.54	0.29	5.9	15	5.0	1.1	0.4	1.0	7.5	3	SCL	3.1
2Bw b	76-120	0.9	0.50	0.36	5.9	7	5.0	1.2	1.0	1.6	8.8	5	CL	0
3Bw b	120-160+	0.8	0.58	0.33	6.4	7	7.9	1.7	0.1	0.7	10.4	6	CL	0
<i>Eutric Hapludands (pedon Altares)</i>														
Ap	0-38	0.8	0.46	0.19	5.6	5.8	6.5	3.3	0.2	1.2	11.2	7	SL	7.6
Bw 1	38-87	0.7	0.44	0.25	5.7	4.2	2.5	1.0	0.2	0.6	4.3	15	SCL	3.2
Bw 2	87-155	0.7	0.79	0.32	6.6	3.1	10.7	4.0	0.1	3.1	17.9	24	CL	1.7
2Bw b	155-200+	0.8	0.35	0.21	7.3	0.4	9.0	3.7	0.2	1.9	14.8	10	SCL	10.4
<i>Typic Udivirands (pedon FA 11)</i>														
Ap	0-40	0.8	0.34	0.18	5.4	4.6	3.7	1.5	0.3	1.2	6.7	5	SL	18,5 <sup>f</sup>
BC1	40-70	0.9	0.31	0.13	5.6	2.9	1.2	0.7	0.4	0.8	3.1	7	LS	45,6 <sup>f</sup>
BC2	70-90	ed <sup>a</sup>	0.24	0.09	6.0	0.3	1.1	0.3	0.1	0.8	2.3	2	LS	48,5 <sup>f</sup>
C	90-160+	nd	0.15	0.09	6.3	0.2	0.5	0.2	0.1	0.8	1.6	1	nd	76,8 <sup>f</sup>

<sup>a</sup> depth to bedrock indetermined within the limits of the pedon.<sup>b</sup> determined by the ammonium acetate method at pH 7.<sup>c</sup> estimated according to Parfitt (1986) and based on Si and Al ratio extracted by acid ammonium oxalate (Blakmore et al., 1987).<sup>d</sup> LS - loamy sand; SL - sandy loam; L - loam; SCL - sandy clay loam; CL - clay loam<sup>e</sup> not determined.<sup>f</sup> pomic

514

Table 2. Functional soil parameters and suitability classes of the potential new areas for viticulture in the Azores

Soil parameters	Suitability class		
	S1	S2	S3
Drainage class <sup>a</sup>	Well drained	somewhat excessively drained, or moderately well drained	excessively drained, or somewhat poorly drained
AWC (cm <sup>3</sup> cm <sup>-3</sup> )	>0.20	0.15-0.20	0.15-0.10
Rooting depth (cm)	>100	50-100	25-50
pH (H <sub>2</sub> O)	6.5-7.5	5.5-6.5	4.8-5.5

<sup>a</sup>Soil Survey Manual

515

Table 3. Areas (ha) of the suitability classes for viticulture in the Azores islands

Island	Suitability class (ha)		
	S1	S2	S3
S. Miguel	4052	4421	1794
Terceira	9116	0	0
Faial	1401	1502	0
Graciosa	1483	0	0

516

Table 4. Areas (ha) with potential for grapevine production for each island and climate maturity class

Island	Climate Maturity Class (ha)		
	I	II	III
S. Miguel	8696	1541	30
Terceira	6088	3028	0
Faial	1848	1042	13
Graciosa	1483	0	0
Total	18115	5611	43

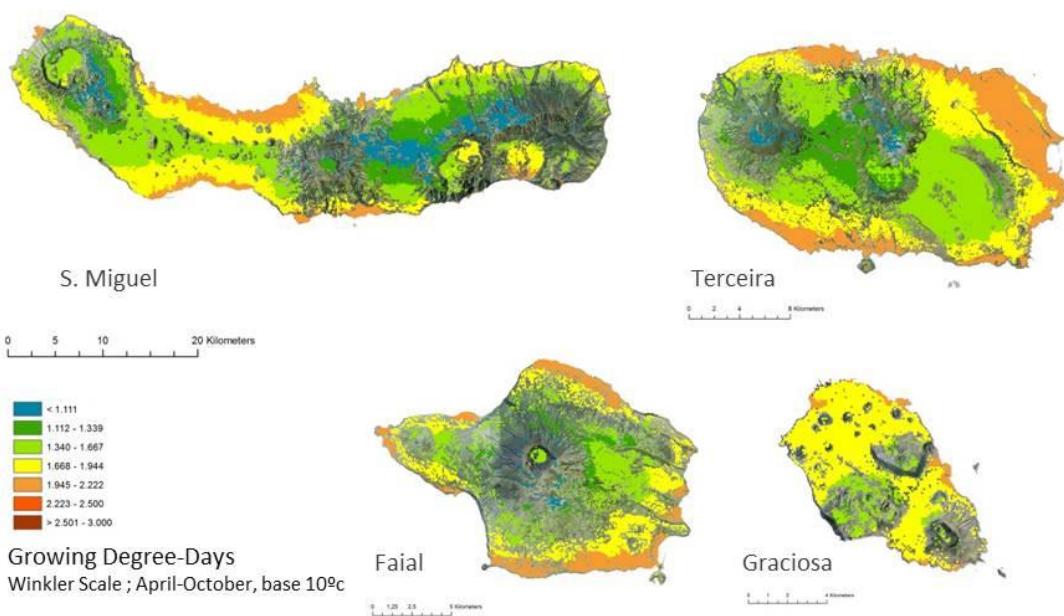
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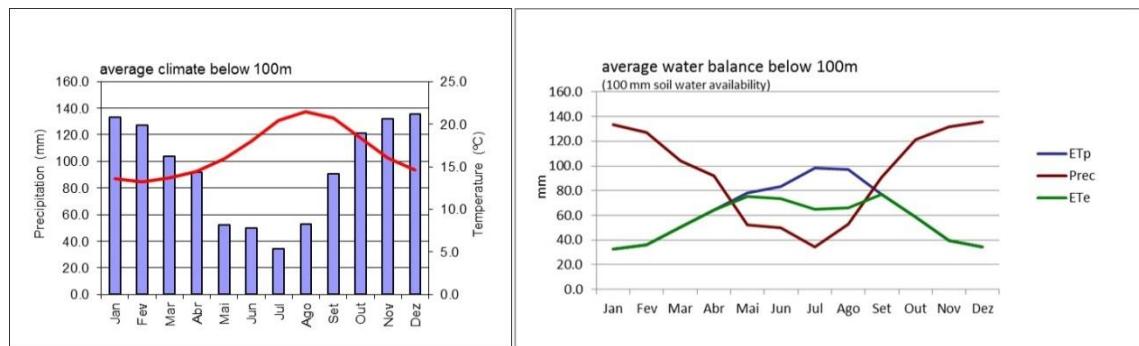
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523 Figure 1. Winkler scale distribution for S. Miguel, Terceira, Faial and Graciosa islands of the Azores.

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

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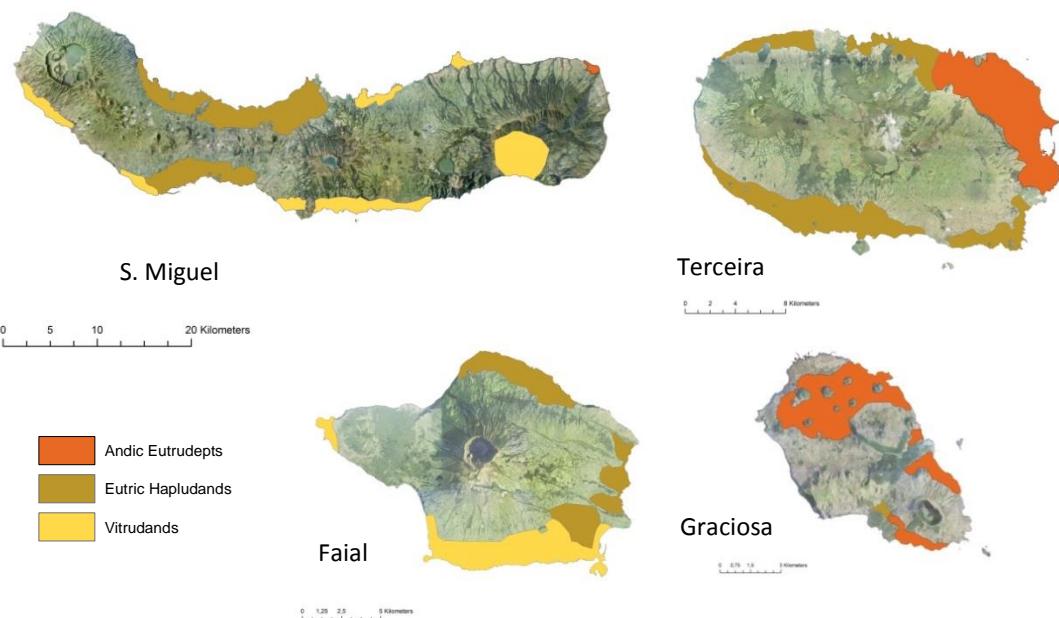
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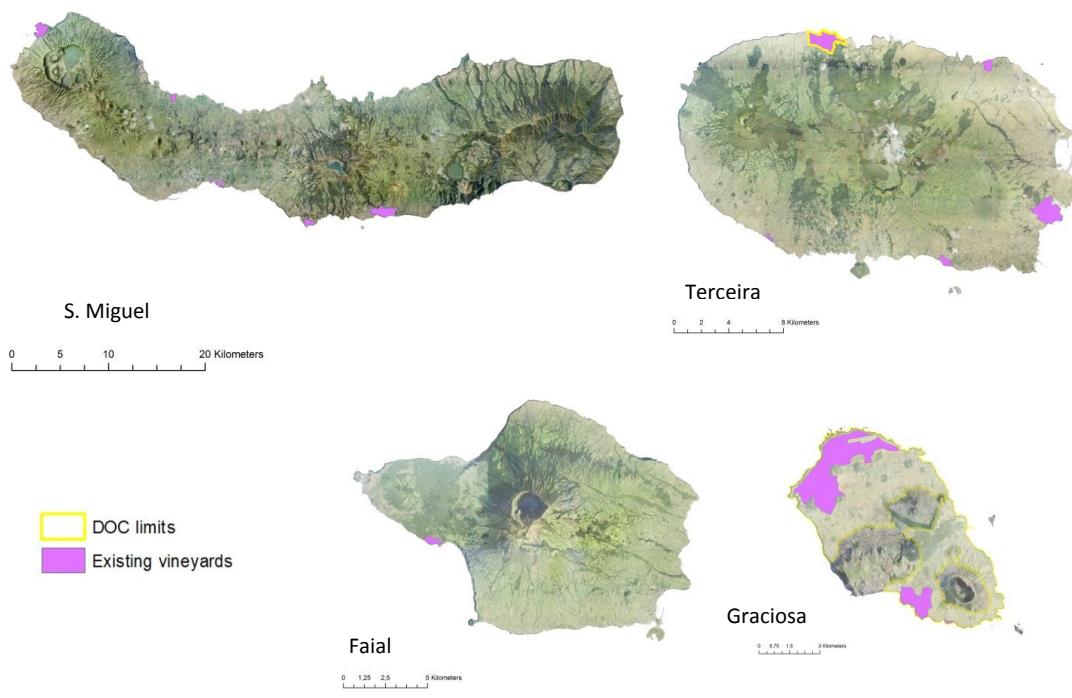
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537 Figure 3 - Major soil categories represented in potential new areas for viticulture in S. Miguel,  
538 Terceira, Faial and Graciosa islands of the Azores

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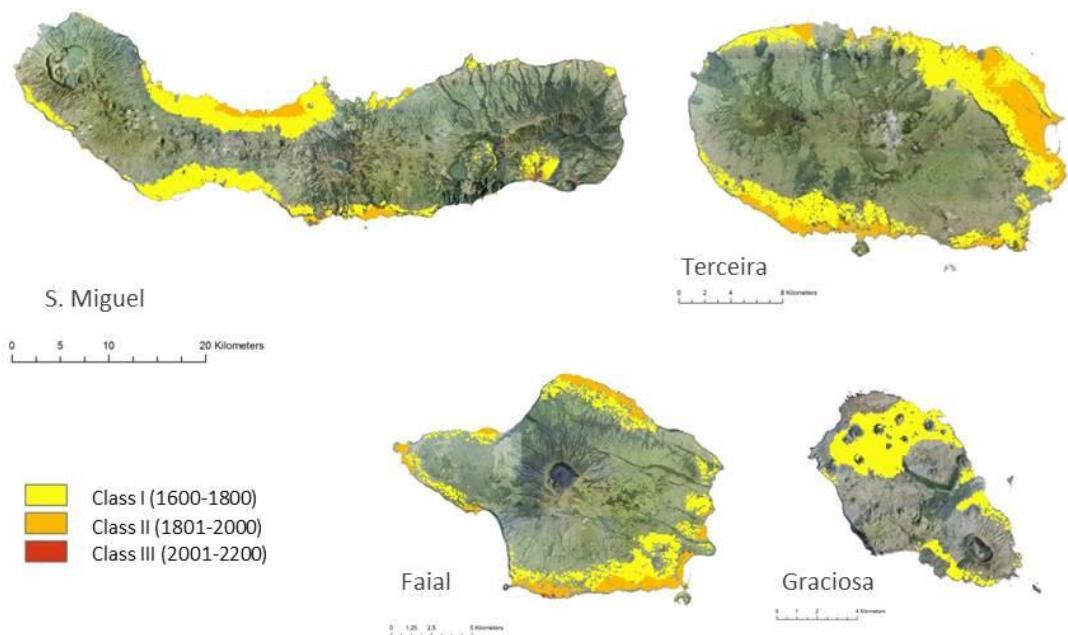


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542 Figure 4. Distribution of the existing traditional vineyard areas and DOC limits in the Azores islands.

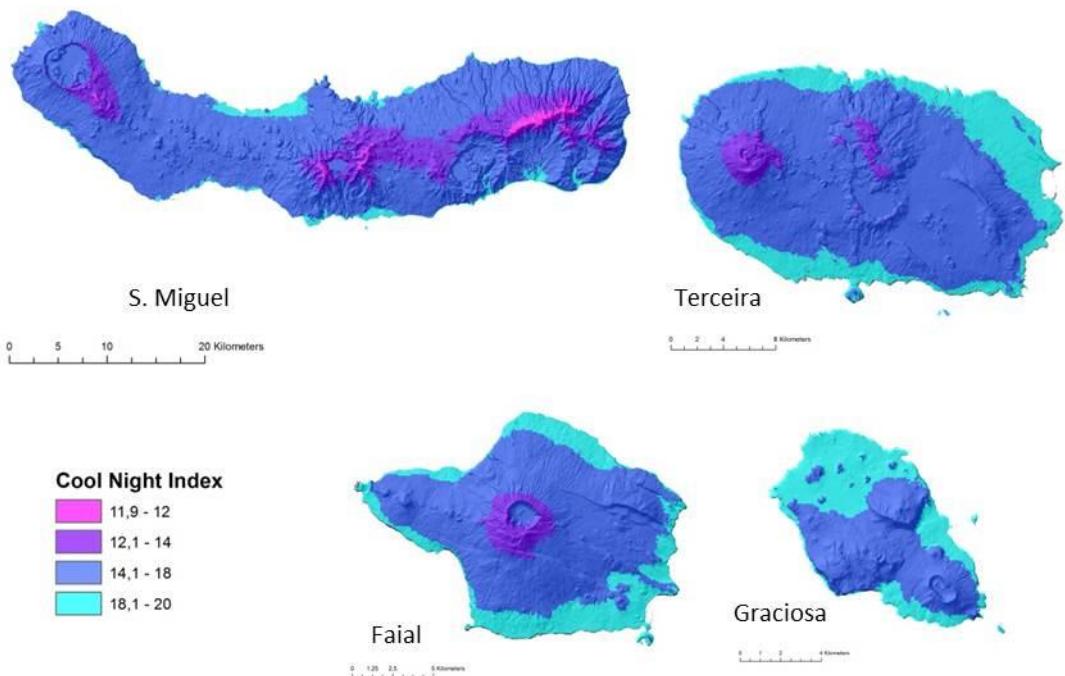
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545 Figure 5. Composite landscape units with potential for viticulture in each island with distribution  
546 depicted by climate maturity groups.

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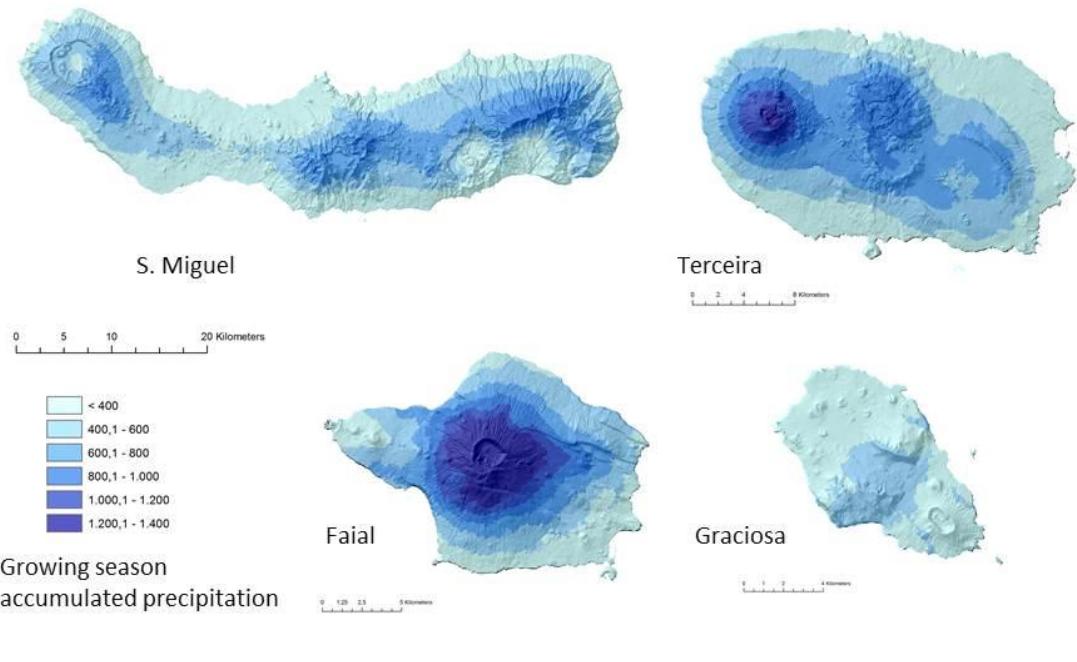


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549 Figure 6 – Cool Night Index (September average minimum temperature)

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553 Figure 7 – Growing season accumulated precipitation in millimeters (April-October)

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555