

Bioclimatology and vegetation series in Sicily: a geostatistical approach

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Tackling the Sicilian woody vegetation as a case-study, this work aims to verify the correspondence between Rivas-Martínez's bioclimatic units and the main vegetation series in the Mediterranean region. Following this approach, one macrobioclimate and 25 bioclimatic type belts can be recognized in Sicily. By means of a geostatistical analysis based on WorldClim data sets, cartographic models of the distribution range of each single bioclimatic unit were obtained and combined with vegetation data, in order to develop a new regional spatial framework, integrating climatic and vegetation data. Fidelity of each vegetation unit to a given climatic range was then evaluated as percent distribution of the occupied surface within a given bioclimatic unit, while the predictive power of the WorldClim data sets was tested by using half of the spatial data of the processed vegetation units as independent variables. Our results suggest that: (1) any kind of numerical threshold used to define bioclimatic units is not effective *a priori*, but only after it has been adjusted to the territory and to the spatial scale used to set the model; (2) bioclimatic indices being an empirical tool, the model can be trained and eventually adjusted when applied to different territories; (3) fidelity of vegetation units to a given bioclimatic unit is highly variable; (4) the mechanistic pitfall that climatophilous vegetation has to be necessarily linked to a single bioclimatic unit should be avoided.

Introduction

Bioclimatology is an ecological science that studies the relationship between climate and distribution of organisms and their communities. In vegetation science, it began with the studies of correlations between temperature and precipita-

tion, and distribution of plant communities. The most recent advances in the discipline incorporated all relevant information on biogeocoenoses (defined as a land unit created by the interaction between vegetation and soil biota) and the new concepts of dynamic-catenal phytosociology, i.e. sigmeta, geosigmeta and geopermasigmeta

according to the terminology of Rivas-Martínez (2007; *see also* “Nomenclature and terms used”, below).

Bioclimatic variables are those climatic features that are physiologically relevant to plant growth and distribution. They are, therefore, widely used in studies on spatial distribution patterns and vegetation mapping (Franklin 1995, Bohn & Neuhausl 2003, Blasi 2010), for predicting consequences of climate change for species distribution (Sykes *et al.* 1996, Peng 2000, Walther *et al.* 2002), in managing and monitoring invasive alien species (Arriaga *et al.* 2004), and in regional planning (Bryan *et al.* 2005).

Predictive vegetation mapping is a process in which empirically established rules are used to create maps of environmental variables such as soils, geology, topography and climate, for habitat modelling. Such rules range from assumed informal relationships to sophisticated statistical models. These models can be set either in a context of vegetation gradient analysis, *i.e.* according to the continuum model (Gleason 1926, Whittaker 1951, Austin 1985) or in the conceptual framework of phytosociology, which classifies discrete Zürich-Montpellier School vegetation types (Braun-Blanquet 1951, Tüxen 1956, Pedrotti 2013). Accurate bioclimatic maps are essential in both approaches to vegetation distribution.

Recently, a considerable interest in relations between bioclimatic and landscape classification has arisen (del Arco-Aguilar *et al.* 2009, Mesquita & Sousa 2009, Metzger *et al.* 2013).

In this work, we examined the relations between vegetation series and climate by means of geostatistical analysis of WorldClim data sets using bioclimatic indices introduced by Rivas-Martínez (1994). Our aims were: (1) to check the accuracy of the WorldClim data sets for the Mediterranean Region, (2) to improve the current bioclimatic maps for Sicily, and (3) to test whether this approach can be used for landscape diagnosis. Sicily is ideal for our study, because of its central position in the Mediterranean and because its vegetation has been thoroughly investigated (*see* Brullo *et al.* 2002 for details). Moreover, the bioclimatic indices proposed by Rivas-Martínez (1994) have already been applied for Sicily by Brullo *et al.* (1996),

and a fairly good number of weather stations and related bioclimatic data are available for the whole island (Duro *et al.* 1996, Cartabellotta *et al.* 2000, Bazan *et al.* 2006).

Material and methods

Study area

Sicily and its surrounding islets are recognized as one of the Mediterranean biodiversity hotspots (Médail & Quézel 1997, 1999). The richness of the Sicilian flora is due to a great variety of habitats and to a complex paleo-geographic history (Brullo *et al.* 1995). The current vascular plant flora includes over 13% of endemic taxa (Raimondo & Di Gristina 2007, Raimondo & Spadaro 2008, Troia & Raimondo 2010, Raimondo *et al.* 2010, 2012, Castellano *et al.* 2012, Marino *et al.* 2012, 2014, Guarino *et al.* 2013) and most of the typical Mediterranean vegetation can be found on the island (Guarino 2011). The total area of Sicily is about 25 700 km², of which approximately 61.4% is hilly, 24.5% is mountainous and 14.1% consists of alluvial plains (Fig. 1).

Vegetation mapping

In order to outline the existing woody vegetation, a detailed physiognomic map of the Sicilian woody vegetation was used (available as digital data at <http://www.sitr.regione.sicilia.it/webgis-portal/default.aspx>). The reasons for choosing the woody vegetation are its relative stability and easy recognisability from aerial photographs. A geographical information system was used to map 10 342 patches of woody vegetation larger than 10 ha (ArcGIS Desktop Release 9, ESRI, Redlands, CA).

Vegetation types were classified on the basis of phytosociological literature and field surveys. The Sicilian woody vegetation has been thoroughly investigated by phytosociologists. In recent years, detailed syntaxonomical schemes have been published by Brullo *et al.* (2002, 2008, 2012). The patches (homogeneous areas larger than 1000 m²) that include phytosocio-

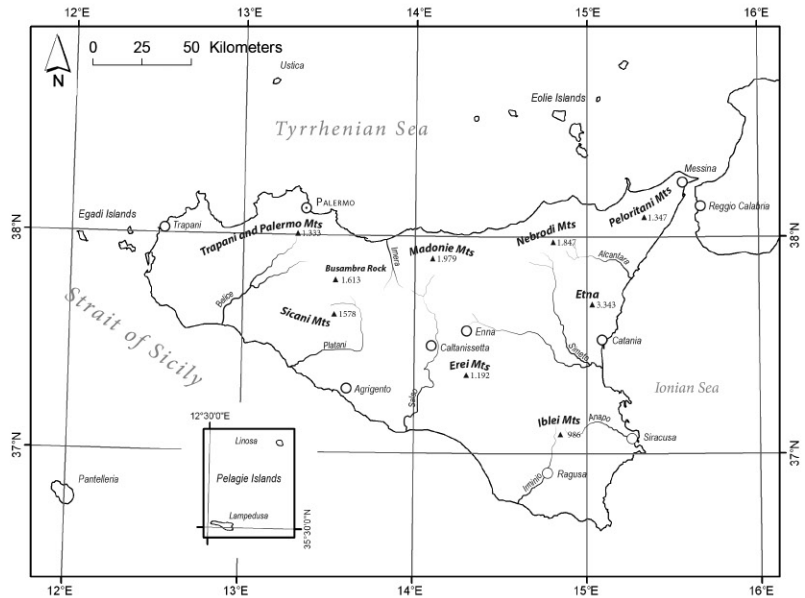


Fig. 1. Toponymic map of Sicily.

logical plots (surface about 100 m²) were used as ‘spectral fingerprints’ of each vegetation unit. All the other patches were classified using supervised multispectral analysis associated with overlaying a soil map of Sicily (Fierotti *et al.* 1998), based on the assumption that neighbouring patches belonging to the same multispectral group, occurring on the same soil unit and at similar altitudes should belong in the same vegetation unit. Boundaries of the patches were verified in the field. Each patch of the considered phytosociological units was further associated with a climatic variable. Sources and use of the climatic data and bioclimatic classification are specified in the following paragraph.

Climatic data and bioclimatic classification

This study is based on the WorldClim data (Hijmans *et al.* 2005) from the period 1950–2000. The WorldClim data (temperature and rainfall) consist of climate grids with a resolution of 1 km² and a net of 38 600 grid cells, with an interval of 30′, which in Sicily corresponds to 734 m (long.) × 926 m (lat.).

The bioclimatic classification of Sicily follows Rivas-Martínez (1994). That classification

is based on formulas calculating temperature and rainfall ranges and distributions, which are used to define the values for respective bioclimatic belts: thermotype and ombrotype (Table 1). Each of them is expressed by a characteristic group of plant communities (*biocoenoses* of Rivas-Martínez 2002). The thermotype indices used in this study are: (1) thermicity index [$It = (T + M + m) \times 10$, where T is the yearly average temperature, m is the average minimum temperature of the coldest months of the years, and M is the average maximum temperature of the coldest months of the years]; (2) continentality index ($Ic = Tmax - Tmin$, where $Tmax$ is the average temperature of the warmest month, and $Tmin$ is the average temperature of the coldest month); (3) compensated thermicity index ($Itc = It + Ci$), where Ci is the compensation value based on the continentality index (Ic), used to compensate the peak of low temperature in areas with continental climate; according to Rivas-Martínez (1994) if $18 < Ic \leq 21$, then $Ci = 5 \times (Ic - 18)$; (4) positive temperature index (Tp , expressed with one decimal accuracy, resulting from the annual sum of the monthly average temperatures higher than 0 °C).

Ombrotypes were defined using the ombrothermic index [$Io = 10 \times Pp/Tp$, where Pp is the annual precipitation (mm)]; as recommended by Rivas-Martínez (1994), only precipitation of the

months with average temperature higher than 0 °C is used in the formula.

Thermotype and ombrotype grids were processed at the resolution of 1 km².

Geostatistical and correlation analysis

The fidelity of each vegetation unit to a given bioclimate (defined through the combination of thermotypes and ombrotypes) was evaluated as a percentage of the total surface it occupies within a given bioclimatic unit (Table 2). Bioclimatic maps were obtained through the application of the above mentioned Rivas-Martínez's indices to the WorldClim grids.

In order to test the usefulness of the WorldClim interpolation as a predictive tool, and its correspondence with the vegetation units, the cen-

teroid coordinates of the vegetation patches were divided into two independent sets: calibration and validation. Grouping was done in order to ensure that the statistical properties of the altitude, i.e. mean, variance, minimum and maximum values were most similar in each group. The calibration set was used to establish average (U) and variance (σ^2) of the WorldClim variables (mean temperature: T_{mean} ; average annual rainfall: P) associated with each considered vegetation unit.

Distance-based redundancy analysis (Legendre & Anderson 1999) was carried out using the *VEGAN* package in R (Oksanen et al. 2009), to calculate the variances of the calibration and validation sets and to score the centroid coordinates of the vegetation units. The goodness of fit (expressed here as percentage of accuracy) was calculated as $R = (V_0 - V)^2 / (V_0)^2$ (Taylor

Table 1. Threshold values for bioclimates, thermotypes and ombrotypes according to Rivas-Martínez (1994): Ic = continentality index, lo = ombrothermic index, It = thermicity index, lct = compensated thermicity index, Tp = positive temperature index.

Bioclimate	Ic	lo
Mediterranean pluviseasonal oceanic	≤ 21	> 2.0
Mediterranean xeric oceanic	≤ 21	1.0–2.0
Thermotype	It, lct	Tp
Lower cryoromediterranean (LCme)	–	150–450
Upper oromediterranean (UOme)	–	450–675
Lower oromediterranean (LOme)	–	675–900
Upper suprasediterranean (USme)	120–150	900–1200
Lower suprasediterranean (LSme)	150–220	1200–1500
Upper mesomediterranean (UMme)	220–285	1500–1825
Lower mesomediterranean (LMme)	285–350	1825–2150
Upper thermomediterranean (UTme)	350–400	2150–2300
Lower thermomediterranean (LTme)	400–450	2300–2450
Upper inframediterranean (UIme)	450–515	2450–2650
Ombrotype		lo
Upper hyperhumid (UHh)		18.0–24.0
Lower hyperhumid (LHh)		12.0–18.0
Upper humid (UHu)		9.0–12.0
Lower humid (LHu)		6.0–9.0
Upper subhumid (USH)		4.8–6.0
Lower subhumid (LSh)		3.6–4.8
Upper dry (UDry)		2.8–3.6
Lower dry (LDry)		2.0–2.8
Upper semiarid (USa)		1.5–2.0
Lower semiarid (LSa)		1.0–1.5

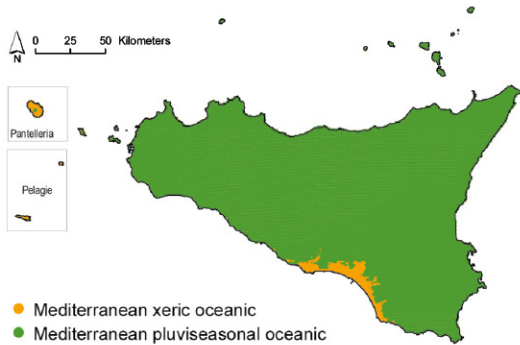


Fig. 2. Bioclimates in Sicily.

1997, Guarino *et al.* 2005), where V_0 is the variance of the calibration set and V is the residual variance of the validation set. The predictive power (“accuracy”) of the WorldClim variables was then evaluated through the percentage of fit of the centroid coordinates of the validation set to the potential distribution areas obtained by means of WorldClim. The procedure was repeated for each vegetation unit in the data set.

Nomenclature and terms used

The taxonomic nomenclature follows Giardina *et al.* (2007) and the syntaxonomical nomenclature follows Brullo *et al.* (2008) for the vegetation units ascribed to the class *Quercetea ilicis*, and Brullo *et al.* 2012 for those ascribed to the class *Querceto-Fagetetea*. Phytosociological terms follow the definitions by Gèhu and Rivas Martínez (1994), Poldini and Sburlino (2005), Pedrotti (2013). Since those terms are not commonly used, a short explanation of the essential phytosociological terminology most frequently used in the present paper is given below.

“Climatophilous vegetation” is the vegetation which best characterizes a given bioclimatic unit and can be used to outline its territorial extension. The term is often juxtaposed with “edaphohydrophilous vegetation” and/or “edaphoxerophilous vegetation”, both referring to vegetation units that, under the same climatic conditions, colonize wet (the former) or dry (the latter) soils. “Vegetation series” is the process of change in the species composition and structure of plant communities over time; succession. In phytoso-

ciology, it is defined by all plant associations and their dynamic relationships (progressive as well as regressive) found within the same land unit. “Sigaretum” is the nomenclatural term comprising all successional stages of a vegetation series. “Head vegetation” is the most mature community in a vegetation series; i.e., climax community. It corresponds to the “Potential Natural Vegetation” (*sensu* Tüxen 1956).

Results

According to our results, Sicily encompasses the following Rivas-Martínez’s bioclimatic units: one macrobioclimate (Mediterranean); two bioclimates: Mediterranean pluvisesonal oceanic ($CI \leq 21$, $OI > 2.0$) and Mediterranean xeric oceanic ($CI \leq 21$, $1.0 < OI < 2.0$), and 25 bioclimatic units (Figs. 2–4). The percentages of accuracy (R) of the vegetation series in the bioclimatic belts are given in Table 2. Based on the distribution analysis of bioclimates (Table 2) and the edaphic preferences of each vegetation unit, a synoptic key was obtained (Table 3).

Each vegetation unit mentioned here corresponds to the most mature stage of a vegetation series, for which syndynamic information and catenal contacts (cf. Rivas-Martínez 2002) can be easily obtained from literature (Bazan *et al.* 2010, Brullo *et al.* 2008, 2012). All the bioclimatic units found in Sicily are briefly commented in Appendix, with reference to the related vegetation series.

Discussion

Information on ecosystems and practical methods to delimit habitats and biotopes are needed for all kinds of studies at landscape scale. Spatial planning requires knowledge of the landscape that does not rely on purely perceptual, but also on objective and quantifiable data. In this respect, landscape ecology for about 30 years has come up with theories, methods and tools necessary for the analysis and interpretation of the land mosaic (Forman & Godron 1986, Ingegnoli 2004). Among the most topical issues of this discipline is identification of homogeneous land

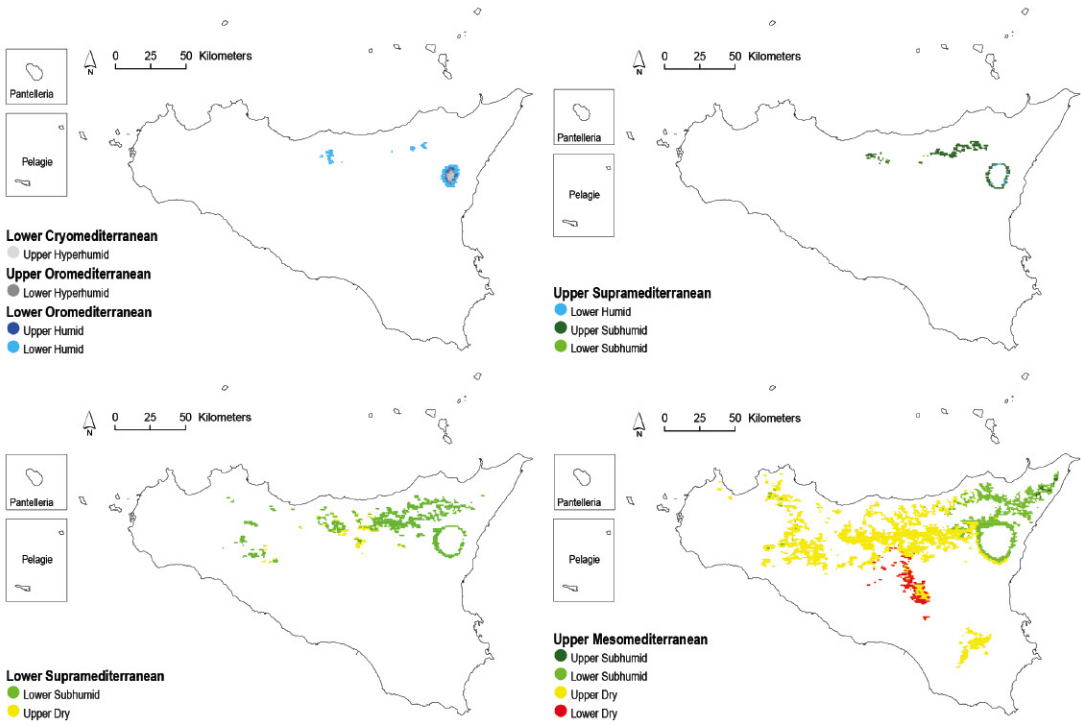


Fig. 3. Bioclimatic belts in Sicily (Lower Cryomediterranean to Upper Mesomediterranean).

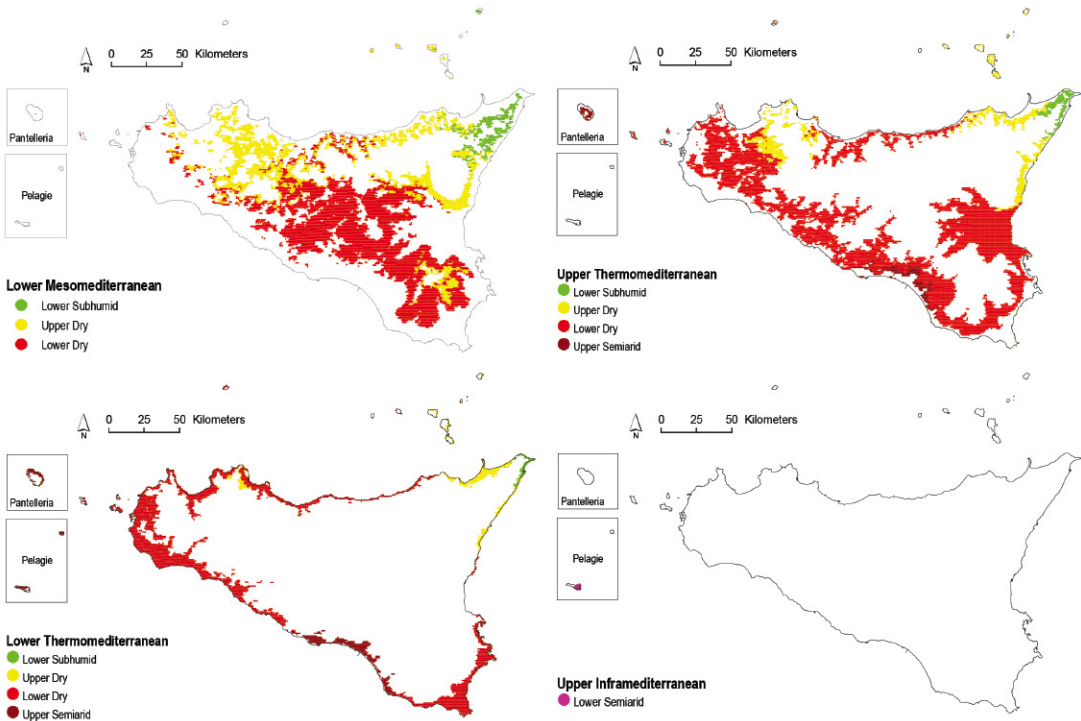


Fig. 4. Bioclimatic belts in Sicily (Lower Mesomediterranean to Upper Inframediterranean).

Table 3. Diagnostic key to define vegetation series according to bioclimatic belts. The vegetation units corresponding to the optimal bioclimatic units (defined as the highest value of the respective percentage distributions reported in Table 2) are given in boldface; other vegetation units frequently found within the considered bioclimatic unit are given in regular face; extrazonal vegetation units are given in italics. For the explanation of bioclimatic unit abbreviations, see Table 1.

Thermotypes	Ombrotypes	Basiphilous head vegetation series	Acidophilous head vegetation series
LCme	Uhh		Rumici aetnensis-Astragalion siculi
UOme	LHh		Rumici aetnensis-Astragalion siculi
LOme	UHu		Rumici aetnensis-Astragalion siculi
	LHu		Rumici aetnensis-Astragalion siculi
USme	LHu	Luzulo siculae-Fagetum	Epipactido meridionalis-Fagetum <i>Cephalanthero longifoliae-Betuletum aetnensis</i> Junipero-Abetum nebrodense
	USh	Luzulo siculae-Fagetum <i>Hieracio madoniensis-Fagetum sylvaticae</i>	Junipero-Abetum nebrodense <i>Junipero hemisphaericae-Pinetum calabricae</i> Anemono apenninae-Fagetum <i>Illici aquifolii-Taxetum baccatae</i> Epipactido meridionalis-Fagetum Agropyro panormitani-Quercetum congestae Geranio versicoloris-Quercetum ilicis Anemono apenninae-Fagetum
	LSh		Agropyro panormitani-Quercetum congestae <i>Agropyro panormitani-Populetum tremulae</i> <i>Daphno laureolae-Pinetum calabricae</i> Arabido turritae-Quercetum congestae Arrhenathero nebrodensis-Quercetum cerridis <i>Vicio cassubicae-Quercetum cerridis</i> <i>Rubo aetnici-Fagetum sylvaticae</i> Geranio versicoloris-Quercetum ilicis Anemono apenninae-Fagetum Agropyro panormitani-Quercetum congestae Arrhenathero nebrodensis-Quercetum cerridis <i>Melitto albidae-Fagetum sylvaticae</i> <i>Illici aquifolii-Quercetum cerridis</i> Arabido turritae-Quercetum congestae Quercetum gussonei Illici-Quercetum austrotyrrhenicae <i>Illici aquifolii-Quercetum leptobalani</i> Geranio versicoloris-Quercetum ilicis Teucro siculi-Quercetum ilicis Teucro siculi-Quercetum ilicis
LSme	LSh	Sorbo torminalis-Quercetum virgiliana Aceri campestris-Quercetum ilicis <i>Sorbo graecae-Aceretum pseudoplatani</i>	Erico arborea-Quercetum virgiliana Agropyro panormitani-Quercetum congestae Arrhenathero nebrodensis-Quercetum cerridis Arabido turritae-Quercetum congestae <i>Aceri obtusati-Ostryetum carpiniifoliae</i> <i>Doronico orientalis-Castanetum sativae</i> Quercetum gussonei Festuco heterophyllae-Quercetum congestae Erico arborea-Quercetum virgiliana Arrhenathero nebrodensis-Quercetum cerridis Illici-Quercetum austrotyrrhenicae Quercetum gussonei Festuco heterophyllae-Quercetum congestae Mespilo germanice-Quercetum virgiliana <i>Lauro nobilis-Quercetum virgiliana</i> Quercetum leptobalanae Geranio versicoloris-Quercetum ilicis Teucro siculi-Quercetum ilicis
UMme	Udry		
	USh		
	LSh		
	UDry	Sorbo torminalis-Quercetum virgiliana Aceri campestris-Quercetum ilicis <i>Ostryo carpiniifoliae-Quercetum ilicis</i>	
	LDry	Oleo sylvestris-Quercetum virgiliana	

continued

Table 3. Continued.

Thermotypes	Ombrotypes	Basiphilous head vegetation series	Acidophilous head vegetation series
LMme	LSh		Erico arboreae-Quercetum virgilianae
	UDry	Sorbo torminalis-Quercetum virgilianae Oleo sylvestris-Quercetum virgilianae Aceri campestri-Quercetum ilicis Pistacio lentisci-Quercetum ilicis Doronico orientalis-Quercetum ilicis Rhamno alaterni-Quercetum ilicis	Quercetum gussonei Festuco heterophyllae-Quercetum congestae Mespilo germanice-Quercetum virgilianae Quercetum leptobalanae Erico arboreae-Quercetum virgilianae Genisto aristate-Quercetum suberis Quercetum leptobalanae
	LDry	Oleo sylvestris-Quercetum virgilianae <i>Celtido aetnensis-Quercetum virgilianae</i> Thymo capitati-Pinetum halepensis Pistacio lentisci-Quercetum ilicis Doronico orientalis-Quercetum ilicis	Erico arboreae-Quercetum virgilianae Stipo bromoidis-Quercetum suberis Erico arboreae-Quercetum ilicis
UTme	LSh		Cisto crispi-Pinetum pineae
	UDry	Oleo sylvestris-Euphorbietum dendroidis	Erico arboreae-Quercetum virgilianae Genisto aristate-Quercetum suberis
	LDry	Oleo sylvestris-Quercetum virgilianae Calicotomo infestae-Rhoetum tripartitae Chamaeropo humilis-Quercetum calliprini Doronico orientalis-Quercetum ilicis Pistacio lentisci-Quercetum ilicis Rhamno alaterni-Quercetum ilicis Oleo sylvestris-Euphorbietum dendroidis	Genisto aristate-Quercetum suberis Thymo capitati-Pinetum halepensis Junipero turbinatae-Quercetum calliprini Stipo bromoidis-Quercetum suberis
LTme	USa		Junipero turbinatae-Quercetum calliprini
	LSh		Cisto crispi-Pinetum pineae
	UDry	Oleo sylvestris-Euphorbietum dendroidis	Cisto crispi-Pinetum pineae
	LDry	Calicotomo infestae-Rhoetum tripartitae Chamaeropo humilis-Quercetum calliprini Myrto-Pistacietum lentisci Pistacio lentisci-Chamaeropetum humilis Doronico orientalis-Quercetum ilicis Rhamno alaterni-Quercetum ilicis Ephedro fragilis-Pistacietum lentisci <i>Calicotomo infestae-Juniperetum turbinatae</i> Ephedro fragilis-Juniperetum macrocarpae	Genisto aristate-Quercetum suberis Junipero turbinatae-Quercetum calliprini
Ulme	USa		Junipero turbinatae-Quercetum calliprini
	LSa	Periploco angustifoliae-Juniperetum turbinatae <i>Periploco angustifoliae-Euphorbietum dendroidis</i>	

areas, to which individual actions of management should be applied (Blasi *et al.* 2000).

The geobotanical approach in vegetation analysis is well suited not only to understanding natural and anthropogenic processes in progress, but also to identifying and mapping areas corresponding to homogeneous vegetation series. The visual aspect and the structure of vegetation are a result of complex interactions, in which climate, edaphic conditions and orography are the most significant variables. Nevertheless, there are some issues worth discussing when analysing the correspondence between phytosociological and bioclimatic units.

Bioclimatic units and geostatistical climate models

Bioclimatic indices took their origin in a time when sophisticated numerical models and technical tools with computational capabilities on grid and DTMs were not available. It was therefore useful, in that time, to propose 'simple' numerical approaches and threshold values to compare and possibly relate flora to vegetation. The classical application of bioclimatic indices was biased by the spatio-temporal heterogeneity of data, due to the scattered distribution of thermo-pluviometric monitoring stations and to

the discontinuity of historic climate data. For that reason, until recent years, bioclimatic maps were based on the distribution range of the vegetation units and/or series, with which a given bioclimatic unit was empirically associated.

Currently, the problem of the uneven geographic distribution of climatic records can be overcome through the development of sophisticated climate models based on statistical prediction, so it is possible to obtain reasonably precise bioclimatic maps without considering the observable distribution of vegetation units. In this way, the distribution range of vegetation units can be used to check the validity of the discrete bioclimatic units. In our test (Table 2), the applicability of the WorldClim maps as predictive models for the distribution of the considered vegetation units was good. In particular, the bioclimatic indices calculated using the WorldClim data set turned out to depend mainly on altitude and thermotypes, while ombrotypes were linked to latitude, longitude and exposure. Such evidence is coherent with field observations and literature data, so the WordClim interpolation procedure seems to be applicable also at local scales.

Bioclimatic units and vegetation

In recent years, the most widely adopted bioclimatic indices in the Mediterranean phytosociological literature are those proposed by Rivas-Martínez, whose uneven threshold values (Table 1) are used in the whole Mediterranean region, even if they were a result of a trial–error-adjustment procedure firstly based on the vegetation of the Iberian Peninsula (Rivas-Martínez 1981).

In our work, Rivas-Martínez’s bioclimatic units were adopted as working hypotheses, and their correspondence with the vegetation units was verified only after producing the bioclimatic maps through the application of Rivas-Martínez’s algorithms to a high-resolution WorldClim grid. The result was that few of the vegetation units sharply overlapped with a given bioclimatic unit, while many units showed a more blurred bioclimatic assemblage (Table 2). This could be due to a mix of the following reasons and consequences:

1. All vegetation units do not have the same ecological amplitude. Fidelity (i.e., the more or less exclusive occurrence of certain species in a given community) and/or a recurrent combination of constant and dominant species is a satisfactory basis for the diagnosis and classification of plant communities, but certainly not all diagnostic species have similar ecological amplitudes. For this reason, the bioclimatic thresholds established through the distribution range of vegetation units occurring in a given territory should be checked and eventually adjusted when moving to another territory. If we assume that bioclimatic units are an empirical tool to express in a synthetic way the climatic preferences of a given vegetation type, the adjustment of bioclimatic thresholds should be allowed if necessary, when applying bioclimatic indices to different territories. Expressions like “Thermomediterranean” or “Oromediterranean” (the accuracy of which cannot be known beforehand) should represent a complement of bioclimatic indices and thermometric/pluviometric average measurements.
2. Bioclimatic indices exclusively based on thermometric and pluviometric data are not always good descriptors of the ecological amplitude of vegetation units and series, because they neglect important local factors, such as, e.g., moisture condensation, wind, and water availability. These factors are particularly important in the geologically and morphologically heterogeneous Sicily. A way to sharpen the discriminative character of bioclimatic indices is to include in their formulas additional algorithms that consider the influence of local factors. This was done, for instance, in the method for estimating how slope gradient and exposure, altitude and distance from the sea may influence the Mitrakos’ Winter Cold Stress and Summer Drought Stress indices (Guarino 2001).
3. Resolution of the WorldClim model may be not good enough for applications at local scales. This assumption is in contrast with our results and with many other studies aimed at checking the usefulness of the model at different scales (e.g. Hijmans *et al.* 2005). An accurate prediction of a dynamic

phenomenon such as vegetation cover range is very difficult. However, the use of numerical predictive modelling methods like WorldClim, together with the analysis of aerial photographs and field surveys, allows us to produce a reasonably good geographical representation of the vegetation and, most importantly, it provides a useful basis for measuring applicability of any kind of bioclimatic index.

A more general criticism of the patterns obtained by the application of bioclimatic indices is that the whole approach may be an artefact imposed by clever shuffling of data and as such not mirroring nature. This is a valid objection, although, even without any adjustment, it has been demonstrated in this paper that higher syntaxonomical units turn out to overlap well with the Rivas-Martínez bioclimatic units: the correspondence of the Sicilian *Querc-Fagetea* vegetation with the Supramediterranean thermotype and the *Quercetea ilicis* vegetation with the Meso- and Thermomediterranean was very strong, as well as the correspondence of the *Quercion calliprini* vegetation with the Lower Thermomediterranean thermotype.

Conclusions

Bioclimatic models, integrated with the indubitable value of species distribution as an ecological indicator, can be useful tools for exploring the responses of living organisms to current and future climates (Grabherr *et al.* 1994, Pignatti *et al.* 2001, Walther *et al.* 2002, Moser *et al.* 2005). A geobotanical approach to spatial vegetation analysis, including bioclimatic indexation and mapping, is a practical way to describe natural vegetation dynamics, even when mature vegetation stands are missing. This approach can be useful in management of protected areas, biodiversity conservation and environmental restoration, taking into consideration that: (1) any kind of numerical threshold used to define bioclimatic units is not valid *a priori*, but only after it has been adapted to the territory and to the spatial scale used to set the developed model; (2) bioclimatic indices being an empirical tool, the

model can be adjusted when applied to different territories; (3) the fidelity of any vegetation unit to a given bioclimatic unit is highly variable; (4) the mechanistic pitfall that climatophilous vegetation has to be necessarily linked to a single bioclimatic unit should be avoided. Instead, multifactorial hypotheses are required for the investigation of climatophilous vegetation, for which a strong correspondence to bioclimatic units can be true, but mechanistic understanding is always limited, because of long causal chains and indirect effects.

Climate can be described by a very large number of variables and indices. The bioclimatic approach, particularly when driven by the use of statistical climatic models, can be used for exploratory analyses that can be useful in predicting vegetation units. Climate research can generate hypotheses worth be tested further, even if ecological research has demonstrated that, sometimes, highly predictable vegetation dynamics under given climatic data are invalidated by subsequent investigation (e.g. Myers 1998, Carrión & Fernández 2009, Chiarucci *et al.* 2010).

At best, we can use the bioclimatic descriptors to develop hypotheses in an inductive framework. Difficulties will arise if we accept these hypotheses without critical testing by means of appropriate, in-depth investigations. Too often a model of vegetation series and its correspondence with bioclimatic units has been proposed as a universally informative system that can be adopted to forecast and eventually design natural vegetation dynamics.

Even if the bioclimatic approach can be used to explore the current distribution of vegetation units, its use to draft predictive scenarios should involve careful judgement. The key question concerns habitat changes in plant community composition and structure, and the changes this will entail for single plant species, animal populations and ultimately for species interactions. How communities shifted and changed in the past may give some indications, but the rates of future changes may be too different to make that analogy very useful. More importantly, habitat fragmentation has increased dramatically during the last centuries, which further complicates the usefulness of historical analogies.

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Appendix. Bioclimatic belts and their characterization in Sicily. Tp = Positive Temperature Index, It = Thermicity Index, lo = Ombrothermic Index.

1. Upper Cryomediterranean (UCme), Tp = 1–150

Distribution: Mt. Etna, at altitudes above 3000 m a.s.l.
 Ombrotypes: Upper Hyperhumid (UHh), $18 < lo < 24.0$
 Vegetation series: Volcanic desert, without any visible vascular vegetation.

2. Lower Cryomediterranean (LCme), Tp = 150–450

Distribution: Mt. Etna, between 2400 and 3000 m a.s.l.
 Ombrotypes: Lower Hyperhumid (UHh), $12.0 < lo < 18.0$
 Vegetation series: Volcanic desert and recent lava flows with scattered pioneer vegetation of *Rumici-Anthemidetum aetnensis* (Brullo et al. 2006).

3. Upper Oromediterranean (UOme), Tp = 450–675

Distribution: Mt. Etna, between 2000 and 2400 m a.s.l.
 Ombrotypes: Lower Hyperhumid (LHh), $12.0 < lo < 18.0$
 Vegetation series: The vegetation is characterized by pulvinate shrubby communities of *Astragaletum siculi* (*Rumici-Astragalion siculi*). It forms a discontinuous formation of high phytogeographic interest with a set of endemic and rare species. *Astragaletum siculi* is physiognomically differentiated by the thorny pulvinate *Astragalus siculus*, growing together with *Senecio aethnensis*, *Galium aetnicum*, *Festuca circummediterranea*, *Robertia taraxacoides*, *Tanacetum siculum* and *Viola aetnensis* (Brullo et al. 2006).

4. Lower Oromediterranean (LOme), Tp = 675–900

Distribution: Madonie, Nebrodi, Mt. Etna between 1550 and 2000 m a.s.l.
 Ombrotypes: Upper Humid (UHh), $9.0 < lo < 12.0$; Lower Humid (LHu), $6.0 < lo < 9.0$
 Vegetation series: Orophilous shrubby communities of highest peaks adapted to cold environmental conditions. The occurrence of several rare taxa with relict distribution has high phytogeographical and ecological significance. On Mt. Etna, *Astragaletum siculi* becomes progressively denser and rich in taxa. In the Nebrodi and Madonie Mts. the vegetation has a similar structure, but different floristic settlement, which is ascribed to the alliance *Cerastio-Astragalion nebrodensis* (Brullo et al. 2006).

5. Upper suprasediterranean (USme), It = (120)–150

Distribution: Madonie Mts., Nebrodi Mts., Mt. Etna between 1370 and 1550 m a.s.l.
 Ombrotypes: Lower Humid (LHu) $6.0 < lo < 9.00$; Upper Subhumid (USh), $4.8 < lo < 6.0$; Lower Subhumid (LSh), $3.6 < lo < 4.8$. The Upper Subhumid is widespread within this thermotypic horizon.
 Vegetation series: The USme thermotype is characterized by beech forests, floristically distinguished by different edaphic conditions. On Mt. Etna, in the LHu horizon, the mature stage of vegetation is represented by *Epipactido meridionalis-Fagetum*, floristically very poor and with a scarce shrub layer. Under the same ombrotype, the Etnean birch woods (*Cephalanthero longifoliae-Betuletum aetnensis*) are also occurring, as edapho-xerophilous replacement of *Epipactido meridionalis-Fagetum sylvaticae* (Brullo et al. 2012).
 In the Sicilian Apennines, USh is the most prevalent ombrotype. On carbonatic substrata of the Madonie, beech woods are represented by *Luzulo siculae-Fagetum*, while on siliceous substrata of the Madonie and Nebrodi Mts., the mature stage of vegetation series is *Anemono-Apenninae-Fagetum*. In the climatophilous belt of *Luzulo siculae-Fagetum*, narrow gorges with a microclimate characterized by a high degree of atmospheric moisture, on dolomites, are settled by *Hieracio madoniensis-Fagetum sylvaticae*. Additionally, *Junipero hemisphaericae-Abietetum nebrodensis* represents the edapho-xerophilous vegetation type, with a remarkable pioneer character, occurring in the Madonie Mts. within the area potentially occupied by the acidophilous beech forest (Brullo et al. 2001).
 On the northern slopes of the Nebrodi Mts., the beech forests of *Anemono apenninae-Fagetum sylvaticae* are replaced by *Taxus baccata* forests (*Ilici aquifolii-Taxetum baccatae*) in stands characterized by colder and more humid and oceanic conditions. On rocky substrata, slightly acidic and well humified of the Madonie, Nebrodi and Peloritani Mts., the acidophilous holm oak forest named *Geranio versicoloris-Quercetum ilicis* is also found (Bazan et al. 2010). The Lsh ombrotype, on the north-eastern slopes of Mt. Etna, is characterized by mesophilous *Quercus congesta* woods (*Agropyro panormitani-Quercetum congestae*). This association in

more xeric conditions is replaced by *Daphno laureolae-Pinetum calabricae*, and on the eastern slopes of Mt. Etna at higher altitudes by *Vicio cassubicae-Quercetum cerridis*. In the sheltered and shady valleys, linked to more mesic conditions in comparison with the previous two associations, *Agropyro panormitani-Populetum tremulae* is occurring.

6. Lower supramediterranean (LSme), It = 150–220

Distribution: Sicani Mts., Busambra Rock, Palermo Mts., San Calogero, Favara and Granza, Madonie Mts., Nebrodi Mts., Peloritani Mts., Mt. Etna, between 960 and 1400 m a.s.l.

Ombrotypes: Lower subhumid (LSh), $3.6 < I_o < 4.8$; Upper dry (Udry), $2.8 < I_o < 3.6$.

Vegetation series: Within the Lsh ombrotype, in the mountain ridges of the Nebrodi Mts., the most widespread type of wood is *Arrhenathero nebrodensis-Quercetum cerridis*. This association represents the mature stage of a vegetation series made up by the shrubby vegetation of *Pruno-Rubion ulmifolii* and mesophilous meadows of *Plantaginion cupanii*.

Arrhenathero nebrodensis-Quercetum cerridis is floristically well differentiated from other Turkey oak woods of the Southern Apennines for the occurrence of several endemic species such as *Arrhenatherum nebrodense*, *Aristolochia sicula*, and *A. clusii*.

On the northern slopes of the Nebrodi Mts., with a remarkably oceanic mesoclimate caused by the exposure to moisture condensation from the sea, *Arrhenathero nebrodensis-Quercetum cerridis* is replaced by *Ilici aquifolii-Quercetum cerridis*. This association is well differentiated from the floristic, ecological and syndynamic viewpoint.

Within the *Arrhenathero nebrodensis-Quercetum cerridis* distribution area, in the north-facing slopes of the valleys of the Peloritani Mts., with remarkably humid microclimatic conditions, the turkey oak vegetation is replaced by *Melitto albidae-Fagetum sylvaticae*, which has to be regarded as an extrazonal community (Brullo *et al.* 2012).

In the Madonie Mts., on quartz sandstones and flysch, under oceanic mesoclimate conditions, *Ilici aquifolii-Quercetum austrothyrrhenicae* is occurring. Within the same bioclimatic belt, on gently slopes less humid, this association is replaced by *Ilici aquifolii-Quercetum leptobalani*. Its physiognomy is given by the occurrence of many different oak species, such as *Quercus leptobalanos*, *Q. congesta*, *Q. dalechampii* and sometimes *Q. ilex*.

LSme Udry is quite a rare bioclimatic combination in Sicily, well identified by the series of *Teucrio siculi-Quercetum ilicis*, limited to restricted areas of the Madonie and western Nebrodi Mts.

7. Upper mesomediterranean (UMme), It = 220–285

Distribution: Mountain areas between 620 and 1030 m a.s.l. This termotype is widespread on the mountain areas of Sicily: Palermo Mts., High Belice Corleonese, Sicani Mts., Madonie Mts., Upper Valley of the Salso River, Nebrodi Mts., highest hills of Enna, Peloritani Mts., Erei Mts., Etna and Hybalean Mts.

Ombrotypes: Lower dry (Ldry), $I_o = 2.0-2.8$; Upper dry (Udry), $I_o = 2.8-3.6$; Lower subhumid (Lsh), $I_o = 3.6-4.8$; Upper subhumid (Ush), $I_o = 4.8-6.00$.

Vegetation series: The subhumid ombrotype, occurring in the Peloritani Mts. and Mt. Etna areas is linked to acidophilous vegetation series. On Mt. Etna, it is outlined by *Agropyro panormitani-Quercetum congestae* and by *Arabido turritae-Quercetum congestae*. The last one is a basiphilous forest physiognomically characterized by the dominance of southern oaks, such as *Quercus congesta*, *Q. dalechampii* and *Q. ilex*. In narrow impluvia, where there are particular environmental conditions, represented by elevated atmospheric moisture, the series of *Aceri obtusati-Ostryetum carpiniifoliae* is found. On the eastern slopes of Mt. Etna, *Doronico orientalis-Castanetum sativae* is occurring: a chestnut wood that appears floristically and ecologically quite natural.

The Udry ombrotype is localized on the southern and western slopes of Mt. Etna, on the southern slopes of the Nebrodi and Madonie Mts. The vegetation series is called *Festuco heterophyllae-Querceto congestae sigmetum*, whose stationary state is a wood physiognomized by dominant *Quercus congesta* which grows together with other oaks, such as *Q. dalechampii*, *Q. ilex* and *Q. amplifolia* (Guarino *et al.* 2013).

The *Arrhenathero nebrodensis-Querceto cerridis sigmetum*, mainly linked to supramediterranean termotype, is gradually replaced by the *Querceto gussonei sigmetum* in the Upper mesomediterranean belt, on siliceous sandy soils resulting from the weathering of quartz sandstones and flysch. The stands of *Quercus gussonei* are widespread along the northern slopes of the Nebrodi Mts. and Mt. Busambra, at the elevations between 600 and 900 m a.s.l.

At the highest elevations of the Hybalean Mts. (600–900 m a.s.l.), this bioclimatic belt is correlated to *Mespilo germanicae-Quercus virgiliana* *sigmetum*. The *Quercus virgiliana* forest represents a mesophilous plant community, strictly linked to basaltic substrata, differentiated from the other thermophilous oak woods by the occurrence of *Mespilus germanica*. Within this series, in localities characterized by a high degree of soil moisture, *Mespilo germanicae-Quercetum virgiliana* is replaced by the edaphophilous vegetation of *Lauro nobilis-Quercetum virgiliana*.

The vegetation series of *Teucrio siculi-Quercetum ilicis* is widespread along the valleys and north-facing slopes of the Sicilian mountains, on siliceous substrata (schists, granites, gneiss, vulcanites, quartz sandstones and flysch). This association is an acidophilous holm oak forest, characterized by the occurrence of calcifuge species such as *Cytisus villosus*, *Erica arborea*, *Pulicaria odora*, *Festuca exaltata* and *Teucrium siculum*.

In the Sicani and Palermo Mts., the *Sorbo torminalis-Quercus ilicis* *sigmetum* is occurring. The vegetation head series is physiognomically characterized by the dominance *Quercus virgiliana* and other rare species in Sicily such as *Sorbus torminalis*, *Physospermum verticillatum* and *Geocaryum cynapioides*. Frequent trees in this vegetation are: *Quercus ilex*, *Q. amplifolia*, *Fraxinus ornus*, *Acer campestre* and *Ostrya carpinifolia*.

On calcareous and dolomitic rocks, stable screes and immature soils, the woody vegetation is usually represented by *Aceri campestris-Quercetum ilicis*. It is an orophilous wood, characterized by *Ilex aquifolium*, *Acer campestre*, *A. monspessulanum*, *Sorbus graeca* and *Ulmus glabra*, floristically well differentiated from the other *Quercus ilex* woods of the Mediterranean Region.

8. Lower mesomediterranean (LMme), It = 285–350

Distribution: Palermo Mts, Sicani Mts., Erei Mts., uplands of the Gypsum-Sulphur Outcrops and Hybalean Mts. between 250 and 700 m a.s.l. It is the most widespread thermotype of Sicily and covers the 33.9% of the regional surface.

Ombrotypes: Lower dry (Ldry), Io = 2.0–2.8; Upper dry (Udry), Io = 2.8–3.6; Lower subhumid (Lsh), Io = 3.6–4.8; The distribution follows a geographical gradient, increasing from west to east and from south to north.

Vegetation series: The mature stands of vegetation are climatophilous forests ascribed to the order *Quercetea ilicis*.

The Lsh ombrotype is localized in the Peloritani Mts. This thermotypic horizon is linked to the vegetation series of *Erico arboreae-Quercetum virgiliana*. The head of series is a forest physiognomically dominated by *Quercus virgiliana* with a dense shrubby layer characterized by many calcifuge species, such as *Erica arborea*, *Cytisus villosus*, *Arbutus unedo*, *Teline monspessulana*, etc. The *Erico arboreae-Quercus virgiliana* *sigmetum* occurs in all ombrotypes of the LMme vegetation belt, on siliceous substrata with deep and well humified soils, and is also widespread in the Nebrodi Mts., Madonie Mts. and Eolie Islands.

The vegetation series most closely related to the Udry ombrotype is *Quercus leptobalanae* *sigmetum*. It is acidophilous vegetation characterized by *Quercus leptobalanos*, together with *Q. dalechampii*, *Q. congesta*, *Q. amplifolia*.

On marl formation, in the Ldry ombrotype, the *Pinus halepensis* series is occurring. The mature stand of the series is *Thymo capitati-Pinetum halepensis*, a pine wood with a rich shrubby layer, containing *Thymus capitatus* and other sclerophyllous species such as *Pistacia lentiscus*, *Chamaerops humilis*, *Phillyrea latifolia*, and *Teucrium fruticans*.

Within deep and mature soils on calcareous substrata, the most widespread vegetation series is the *Oleo sylvestris-Quercus virgiliana* *sigmetum* that characterizes whole LMme and Upper Thermomediterranean (UTme). The different aspects of the series are connected by a catenal contact with series of *Pistacio-Rhamno alaterni* *sigmetum* and *Quercus-Fago* *sigmetum*.

The potential natural vegetation is a *Quercus virgiliana* forest which includes other tree species, such as *Q. amplifolia*, *Q. ilex*, *Fraxinus ornus*, and *Acer campestre*. This vegetation has more xeric requirements, as shown by the occurrence of Mediterranean species such as *Olea europaea* var. *sylvestris*, *Pistacia lentiscus*, *Teucrium fruticans*, *Prasium majus*, and *Asparagus albus*.

The oak woods of *Oleo sylvestris-Quercus virgiliana* *sigmetum* are quite rare, in relation to their potential distribution, due the human settlements. The growing settlements had agricultural and pastoral activities dating back at least to the 2nd century BC. The residual well preserved patches occur in areas owned by the church, or in private hunting reserves. The LMme and UTme thermotypes occur in 68.6% of the regional area. This large surface

could be probably not only linked to the *Oleo sylvestris-Quercetum virgiliana*. This association, and the related sigmetum should be considered *sensu lato*, because of the lack of knowledge on other vegetation types.

In the deep canyons of the Hyblean Plateau (Cave), *Doronico orientalis-Quercetum ilicis* is found. This is a mesophilous association characterized by the dominance of *Quercus ilex* and sporadic deciduous oaks, such as *Q. virgiliana* and *Q. amplifolia*.

9. Upper thermomediterranean (UTme), It = 350–400

Distribution: Hills between 0 and 450 m a.s.l. This thermotype characterizes the hilly landscape of southern Sicily, the alluvial plains of Catania and along the Tyrrhenian coast, from Cape Zafferano to Cape of Orlando. It is a very representative bioclimatic belt of Sicily, covering 32.8% of the regional surface.

Ombrotypes: Upper semiarid (Usa), Io = 1.5–2.0; Lower dry (Ldry), Io = 2.0–2.8; Upper dry (Udry), Io = 2.8–3.6; Lower subhumid (Lsh), Io = 3.6–4.8; The values of the Ombrothermic Index (Io) are increasing from south to north-east. The lowest values (Semiarid) are located in the Plain of Gela.

Vegetation series: The Ldry ombrotype is linked either to cork oak and holm oak woodlands. On the Tyrrhenian slopes of the Madonie and Nebrodi Mts., on siliceous sandy substrata, the most mature vegetation stand is represented by *Genisto aristatae-Quercetum suberis*. It is a cork-oak wood dominated by *Quercus suber* and *Q. congesta*, *Q. dalechampii*, *Q. amplifolia*, *Q. ilex*, *Q. gussonei*, and *Q. × fontanesii* (Marino *et al.* 2012).

In southern Sicily cork oak woods are ascribed to *Stipo bromoides-Quercetum suberis*. The vegetation series is widespread in the Caltagirone, Niscemi, Mazzarino territories (SE Sicily), Menfi and Castelvetro territories (SW-Sicily). *Stipo bromoidis-Quercetum suberis* is a xerophilous association, localized on Pleistocenian sand deposits. On sandy soil of fossil dunes in SE Sicily, the *Junipero turbinatae-Quercetum calliprini sigmetum* is occurring. The series is localized between Gela and Marina di Ragusa, and around the Gulf of Castellammare. The *Junipero-Quercetum calliprini* association represents a maquis with small trees of *Quercus calliprinos* and *Juniperus turbinata* growing together with *Pistacia lentiscus*, *Phillyrea latifolia* and *Rhamnus alaternus*.

On carbonatic substrata in this thermotype, the *Pistacio lentisci-Quercetum ilicis sigmetum* and the *Rhamno alaterni-Quercetum ilicis sigmetum* occur. Both are *Quercus ilex* stands, rich in thermophilous species featuring the order *Quercetalia calliprini* such as *Pistacia lentiscus*, *Rhamnus alaternus*, *Pistacia terebinthus*. The series of *Pistacio lentisci-Quercetum ilicis* is localized on shallow and rocky soils, widespread everywhere in the Island, *Rhamno alaterni-Quercetum ilicis* is localized on humid costal slopes in northwestern Sicily. This association is rich in lauriphylls such as *Rhamnus alaternus*, *Viburnum tinus*, *Laurus nobilis* and climbers like *Hedera helix*, *Smilax aspera*, *Rosa sempervirens*, *Rubia peregrina*, etc. The more humid microclimatic conditions, due to sea breeze, determines the presence of this extrazonal vegetation linked to subhumid condition within the Ldry ombrotype horizon (Marino *et al.* 2013).

10. Lower thermomediterranean (LTme), It = 400–450

Distribution: Coastal areas between 0 and 220 m a.s.l. The thermotype unit characterizes the coastal area of the whole region and covers 11.5% of its surface.

Ombrotypes: Upper semiarid (Usa), Io = 1.5–2.0; Lower dry (Ldry), Io = 2.0–2.8; Upper dry (Udry), Io = 2.8–3.6; Lower subhumid (Lsh), Io = 3.6–4.8. The values of the Ombrothermic Index (Io) are increasing from south to northeast. The lowest values (Semiarid) are located in the Plain of Gela; the most humid (subhumid) along the coast of the Strait of Messina.

Vegetation series: The vegetation of Lsh is characterized by *Pinus pinea* woodlands, with a shrub layer rich in acidophilous species belonging to *Cisto-Lavanduletea* such as *Cistus crispus*, *C. salvifolius*, *Tuberaria guttata*, and *Erica arborea*. The vegetation series of *Cisto crispus-Pino pineae sigmetum* is linked to sandy schistose soils of NE Peloritani, near Messina (Bartolo *et al.* 1994).

The Udry ombrotype is characterized by the occurrence of *Oleo-Euphorbio dendroidis sigmetum*. The head vegetation series, *Oleo-Euphorbietum dendroidis*, in most of the Island has to be considered an azonal community linked to the steepest rocky slopes. However, within the coastland of Etna and Peloritani, the coastland of Agrigento and the islands of Lipari, Vulcano, Ustica, this association represents a climatophilous community.

Lower dry ombrotype is characterized by the occurrence of shrubland/maquis communities, chiefly dominated by evergreen sclerophyll and summer-deciduous shrub, belonging to

the alliance *Oleo-Ceratonion siliquae*. The mature stands of the vegetation series are *Chamaeropo humilis-Quercetum calliprini*, *Pistacio lentisci-Chamaeropotum humilis*, *Myrto communis-Pistacietum lentisci* and *Calicotomo infestae-Rhoetum tripartitae*. These associations are widespread especially along the coastland of Sicily and are related to different substrata. These vegetation series are in catenal contact with the climatophilous series of *Quercu ilicis sigmetalia* and halophilous communities of *Chritmo-Limonietea*.

11. **Upper Inframediterranean** (Ulme), It = 450–515

Distribution: Lampedusa at from 0 to 30 m a.s.l.

Ombrotypes: Lower Semiarid (Sar), Io = 1.0–1.5. Localized on the eastern part of Lampedusa Island.

Vegetation series: *Periploco-Juniperetum turbinatae sigmetum*. The head of vegetation series is a termo-xerophilous maquis dominated by *Juniperus turbinata* and *Periploca angustifolia*. Some shrubs of *Quercetalia calliprini* are abundant: *Pistacia lentiscus*, *Prasium majus*, *Olea europaea* var. *sylvestris*, *Teucrium fruticans*, *Asparagus albus*, etc.