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Methodology for edaphoclimatic assessment of olive cultivation: Application to the area of the quality mark “Olive Oil Madrid” (Spain)

Metodología para la evaluación edafoclimática del cultivo del olivo: aplicación al área de la marca de calidad “Aceite de Madrid” (España)
Metodologia para a avaliação edafoclimática do cultivo da oliveira: aplicação à área da marca de qualidade "Aceite de Madrid" (Espanha)

AUTHORS

Bienes R.[1,@]
ramon.bienes@madrid.org

Rodríguez Rastrero M.[2]

Gumuzzio Fernández J.[3]

García-Díaz A.[1]

Sastre B. E.[1]

Gumuzzio Such A.[4]

[@] Corresponding Author

[1] IMIDRA, Applied Research Department. Finca El Encín, Autovía del Noreste A-2, Km. 38.200. 28805 Alcalá de Henares, Madrid (Spain).

[2] CIEMAT, Department of Environment. Avenida Complutense, 40. 28040 Madrid (Spain).

[3] Autonomous University of Madrid, Faculty of Science, Department of Geology and Geochemistry. Cantoblanco Campus. C/Francisco Tomás y Valiente, 7. 28049 Madrid (Spain).

[4] Autonomous University of Madrid. Fundación General de la Universidad Autónoma de Madrid. Cantoblanco Campus. C/Einstein, 13. 28049 Madrid (Spain).

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ABSTRACT

The present work proposes a methodology to select the most suitable areas for olive cultivation under rainfed conditions in the Madrid Region (Central Spain). This methodology is based on an analysis of the significant edaphoclimatic parameters that characterize the study region matched with the crop requirements of the olive tree, in the framework of the Land Suitability Classification system. A key component of the proposed methodology is the selection and rating of edaphic and climatic parameters as limitations associated with olive crop requirements in rainfed conditions. The climatic parameters considered are: average temperature of the absolute minimum of the coldest month (during dormancy and growth periods), average temperature of the minimum in the phenological stages of flowering, growth and ripening, mean relative humidity in spring and autumn, and average annual sunshine hours. The edaphic parameters considered (both extrinsic and intrinsic to soil profiles) include: slope, stoniness and rockiness, drainage, presence of perched water table, infiltration rate, effective depth, available water retention capacity (AWC), cation exchange capacity (CEC), pH, base saturation, active lime, salinity, Ca/K antagonism and organic matter content. For each of these parameters, five levels of severity have been established, from "very unfavorable" (excluded) to "very favorable" (optimal), establishing specific limits within each of these ranges to compare them with the requirements of olive trees. The final phase of the evaluation is the allocation of Suitability Categories to certain areas of interest for olive growing, established according to soil and climate criteria, on the basis of Land Mapping Units defined on the studied territory. The interest of an edaphoclimatic assessment in this geographical area lies in its marginal location with respect to the main olive groves in the Iberian Peninsula, and in the variety of existing climatic and edaphic conditions, some of them generally considered as limiting the cultivation of the olive grove, as well as in an evident current expansion of this crop. The most relevant edaphic limitations derive especially from a low available water capacity, and locally, by factors such as acid pH, Ca/K antagonism or high active lime. The exclusionary limitations derive, to a great extent, from climatic characteristics, associated with low temperatures combined with high relative air humidity. This methodology is expected to serve as a basis for the delimitation of new areas on which the implantation of the olive grove may be foreseen within a period, like the present one, of remarkable expansion of this crop.

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RESUMEN

El presente trabajo propone una metodología para la selección de las áreas más adecuadas para el cultivo del olivo bajo condiciones de secano en el contexto geográfico de la Comunidad de Madrid (España). Esta metodología se basa en un análisis contrastado de los parámetros edafoclimáticos significativos que caracterizan la región de estudio, en concordancia con los requerimientos del olivo como cultivo en el marco del sistema de Land Suitability Classification. *Un componente clave de la metodología propuesta es la selección y clasificación de las limitaciones edafoclimáticas asociadas a los requerimientos del cultivo del olivo en secano. Los parámetros climáticos considerados incluyen: temperatura media de las mínimas absolutas del mes más frío (durante la parada vegetativa y el período de desarrollo), temperatura media de las mínimas en los estadíos fenológicos de floración, crecimiento y maduración, humedad relativa media en primavera y otoño, y promedio del número de horas de sol. Los aspectos considerados para evaluar limitaciones edáficas son: pendiente, pedregosidad y rocosidad, drenaje, presencia de capa colgada de agua, infiltración, profundidad efectiva, capacidad de retención de agua disponible (AWC), CEC, pH, saturación de bases, caliza activa, salinidad, antagonismo Ca/K y materia orgánica. Para cada uno de estos parámetros se han establecido 5 niveles de severidad, desde "muy desfavorable" (exclusivo) hasta "muy favorable" (óptimo), estableciendo límites específicos dentro de cada uno de estos rangos para compararlos con los requerimientos del olivar. La fase final de la evaluación es la asignación de categorías de aptitud a determinadas áreas de interés para el olivar, con características edafoclimáticas definidas, lo que implica la aplicación de la metodología propuesta sobre la base de unidades territoriales (Land Mapping Units) establecidas en el área objeto de estudio. El interés de una evaluación edafoclimática en esta zona geográfica radica en su ubicación marginal con respecto a los principales olivares de la Península Ibérica, y en la variedad de condiciones climáticas y edáficas existentes, algunas de ellas consideradas generalmente como limitantes del cultivo del olivar, así como en una evidente expansión actual de dicho cultivo en la región. Las limitaciones edáficas más relevantes derivan especialmente de una baja capacidad de agua disponible y, con carácter más local, por factores como la acidez, el antagonismo Ca/K o la elevada caliza activa. Las limitaciones excluyentes se derivan, en gran medida, de características climáticas, asociadas a bajas temperaturas y elevada humedad. La principal utilidad de la metodología propuesta se basa, principalmente, en la delimitación de nuevas áreas sobre las que se puede orientar la implantación del olivar en un periodo como el actual, de notable expansión de este cultivo.*

RESUMO

No presente trabalho propõem-se uma metodologia para selecionar as áreas mais adequadas para a cultura da oliveira em condições de sequeiro na Região de Madrid (centro de Espanha). Esta metodologia baseia-se na análise de parâmetros edafoclimáticos considerados significativos e que caracterizam a região em estudo em concordância com os requisitos da cultura da oliveira no quadro do sistema Land Suitability Classification. *A componente chave da metodologia proposta é a seleção e classificação dos parâmetros edáficos e climáticos limitantes associados aos requisitos da cultura da oliveira em condições de sequeiro. Os parâmetros climáticos considerados incluem: temperatura média das mínimas absolutas do mês mais frio (durante os períodos de dormência e desenvolvimento), temperatura média das mínimas nos estádios fenológicos de floração, crescimento e amadurecimento, humidade relativa média na primavera e outono, e média anual do número de horas de sol. Os parâmetros edáficos considerados (intrínsecos e extrínsecos ao perfil do solo) incluem: declive, pedregosidade e afloramentos rochosos, drenagem, presença de toalha freática superficial, taxa de infiltração, profundidade efetiva, capacidade de retenção de água disponível (AWC), capacidade de troca catiónica (CEC), pH, saturação em catiões, calcário ativo, salinidade, antagonismo Ca/K e matéria orgânica. Para cada um destes parâmetros foram estabelecidos cinco níveis de severidade, desde "muito desfavorável" (exclusivo) a "muito favorável" (ótimo), estabelecendo limites específicos dentro de cada uma destas gamas para os comparar com os requisitos do olival. A fase final de avaliação é a alocação de categorias a determinadas áreas de interesse para a cultura da oliveira, de acordo com os critérios de solo e clima, tendo por base a aplicação da metodologia proposta com base nas unidades territoriais (Land Mapping Units) estabelecidas para o território em estudo. O interesse de uma avaliação edafoclimática nesta área geográfica radica na sua localização marginal relativamente aos principais olivais da Península Ibérica e na variedade das condições climáticas e edáficas existentes. Algumas destas características são geralmente consideradas como limitantes da cultura da oliveira, assim como da sua expansão atual na região. As limitações edáficas mais relevantes derivam especialmente da baixa capacidade de água disponível e, com carácter mais local, de fatores como o pH ácido, antagonismo Ca/K e elevada concentração de calcário ativo. As limitações exclusivas são função, em grande medida, das características climáticas associadas a temperaturas baixas combinadas com elevada humidade relativa do ar. Espera-se que esta metodologia possa servir de base para a delimitação de novas áreas de expansão do olival nas quais a implantação desta cultura possa ser recomendada dentro de um curto período de tempo, como o presente.*

KEY WORDS
Land suitability classification, olive grove, soil and climate, land mapping units, severity levels, suitability classes.

PALABRAS CLAVE
Clasificación de Aptitud de las Tierras, olivar, suelo y clima, unidades territoriales de evaluación, niveles de severidad, clases de aptitud.

PALAVRAS-CHAVE
Classificação de Aptidão das Terras, olival, solo e clima, unidades territoriais de avaliação, níveis de severidade, classes de aptidão.

1. Introduction

The Mediterranean Region, characterized by dry and warm summers (Civantos 2008), is the largest olive production area worldwide with 10.0 million ha from a total of 10.3 million ha in the world (FAOSTAT 2015). Spain has the largest olive growing area in the world, with a total of 2.6 million ha (MAPAMA 2016a), representing one half of the European Union (EU) olive area (Camarsa et al. 2010).

The environmental impact of olive cultivation and olive oil production is particularly important for the EU in southern countries as Spain, Italy or Greece (Camarsa et al. 2010). Specific problems of the olive groves include soil erosion, rising water consumption or desertification. In this context, land assessment oriented towards the optimization of olive growing is of particular interest.

Olive groves in Spain include large areas of the Guadalquivir basin and the Southern Plateau, and to a lesser extent, in areas of the Ebro basin and the Iberian South-east. Olive groves are very scarce in the north of the Central System and west of the Iberian Mountain Range.

Olive grove requirements under rainfed conditions, related to edaphic and climatic characteristics, have been established by consulting the relevant references and the particular expertise of the IMIDRA group.

Soil and climate characteristics of the Quality Mark "Olive Oil Madrid" will be described in this work, with the aim of a further definition of Land Mapping Units to be evaluated under the proposed methodology.

1.1. Conditioning factors related to the phenological cycle of the olive grove

Six or seven months are required from flowering to harvesting the ripe fruit, which characterize a climate of short and not excessively cold winters (Sundseth 2009). Within the climatic conditions of the Iberian Southern Plateau, the flowering period extends from late May to early June, following an altitude gradient, positively correlated with temperature (Rojo 2014). The period between fruit set and ripening occurs over four to five months, and the pit hardening happens in July in the study area, beginning the biosynthesis and accumulation of the oil (Beltrán et al. 2008).

As an evergreen species, the photosynthesis of the olive tree takes place throughout the whole annual cycle. However, it has its optimum between 15 ºC and 30 ºC (Rojo 2014).

1.2. Climate requirements for olive cultivation

The basic requirements for olive cultivation are a climate of mild winter, rainy spring and autumn, with a long and dry summer with high luminosity (Bienes et al. 2011). Climatic hazards affecting plant growth (mainly frost events) and air humidity and temperature (as affecting flower and fruit development) (Orlandi et al. 2005), are considered the more relevant characteristics in the climatic evaluation.

According to Elías and Ruiz (1977), the isotherm of –7 ºC for the average temperatures of the absolute minimum limits the geographical area of the olive cultivation. Barranco et al. (2005a), place that limit below -8 °C. However, frost tolerance is a characteristic that depends on olive cultivars (Barranco et al. 2005b).

The optimum of the minimum average temperature of the coldest month ranges between –4 ºC and 2 ºC (Sys et al. 1993). In the dormancy state of the olive tree (generally from December to April), temperatures between –5 ºC and –10 ºC can cause damage to a greater or lesser extent (Sanzani et al. 2012).

Rainfall over 600 mm is acceptable for olive cultivation (Consejo Oleícola Internacional 2007) and optimum precipitation is considered around 650 mm per year. The optimum value of light requirement for olive trees is above 2,800 sunshine hours per year (Bienes et al. 2011), reducing flower formation or its viability below that value. Prolonged periods of high environmental humidity favor the development of mycosis, which are especially important during the period of flowering (García-Rojas et al. 2002).

1.3. Soil requirements for olive cultivation

Olive trees require aerated soils without flooding, since they are very sensitive to root asphyxia (Civantos 2008). Lower infiltration rates are related to soil aeration problems, the reduction of external water inputs, and the increase in runoff. The intervals established by Hillel (1980) have been considered in the assessment developed in this work.

Among the extrinsic factors to consider are: slope, stoniness and rockiness. Slope influences the erosive processes, which can be very intense in olive groves with bare and tilled soils (Gómez et al. 2009a, 2009b). Surface stoniness is also related to a lower risk of erosion (Yuksel et al. 2008; Barakat et al. 2015). Rock outcrops reduce soil surface and effective depth, which is considered as that thickness of soil in which the root system does not present limitations observed morphologically in the field.

The presence of lithic contact, high compactness and cementation are considered as restrictive characteristics. Despite its appearance as a well-developed and long-lived tree, the olive tree has a rather shallow root system (Arquero et al. 2003). Most of the roots are found in the first 60 cm (Connell and Catlin 1994; Melgar et al. 2009), although other authors have found that the olive tree roots can explore between 15–20 cm to 80–100 cm (Morettini 1972), or up to 1 m deep (Fernández 2014). The root system depends on the type and depth of the soil, as well as the aeration and water content of the depth in which root system can develops (Fernández et al. 1991).

Available water capacity (AWC) is the amount of water available for plants that can be stored in a certain soil thickness, and it is the water retained between the field capacity (–33 KPa) and the permanent wilting point (–1500 KPa).

Olive trees can grow with medium to high active lime contents. However, under such conditions, yields could decrease and tree growth is slower than usual (Pedrajas et al. 2009). Gil-Albert (1998) reports that the olive tree can grow without significant problems even with 30% active lime. However, other researchers found 30% of active lime as excessive (Bienes et al. 2011). Values around 12–15% of active lime are frequently considered as high (García et al. 2004).

In carbonated soils, potassium deficiencies may be caused by interactions with ions such as Ca^{2+} and Mg^{2+} (Fernández-Escobar et al. 1994). An index of the degree of this antagonism is the Ca/K ratio, which has its optimal between 8 and 12.

Olive trees are moderately sensitive to salinity, supporting well up to 2.7 dS m^{-1} of electrical conductivity in saturation extract (ECe) (FAO 1976; Maas and Hoffman 1977), there is no a decrease in olive yield when soil salinity is below 2.7 to 3.0 dS m^{-1} of ECe (Aragüés et al. 2005). Tolerance is a cultivar-dependent characteristic (Chartzoulakis 2005). Salinity is generally accepted to reduce shoot growth (Tattini et al. 1992; Klein et al. 1994), pollen viability and germination, number of flowers and fruits (Cresti et al. 1994).

Salinity impacts are manifested in an early ripening, together with a decrease in the harvest and a reduction of the diameter of the fruits (Melgar et al. 2009).

Low pH values are associated with deficiencies in Ca, K, N, Mg, Mo, P, and S and with an excess of Co, Cu, Fe, Mn, and Zn. In particular, soils with pH < 5 are affected by possible toxicity of interchangeable aluminum and manganese. Values of pH > 8.5 may present problems due to Fe chlorosis.

Regarding organic matter, low values (lower than 6 g kg^{-1}) are associated with poorly structured soils that are prone to erosion (Das et al. 2014), as well as to soils with low natural fertility.

2. Materials and Methods

This work is based on a Land Suitability Classification as originally established in FAO (1976) and defined as "the fitness of a given type of land for a defined use". The appraisal and grouping of specific areas of land in terms of their suitability for defined uses is contained in the reference FAO (1976). In this work, selected areas in the Quality Mark "Olive Oil Madrid" have been evaluated in terms of their suitability for olive cultivation under rainfed conditions.

2.1. Study areas

2.1.1. Olive crops in the context of the Quality Mark "Olive Oil Madrid"

The Quality Mark "Olive Oil Madrid" shows typical climatic patterns of the extensive Southeastern Plateau of the Iberian Peninsula. Such patterns correspond to cool and relatively humid winters and warm and very dry summers. Certain variations in altitude (450-800 m) and topography imply differences in several relevant climatic parameters. Olive cultivation in the Madrid Region occupies a surface of 28,728 ha (MAPAMA 2016a), notably located in the Southeastern municipalities of the region (**Figure 1**). Such surface represents a small percentage of the total of the country but an important area of the agricultural sector of Madrid Region, being the second crop in extension after barley, which occupies 40,600 ha (MAPAMA 2016a).

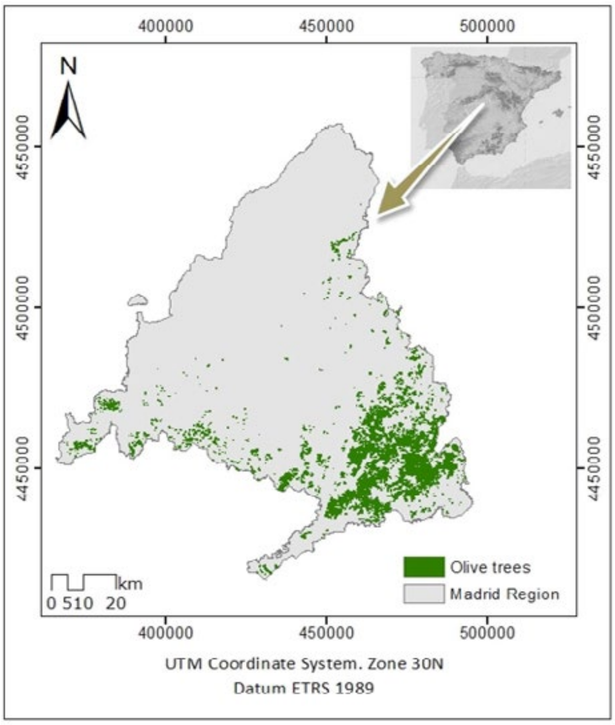

Figure 1. Main areas with presence of olive groves in Madrid Region.

From the 28,728 ha corresponding to olive groves, only about 500 ha (2%) are currently irrigated (MAPAMA 2016a). The main olive cultivar in Madrid Region is the so-called *Cornicabra*, which has a high resistance to droughts and frost (Barranco et al. 2005a).

Madrid Region shows a wide variety from the lithological and geomorphological viewpoints, with two distinct areas: west, dominated by granite rocks, arkoses and associated deposits, and the east one, with a predominance of calcium carbonate-rich rocks as limestone, marl, silts, calcareous sands and massive gypsum. This set is completed with large extensions of quaternary deposits of colluvial and alluvial origin.

Two main areas have been established for olive groves within the Quality Mark "Olive Oil Madrid" for descriptive purposes: *Southern and Southwestern* area and *Southeastern* area. Southern and southwestern area (**Figure 2**) includes agricultural surfaces in the basins of the Alberche and Guadarrama rivers, with general predominance of soils of acid or neutral reaction and loamy and coarse textures; the field observations made within this area show the abundance of olive groves mixed with vineyards and abandoned crops.

The Southeastern area (**Figure 3**) is framed in the agricultural regions of Las Vegas and *La Campiña* and is the most representative area of the olive grove in the Madrid Region. This area is characterized by soils with a basic reaction, rich in calcium carbonate with loamy and fine textures.

Figure 2. Mixed vineyard and olive groves on sandy soils in Southwestern area of the Madrid Region.

Figure 3. Some characteristic landscapes with olive groves in the Southeastern area of the Madrid Region.

2.1.2. Soil characteristics of the Quality Mark “Olive Oil Madrid”

Carbonation, argilluviation and gypsification can be considered as the dominant pedogenetic processes in the geographical context of olive groves in Spain (Ortega et al. 2016), and specifically to Madrid Region.

The classification of the soils presented in this work is based on the most recent version of the USDA-Soil Taxonomy system (Soil Survey Staff 2014). Xeric moisture regime is the only one defined in that context, determining soil classification at suborder and great group levels. *Alfisols, Entisols* and *Inceptisols* are the three soil Orders defined in the region, and totaling 17 subgroups, as represented in **Figure 4**, from a total of 205 soil profiles studied from the areas of major interest in Madrid Region.

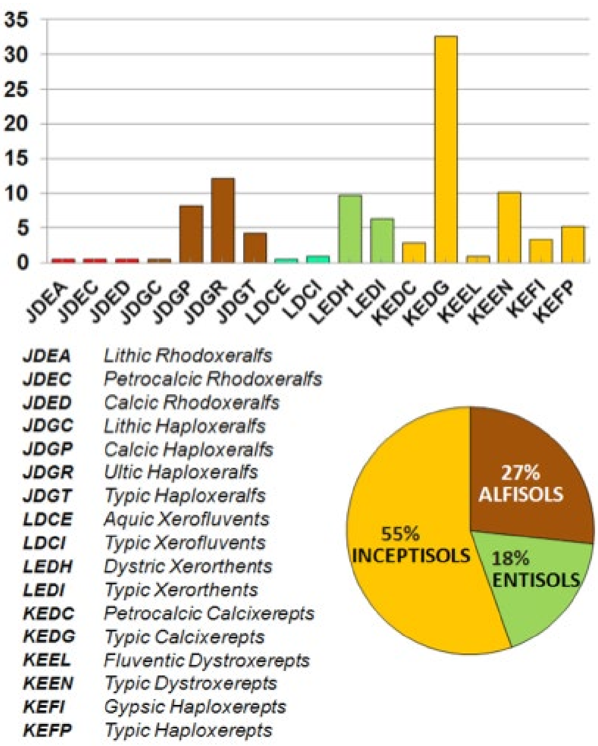

Figure 4. Relative importance of different taxa (Soil Taxonomy's Subgroups and Orders) with the base of soil profiles obtained under olive crops within the Quality Mark “Olive Oil Madrid“.

The soils associated with olive cultivation in Madrid Region indicate a high diversity at the Soil Taxonomy's Subgroup level, predominantly those developed under argilluviation (**Figures 5a and 5b**) and carbonation processes, showing general evidences of scarce humification and good aeration in the whole soil profile.

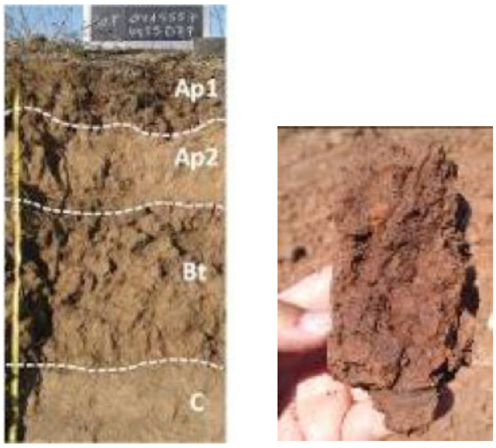

Figure 5. Argilluviation: a) *Typic Haploxeralf* in the Southwestern area of the Madrid Region; b) detail of the structure of Bt horizon.

Typic Dystroxerepts and *Ultic Haploxeralfs* are the dominant subgroups in the Southern and Southwestern areas, whereas *Typic Calcixerepts* are dominant in the Southeastern. In the three cases, these are soils with contrasted properties. *Xerorthents* group (about 15% of the soil profiles) corresponds mainly to soils whose evolution is severely limited by erosion processes. The accumulation of calcium carbonate occurs in different forms (**Figures 6a to 6d**): calcans, pseudomycelia, nodules with different degrees of hardness, and laminar accumulations with different degrees of cementation.

Calcium carbonate accumulations occasionally result in the formation of petrocalcic horizons in the Southeastern area of Madrid Region. In soils where these horizons appear relatively close to the surface, they are commonly fragmented as a result of plowing, which would allow the root system of the olive tree to take advantage of underlying non-cemented C horizons. Likewise, root horizontalization phenomena have been

Figure 6. Some details of $CaCO_3$ accumulations in the study area: a) pendants below pebbles (*Typic Calcixerept* on alluvial terrace); b) pseudomycelia and calcans in Bt / Ck contact (*Typic Haploxeralf* on arkoses); c) indurated Ck horizon (*Typic Calcixerept*); d) nodules in Ck of a *Calcic Haploxeralf* on decalcification clays).

observed in contact with high calcium carbonate content horizons, not necessarily cemented or strongly compacted.

The soil cartographic units (based on Soil Taxonomy Subgroups) making the soil components of the Land Mapping Units established in this work, within the areas of major interest for the olive grove in the Madrid Region, are listed in the **Table 1**. The sequence of taxa in which the units are presented is equivalent to the structure of Soil Taxonomy (Soil Survey Staff 2014).

2.1.3. Climatic characteristics of the Quality Mark "Olive Oil Madrid"

According to Ortega et al. (2016) the area of olive cultivation in the Madrid Region is included in the so-called "Second Modal Climate", which is consistent with the conditions of the xeric soil moisture regime as defined in Soil Taxonomy (Soil Survey Staff 2014). Within Mediterranean climate, certain differences are evident according to physiographic criteria within studied region that clearly shows the particularities of the Spanish Central Plateau, i.e. relative long periods of possible frost and low annual precipitation.

Table 1. Synopsis of soil taxonomic components of Land Mapping Units and physiographical criteria for delineation

	Soil Taxonomy Subgroups	Kind of Unit (*)	Physiographical criteria
Southern and Southwestern areas	*Ultic Haploxeralfs / Typic Haploxeralfs / Typic Dystroxerepts*	Complex	Arkosic slopes
	Ultic Haploxeralfs/Typic Dystroxerepts	Complex	High terraces (Alberche river) and arkosic slopes
	Typic Xerofluvents / Typic Xerorthents / Aquic Xerofluvents	Complex	Valley bottoms
	Typic Xerofluvents/ Miscellaneous area: water table	Complex	Alluvial floodplains
	Lithic Xerorthents/Dystric Xerorthents/Typic Humixerepts	Complex	Granite slopes, with local presence of outcrops
	Lithic Xerorthents/Dystric Xerorthents / Miscellaneous area: rock outcrops	Complex	Granite slopes with abundance of outcrops
	Dystric Xerorthents	Consociation	Granite colluvials with abundant erosive features
	Dystric Xerorthents/Typic Xerofluvents	Consociation	Very sandy alluvials. Alberche river low terraces
	Dystric Xerorthents / Typic Xerorthents	Consociation	Eroded summits and escarpments in arkoses
	Dystric Xerorthents/Fluventic Dystroxerepts	Consociation	Sandy alluvials (Alberche river catchment)
	Dystric Xerorthents / Typic Dystroxerepts	Consociation	Debris cones, glacis and colluviums in arkoses
	Dystric Xerorthents / Typic Dystroxerepts / Typic Xerofluvents	Consociation	Low terraces (Guadarrama river)
	Aquic Dystroxerepts/Typic Dystroxerepts	Complex	Depressions with temporary flooding
	Fluventic Dystroxerepts/Dystric Xerorthents/Typic Xerofluvents	Consociation	Low slopes and valley bottoms: alluvium-colluvial deposits
	Typic Dystroxerepts/Ultic Haploxeralfs	Complex	Quaternary deposits in non-flooded granitic flat areas
	Typic Dystroxerepts/Ultic Haploxeralfs/Dystric Xerorthents	Complex	Medium and high terraces (Alberche river)
	Typic Dystroxerepts/Dystric Xerorthents	Consociation	Low granite slopes and associated deposits. Mid terraces (Guadarrama river)
	Typic Dystroxerepts/Dystric Xerorthents/Typic Humixerepts/Lithic Xerorthents	Complex	Granite slopes and summits
	Miscellaneous area: gravel pits / Typic Xerofluvents	Complex	Gravel pits in terraces (Guadarrama river basin)
Southeastern areas	*Typic Haploxeralfs / Calcic Haploxeralfs / Typic Calcixerepts*	Complex	Plateaus (N of Tajuña river)
	Typic Xerofluvents / Typic Xerorthents / Gypsic Haploxerepts	Consociation	Alluvial fans in gypsum-rich areas
	Lithic Xerorthents / Typic Xerorthents	Complex	Massive gypsum. Hill summits and high slopes
	Lithic Xerorthents / Lithic Haploxerolls / Typic Calcixerepts / Miscellaneous area: rock outcrops	Complex	Limestone outcrops at Plateaus edges
	Typic Calcixerepts	Consociation	Plateaus edges
	Typic Calcixerepts (stony phase)	Consociation	Low terraces: Jarama and Tagus rivers
	Typic Calcixerepts / Typic Haploxeralfs / Calcic Haploxeralfs	Complex	Plateaus (S of Tajuña river)
	Typic Calcixerepts / Gypsic Haploxerepts	Consociation	Toeslopes in marls and gypsum marls; colluviums and glacis

(*) according to Van Wambeke and Forbes (1986)

The climatic data come from 27 thermopluviometric stations of the SIGA network (MAPAMA 2016a) within the Quality Mark, as well as adjacent areas with similar physiographic characteristics. Observed climatic differences, in terms of minimum temperatures, annual rainfall and other climatic features, can be associated with physiographical criteria as altitude and topography (**Figure 7**). The resulting areas are the basis for the climate assessment on Land Mapping Units carried out in this work.

The climatic characteristics defined in each area, in terms of temperature, rainfall, relative air humidity and insolation are summarized in **Table 2**.

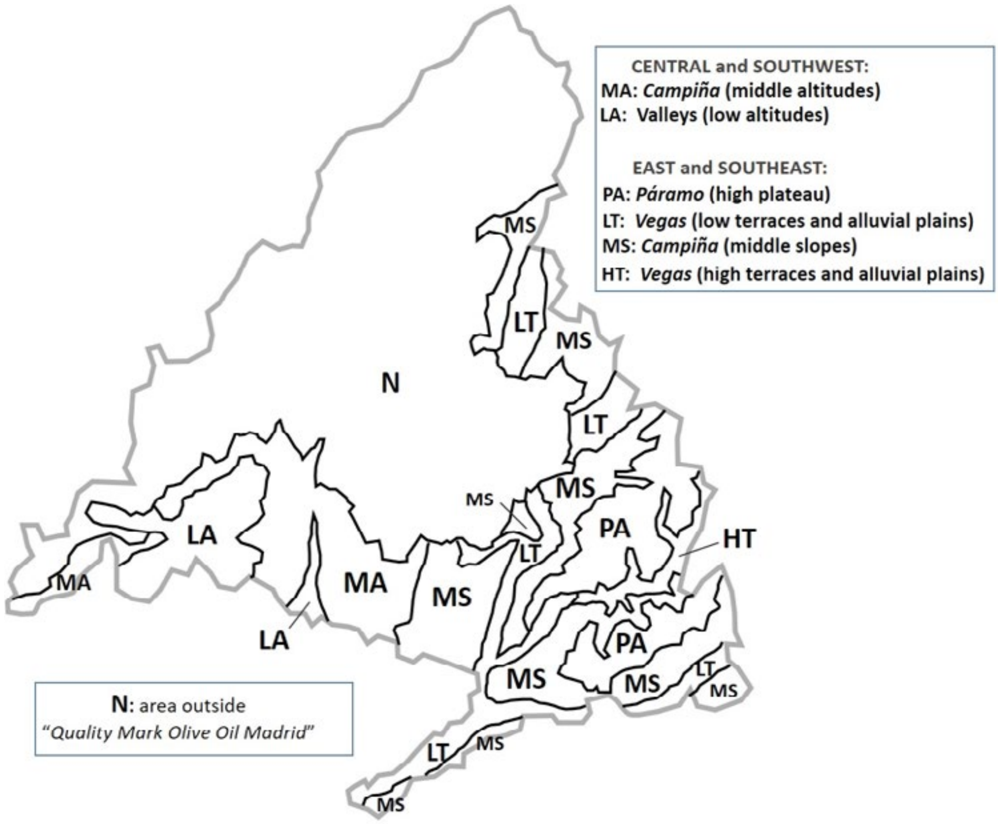

Figure 7. Climatic units established within the Quality Mark "Olive Oil Madrid".

2.2. Land Suitability Classification

Different concepts related with Land Suitability Classification are assumed in this work as follows. The concept of "Land" concern to selected biophysical characteristics of climate and soil from the study area. "Land Characteristics" include measurable simple climate and soil parameters, which have been implemented in significant groups. "Land Qualities" are complex attributes of land, frequently described by means of land characteristics, which act in a distinct manner in its influence on the suitability of olive cultivation. "Land Use Requirements" are considered within the concept of "crop requirements" in terms of physical (soil and climate) parameters and refer to the set of land qualities that are considered significant for olive cultivation. "Limitations" can be considered as land qualities which adversely affect to olive cultivation, and they are expressed in such a way as to demonstrate to what extent certain conditions do not meet the requirements for that use, what leads to establish diverse "severity levels". Additionally, the basic spatial evaluation units correspond to "Land Mapping Units", which

Table 2. Summary of the characteristics of the climatic units within the Quality Mark "Olive Oil Madrid"

Olive crop zones within QM	Physiographic criteria for delineation	Climatic characteristics
Southern and Southwestern zone	Low slopes and valleys (450–600 m)	- Highest average annual temperatures in the Region (15 ºC –16 ºC) - Mild to moderate frost (–1 ºC to –3 ºC) in dormancy period. Frost-free period from March–April to October–November. - Relatively high annual rainfall (500–600 mm). - Relatively high insolation (>2700 hours per year)
	Campiñas: middle altitudes (600–700 m), mainly gentle to undulating slopes	- Moderate average annual temperatures (14 ºC) - Moderate frost during dormancy period (–4 ºC to –7 ºC). Frost free period from April–May to October. - Low to moderate annual rainfall (400–500 mm) - Relatively high insolation (> 2700 hours per year)
Southeastern zone	*Páramo* (high plateau) surfaces: 700–800 m	- Low to moderate average annual temperatures (13 ºC –14.5 ºC) - Moderate to intense frost in dormancy period (–6 ºC to –10 ºC). Frost-free period from May to October - Low to moderate annual rainfall (400–500 mm). - Relatively high insolation (> 2700 hours per year)
	Vegas: lower terraces and alluvial plains: 500–550 m	- Moderate average annual temperatures (14 ºC) - Moderate to intense frost in dormancy period (–6 ºC to –8 ºC). Frost-free period from May to October. - Low average annual rainfall (400–450 mm) - Relatively low insolation (< 2700 hours per year)
	Campiñas: middle slopes: 550–700 m	- Moderate average annual temperatures (14 ºC) - Moderate to intense frost in dormancy period (–6 ºC to –7 ºC). Frost-free period from May to October. - Low average annual rainfall (400–450 mm) - Relatively high insolation (> 2700 hours per year)
	Vegas: higher terraces and alluvial plains (600–650 m)	- Low average annual temperatures (12.5 ºC to 13 ºC) - Intense frost in dormancy period (–9 ºC to –10 ºC). Frost free period from May to September–October. - Low to moderate annual rainfall (400–500 mm). - Relatively low insolation (< 2700 hours per year)

have been established by means of climatic, lithological, geomorphological and land cover criteria. The final result of the evaluation process is the assignment of Land Suitability categories (Orders, Classes, Subclasses and Units) to Land Mapping Units previously characterized and delineated.

Soil profile description (Schoeneberger et al. 2012) constitutes the basis of soil sampling and subsequent physicochemical characterization; thus, soil profile has been emphasized as a central element of this process, on whose basic data are assigned the different levels of severity in relation to soil characteristics concerning olive cultivation. Severity levels applied to each soil profile and meteorological stations are the core for the subsequent assignment of Suitability Classes to the Land Evaluation Units.

The evaluation process is summarized in the **Figure 8.**

In this work, Land Suitability for olive cultivation is based on edaphoclimatic criteria that have been established as key requirements, regardless whether the soil has or not olive grove, and with the aim to delimit the most suitable areas within the Quality Mark. Land Suitability is not dependent on crop yield, which is conditioned by other factors related to cropping and not to land, such as olive cultivar and age, or soil management in each plot.

Different Land Characteristics have been established according to the consulted references, as well as the previous experience of IMIDRA, as described in sections 1.2 and 1.3. These characteristics and, specifically, the

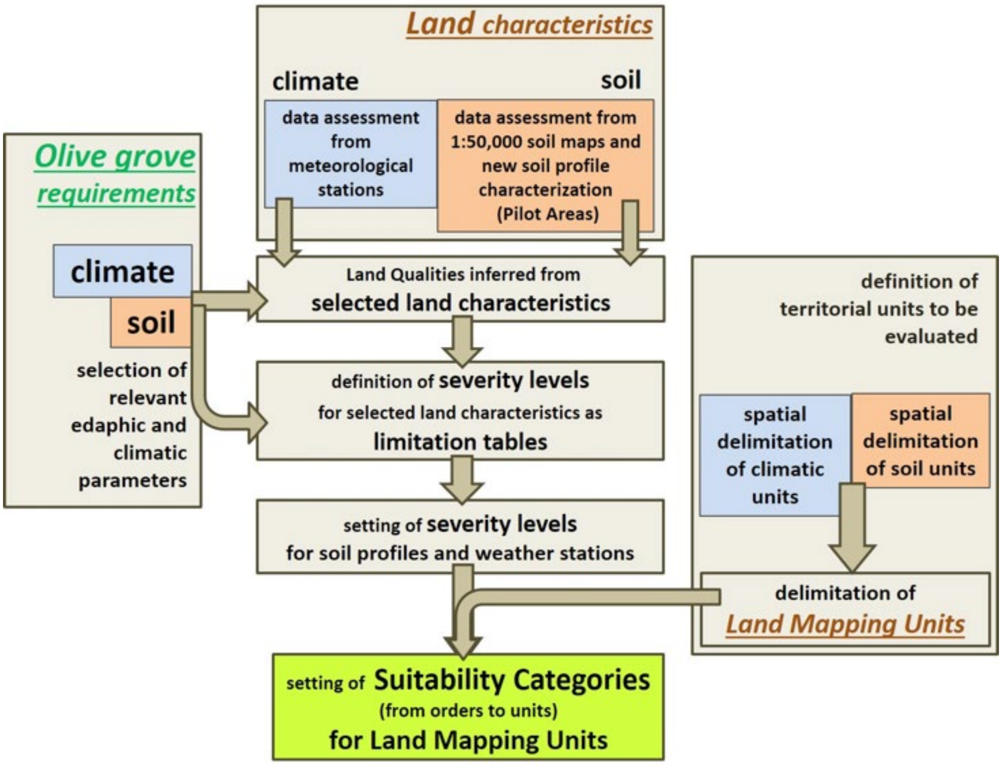

Figure 8. Scheme of the Land Suitability Classification for olive cultivation in the Madrid Region.

severity levels assigned to each soil profile, can be expected to have different importance when assigning Suitability Categories for each Land Mapping Unit. Consequently, the result of the application of this methodological proposal will allow elaborating a cartography that will facilitate the selection of the most suitable areas for the olive grove.

2.3. Base information for the definition of Land Characteristics and Land Qualities in the Quality Mark “Olive Oil Madrid”

The definition of *Land Characteristics* involves the analysis of basic soil and climatic information, which proceeds from the project "Study and elaboration of a map of the soils of the Quality Mark “Oil of Madrid" developed by the IMIDRA. As a synthesis of the information contained in this project, climatic and edaphic information have been described in sections 2.1.2 and 2.1.3.

Specifically, soil data were taken from a characterization of 205 soil profiles located in agricultural plots within the areas of major interest for olive grove in the Region.

The basic climatic data used in this study comes from four complete meteorological stations of the State Meteorological Agency's network (AEMET 2017), namely: Madrid "*Aeródromo de Cuatro Vientos*"; Getafe "*Base Aérea*"; Madrid "*Barajas*" and Torrejón de Ardoz "*Base Aérea*". These data have been complemented with those from 24 thermopluviometric stations within the SIGA network (MAPAMA 2016b) that have allowed a broader climatic characterization, taking into account the physiographic diversity of the Region.

Climate and soil data analysis has allowed the establishment of selected Land Characteristics that define Land Qualities. Regarding climatic parameters, the selected Land Characteristics include: average annual precipitation, minimum temperatures in different phenological stages, average values for relative air humidity and insolation (annual sunshine hours), from which can be defined Land Qualities as “*Climatic risk affecting plant growth*” (FAO 1976).

In relation to soil parameters, the next Land Characteristics have been selected as well as some derived Land Qualities. Selected features are as follows: slope, stoniness, outcrops (*Land workability*), drainage, presence of water table, infiltration rate (*Oxygen availability in the root zone*), effective soil depth, available water holding capacity (*Moisture availability and root limitations*), active calcium carbonate, Ca/K antagonism, soil salinity (*Calcium excess and Salinity*), cation exchange capacity, pH and cations saturation, and soil organic matter (*Nutrient availability*).

2.3.1. General criteria for definition of limitations and severity levels

In order to match Land Characteristics with crop requirements of olive groves, ranges for climatic and soil limitations were defined by means of a total of five severity levels from "very favorable" to "very unfavorable" (**Table 3**), based on the consulted references and in the experience of IMIDRA.

Table 3. Designation of severity levels for climatic and soil limitations in terms of olive cultivation requirements

Designations of severity levels	Implications
Very favorable	No significant constraints for olive cultivation
Favorable	Slight constraints for olive cultivation
Slightly favorable (o indifferent)	Its relevance is not demonstrated for olive cultivation according to literature references or IMIDRA experience
Unfavorable	Very significant constraints that, however do not impede olive cultivation
Very unfavorable or excluded	Constraints of such magnitude that discourage or even exclude olive cultivation

Selected land characteristics have been evaluated in relation to limitations and severity levels described above. Since each land evaluation unit can have several limitation types with different severity levels, it has become necessary to establish a global allocation criterion at the level of Land Mapping Unit.

2.3.2. Definition of severity levels for climatic limitations

The analyzed limiting climatic parameters for olive cultivation are mostly referred to average annual values; in other cases, they refer to the frequency at which certain values are recorded in consecutive series of years (**Table 4**). This is the case of the average minimum temperature of –7 °C, which implies events with a higher severe frost but with a lower frequency that will remain a major limitation. However, it is necessary to establish a minimum frequency for frost. A frequency of one in four years would represent severe damage in the plant in 25% of the years, which would exclude that zone as suitable for the cultivation of the olive trees. The parameters associated to extrinsic limitations to the soil (**Table 4**) have been evaluated according to the values and intervals established by FAO (2006).

As indicated in section 2.1.3, the data analyzed from each station have been considered as representative of an area with certain physiographic characteristics and susceptible to cartographic delimitation, which has allowed the territorial allocation of the climatic characteristics that define those stations, as represented in climatic territorial units delineated (**Figure 7**).

Specific combinations of values of climatic Land Characteristics, associated with different levels of severity, lead to the establishment a level of climatic limitation for each of the meteorological stations studied, and therefore the climatic fitness of specific areas for the olive crop.

Table 4. Severity levels for climatic limitations for olive cultivation assessment

Climatic criteria/ Severity levels	Very unfavorable or excluded	Unfavorable	Slightly favorable (or indifferent)	Favorable	Very favorable
Average annual precipitation	–	< 400 mm	400–500 mm	≥ 500 mm	> 650 mm
Mean minimum temperature observed in the coldest month during dormancy period (one in four years)	≤ –7 ºC (if it coincides with high relative humidity)	≤ –7 ºC (and low relative humidity)	–5 ºC to –7 ºC	≥ –5 ºC	-
Minimum temperature attained in the period prior to November 15 for 3 or more consecutive days and often ≤2 years	< –3 ºC	–3 ºC to –1 ºC	–1 ºC to 0 ºC	> 0 ºC	
Minimum average temperature reached during the flowering period	–	≤ 1 ºC	≥ 1 ºC	–	
Minimum average temperature reached during the growth and ripening periods	–	< 0 ºC	> 0 ºC	–	–
Average values for relative air humidity in spring and autumn (flowering and ripening periods)	–	> 60%	–	< 60%	–
Sunshine: average annual values (hours)	< 2500	–	< 2800	> 2800	

Note: blank cells indicate not relevant conditions in the Madrid Region.

2.3.3. Definition of severity levels for soil limitations

The influence of the slope is shown in soils that are often bare and vulnerable to erosion processes. Surface stoniness is related to the risk of erosion, and rock outcrops reduce soil surface and depth (Civantos 2008). They are taken together as "extrinsic limitations" associated with "Land Workability", as a Land Quality (**Table 5**).

Table 5. Severity levels for extrinsic soil limitations (Land Workability) for soil profiles

Extrinsic limitation / Severity levels	Slope (% and classes)	Surface stoniness (% and classes)	Rock outcrops (% surface)
Very unfavorable or excluded	> 30 (steep to very steep)	–	> 15 (common to dominant)
Unfavorable	15–30 (moderately steep)	–	5–15 (common)
Slightly favorable (o indifferent)	10–15 (strongly sloping to sloping)	≥ 15 (common to dominant)	< 5 (few to none)
Favorable	2–10 (sloping to very gently sloping)	< 15 (none to common)	0 (none)
Very favorable	< 2 (flat to very gently sloping)		

In order to evaluate the limitations associated with soil aeration (**Table 6**), three aspects have been considered: drainage, temporary presence of perched water tables and infiltration. The terminology related to drainage has been taken from Schoeneberger et al. (2012); "subaqueous drainage" and "very poorly drained" classes are considered as not-compatible with olive cultivation. Description of "redoximorphic features" is modified from FAO (2006). The concept of "perched water table" comes from NRCS-USDA (web on line). Infiltration values are based on Hillel (1980).

Table 6. Severity levels for soil aeration limitations: internal drainage (oxygen availability in the root zone) for soil profiles

Internal drainage / Severity levels	Drainage		Perched water table	Infiltration (mm h^{-1})
	Classes	Redoximorphic features		
Very unfavorable or excluded	Poorly drained; somewhat poorly drained	Strong hydromorphism. A significant part of the year with sub-anoxic conditions on C and/or base of B horizons	< 0.5 m	Very slow (< 1)
Unfavorable	Moderately well drained	Mottled between 60–100 cm. Some horizons may be saturated for short periods	0.5–1.0 m	Slow (1–5)
Slightly favorable (or indifferent)	Excessively well drained	-	1.0–1.5 m	Fast/very fast (> 60)
Favorable Very favorable	Somewhat well drained; well drained	Without mottles, saturation of some horizons by very short periods outside the vegetative period	> 1.5 m	Moderately slow (5–60)

In relation to physical constraints in the root zone (**Table 7**), the expression used to calculate the available water capacity (AWC) was the one proposed by Walker and Skogerboe (1987), standardized to a depth of 150 cm (Porta and López-Acevedo 2005). In the assignment of severity levels (**Table 7**), a compensation effect exerted by the precipitation in the vegetative period on the AWC was considered, called AWCc for the purposes of this work. This effect is allowed when the average precipitation of this period is higher than 200 mm, which is applicable for the whole area of olive cultivation in the Madrid Region. Thereby, values of AWCc lower than 64 mm within 150 cm of soil depth are considered "very unfavorable" when the average rainfall in the vegetative period is less than 200 mm, being "unfavorable" when the rainfall is 200 mm or more.

Table 7. Severity levels for physical limitations (moisture availability and root limitations) for soil profiles

Physical limitations / Severity levels	Effective depth (cm)	AWCc (mm/150 cm)
Very unfavorable or excluded	< 30	< 64 (if Pveg (*) < 200 mm)
Unfavorable	30–50	< 64 (if Pveg > 200 mm)
Slightly favorable (or indifferent)	50–70	65–127
Favorable	75–100	128–190
Very favorable	> 100	> 190

(*) Pveg: precipitation in vegetative period.

Table 8 summarizes intervals of values of soil chemical parameters in the root zone and their corresponding severity levels.

The presence in the studied soil profiles, of any of the different soil limitations (as exposed in **Tables 5 to 8**), or their combinations, determines the degree of limitation established for any whole profile. Such classes are summarized in the **Table 9**.

Table 8. Severity levels for chemical limitations (calcium excess and salinity, and nutrient availability) for soil profiles

Chemical limitations / Severity Levels	CEC ($cmol_+$ kg^{-1})	pH and cations saturation		Ca/K ratio (exchange complex)	Active lime ($g\ kg^{-1}$)	ECe ($dS\ m^{-1}$)	SOM ($g\ kg^{-1}$)
		pH	V (%)				
Very unfavorable or excluded	< 5	< 5.5	< 35	> 60	> 200	> 5.5	(*)
Unfavorable	5–10	5.5–6.5 or > 8.5	35–50	45–60	70–200	3.8–5.5	< 6
Slightly favorable (o indifferent)	11–15	–	50–75	30–45	50–70	2.7–3.8	6–12; > 200
Favorable Very favorable	> 15	6.5–8.5	75–100	15–30 < 15	< 50	< 2.7	12–20 20–200

(*) no values are considered as “Very unfavorable or excluded”

Table 9. Designation of climate and/or soil limitations from combinations of severity levels for soil profiles

Number of parameters corresponding to Severity levels					Edaphic or climatic limitations
Very unfavorable or excluded	**Unfavorable**	**Slightly favorable (or indifferent)**	**Favorable**	**Very favorable**	
≥ 1	-	-	-	-	Very severe limitations
0	≥ 3	-	-	-	Severe limitations
0	2	≥ 2	-	-	
0	2	≥ 1	-	-	Moderate limitations
0	2	0	-	-	
0	1	-	-	-	
0	0	≥ 1	-	-	Slight limitations
0	0	0	all parameters		No significant limitations

Soil types represented by profiles with no significant or slight limitations are considered of high general quality for olive cultivation. They do not have any unfavorable or most limiting factor, and only present few limitations with favorable (or indifferent) severity levels that are eventually correctable by means of common agricultural management. Soils with moderate limitations require specific agricultural management techniques. Soils with severe limitations show factors that are not unfavorable enough to consider the soil represented by the corresponding profiles as unsuitable for the crop, but the conjunction of several of them in a specific mapping unit, makes them marginal areas of olive groves. Finally, soils with exclusionary limitations have one or more very unfavorable limiting factors, whose possibility of correction is scarce and involves high cost investments that generally discourage olive cultivation.

2.4. Definition of Land Mapping Units to be evaluated

In the context of the Quality Mark "Olive Oil Madrid", some areas of interest regarding their relative importance of olive cultivation have been considered as "pilot areas". Thus, they have been mapped at a 1: 25,000 scale. This cartography is based on the information provided through field work and the subsequent description, characterization and classification of one hundred new soil profiles, and the analysis of previously existing information on soil map at 1:50,000 scale.

In the definition and delineation of the different pilot areas, representativeness has been considered in terms of soil and climate features considering olive grove areas in the whole Quality Mark, as well as a previous soil knowledge (presence of analyzed soil profiles corresponding to the 1:50,000 cartography database of the Madrid Region), and a definition of perimeter boundaries from significant geographic features, such as riverbeds, highways, main roads, and properties or administrative boundaries.

Soil forming factors as lithology, landforms and contrasting vegetation or land use, constitute the basis for the delineation of soil cartographic units at a 1:25,000 scale. One (or frequently more) soil profiles are further assigned to a specific cartographic unit, thus delimiting areas in which selected relevant edaphic characteristics are spatially expressed.

Each land unit was delineated through digital orthophoto interpretation at a 1:10,000 scale. ArcGIS software was used to establish the land unit maps of the area to a final 1:25,000 scale.

Figure 9 shows an example of a Pilot Area mapped on a scale of 1:25,000 with delineation of the corresponding soil map units.

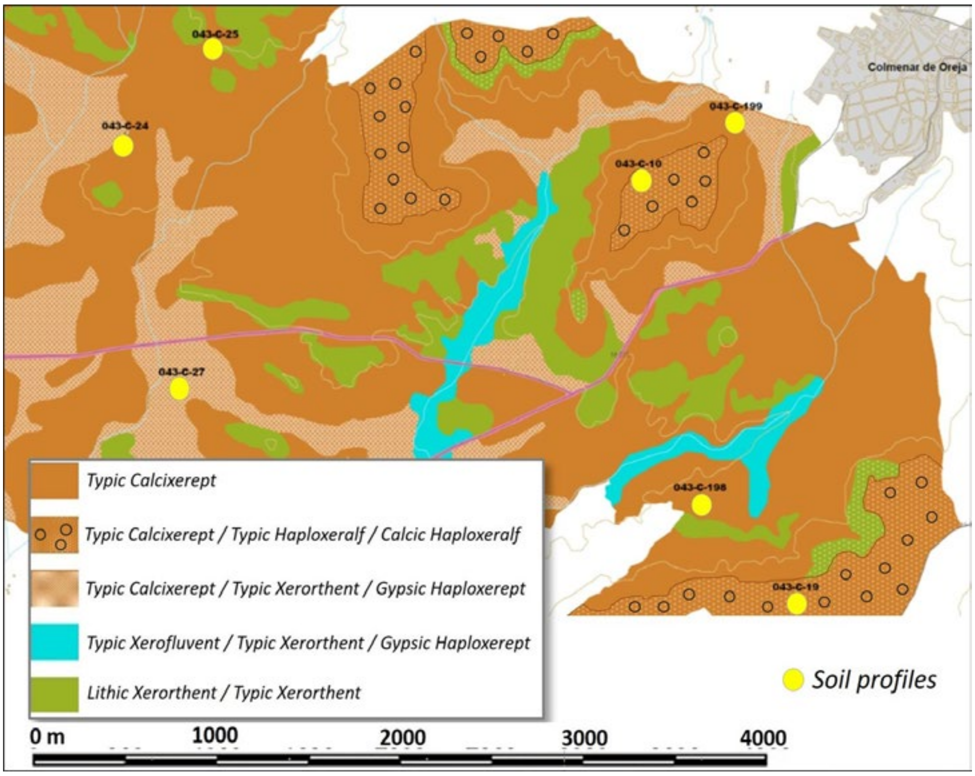

Figure 9. Example of soil mapping at a 1:25,000 scale. Pilot Area in the Municipality of Colmenar de Oreja (SE Madrid Region).

Considering the data coming from the meteorological stations as basic information, the delimitation of territories defined by homogeneous climatic characteristics has been carried out according to physiographic criteria such as altitude, orientation and topographic position.

Figure 10 shows an example of a climatic base map for the definition of Land Mapping Units, corresponding to the southeastern end of the Madrid Region. In this figure, areas in light blue represent large valley bottoms with severe or very severe climatic limitations due to the combination of low temperatures and high relative air humidity.

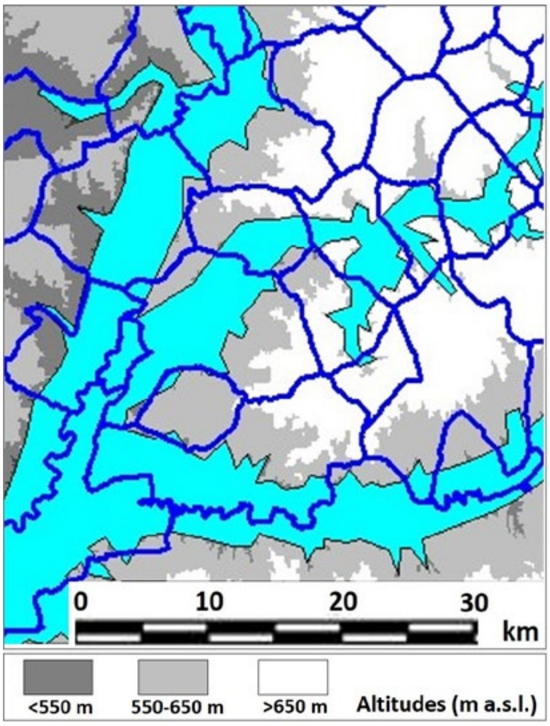

Figure 10. Example of climatic base map for Land Mapping Units delineation. Large valley bottoms with climatic limitations (low temperatures and high relative air humidity) in light blue. Boundaries between municipalities in dark blue.

Territorial units resulting from the combination of soil and climate criteria constitute the "Land Mapping Units".

2.5. Definition of suitability categories for Land Mapping Units

The matching of selected Land Characteristics (soil and climate) with crop requirements, in combinations of soil and climate limitations with severity levels, have led to the definition of suitability categories for the olive cultivation to each of the Land Mapping Units.

The suitability categories (orders and classes), in which Land Mapping Units have been assigned, are described as follows (FAO 1976):

- *Order S* (Suitable): Classes S1 (highly suitable), S2 (moderately suitable) and S3 (marginally suitable).
- *Order N* (Not Suitable): Classes N1 (currently not suitable but susceptible for correction), and N2 (permanently non suitable, uncorrectable, or excluded).

Since different soil profiles can contribute to the definition of a single Land Mapping Unit, and since each of them might show different limitations, it has been necessary to establish a criterion for the Land Suitability assignment for each one of the territorial units established. The presence in the same Land Mapping Unit of soil profiles with different suitabilities has led to the definition of "transitional suitability classes" e.g. S2/S3, as "moderately to marginally suitable" (**Table 10**). Such transitional classes can be considered as an addition of new suitability classes, which has been considered appropriate in this case in order to obtain a more accurate evaluation.

The climatic variations existing within the same Land Mapping Unit are not relevant to the work scale, so that each of these units is defined by a unique level of climatic severity.

Soils with no significant climatic limitations and "very favorable" for climatic severity level are not present in the Madrid Region territory. Moreover, given that "very severe" climatic limitations derived from low temperatures and high humidity (generally with relatively low insolation) cannot be conceptually corrected in any way, such conditions necessarily imply the classification of the specific Land Mapping Unit as N2.

Table 10. Land Suitability Classes for Land Mapping Units

Land Mapping Unit (LMU) / Soil limitations	Climatic severity level (for a specific Land Mapping Unit)	Suitability Classes for Land Mapping Units
LMU with soil profiles with only slight limitations	Slight limitations	S1 S1/S2
LMU dominated by soil profiles with slight limitations and presence of soil profiles with moderate limitations. Absence of severe or excluded limitations	Moderate limitations	S2/S1
	Severe limitations	S2/S3
	Very severe limitations	N2
LMU dominated by soil profiles with moderate limitations. Presence of soil profiles with severe limitations. Absence of soil profiles with excluded limitations	Slight limitations	S2
	Moderate limitations	S2/S3; S3/S2
	Severe limitations	S3
	Very severe limitations	N2
LMU dominated by soil profiles with severe limitations.	Slight limitations	S3
	Moderate limitations	S3/N1
	Severe limitations	N1; N2
	Very severe limitations	N2
LMU dominated by soil profiles with excluded limitations	Slight limitations	N1; N2
	Moderate limitations	
	Severe limitations	N2
	Very severe limitations	

A complete definition in terms of suitability for Land Mapping Units is provided by the addition of suitability "subclasses", as summarized in **Table 11**, and "units", as described after.

Indicating codes for suitability subclasses are thus added in order to provide information on which factors have led to the assigned qualification, but they do not necessarily indicate the intensity of these factors; i.e. an "m" (low AWCc) factor that qualifies a unit as "S2_m" will be presented at a lower intensity for purposes of limitation of use than in a unit rated "S3_m".

Table 11. Codes of suitability subclasses for the olive grove

	Limitations	Subclass code
Climate limitations	Low minimum temperatures, combined or not with high relative air humidity	**w**
Soil intrinsic limitations	Acidification	**a**
	Rooting limitations (massive structures, hardness or compaction, shallow lithic contact).	**c**
	Limitations due to slow drainage (excess moisture)	**d**
	Ca/K antagonism (absorption problems of K)	**k**
	Available humidity limitations (low AWCc)	**m**
	Cation storage limitations (low CEC)	**n**
	Limitations due to very scarce organic matter	**o**
	Limitations due to low effective depth	**p**
	Limitations due to high rockiness / stoniness	**r**
	Textural limitations	**t**
	High level of active lime	**z**
Soil extrinsic limitations	Erosion risk	**e**
	Flood risk	**i**
	Anthropic disturbance (earth-movings, urban areas, gravel pits, communication routes, various large works).	**u**

The definition of "Suitability Units" is based on the concept of "kind of map unit" (Van Wambeke and Forbes 1986), so that the concept of "consociation" has been used when the Land Mapping Unit is made up of soil classification units (taxa) that could be considered as "similar" for management purposes and regardless of their suitabilities. On the contrary, "complex" has been used when the Land Mapping Unit includes "dissimilar" soils as an indicator of greater heterogeneity. They have been represented by the addition of “Unit” codes "-1" and "-2", respectively.

3. Results and Discussion

3.1. Assignment of limitation degrees to soil profiles

Available water retention capacity (AWCc) is by far the most relevant Land Characteristic (77% of the soil profiles) that contributes for “severe limitations” assignments in the 205 studied soil profiles. Both Ca/K antagonism and low CEC imply "very severe" limitation degrees only in a 6% of soil profiles (**Figure 11**).

Low AWC is generally associated with coarse textures. Only occasionally, the determining factor for “severe" and “moderate" limitations is poor drainage, low effective depth or strong acidity. Chemical limitations such as acidity

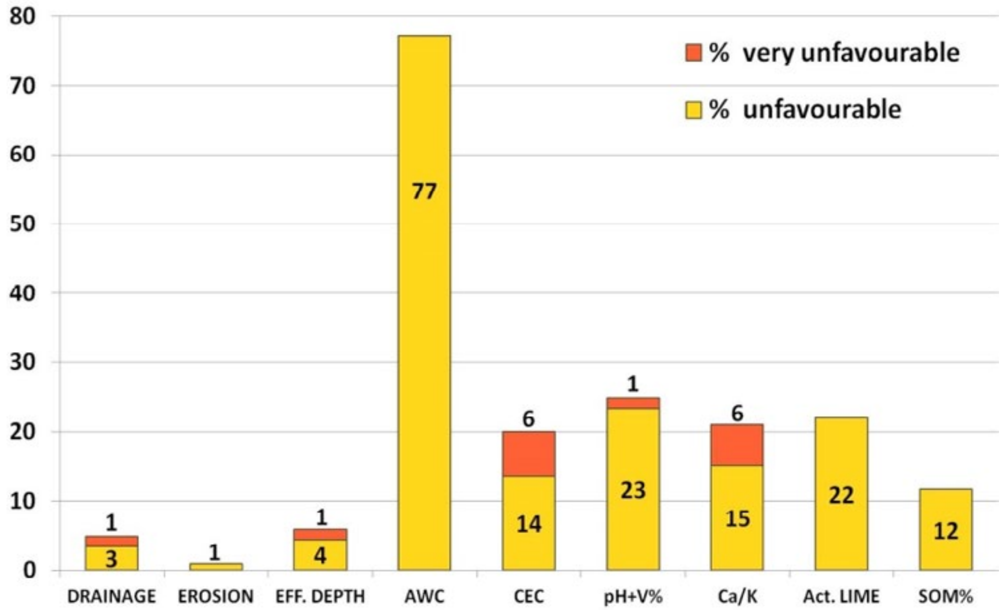

Figure 11. Relative importance (%) of "unfavorable" and "very unfavorable" soil characteristics in the assignment of limitations in soil profiles (n = 205). AWC: Available Water Capacity, CEC: Cation Exchange Capacity, V: base saturation, SOM: Soil Organic Matter.

(23% of the soil profiles), high active lime (22%), Ca/K antagonism (15%), low CEC (14%) and low organic matter content (12%) take on a more relevant role in assigning severe and moderate limitations to soil profiles.

Remarkable differences have been observed between different taxa in relation to the limitation degrees with respect to the olive crop. Figure 12 shows the percentages of five main soil Groups (Soil Survey Staff 2014) assigned to each severity levels, defining the edaphic limitation degrees of the studied soil profiles.

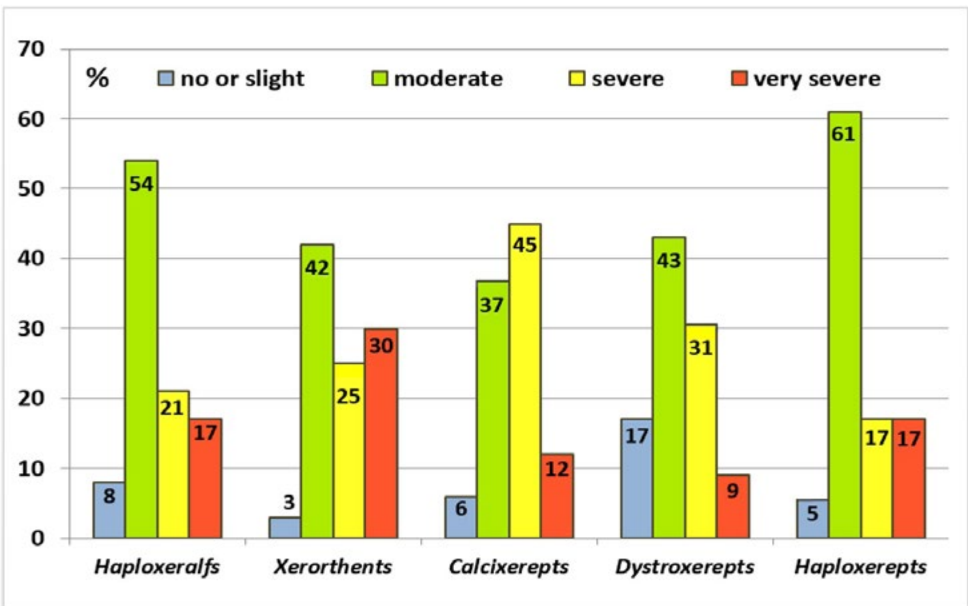

Figure 12. Degrees of limitations assigned to main soil groups.

Xerorthents Group of soils is the one that, to a greater extent, presents soil profiles associated with characteristics that assign them to “severe” and “very severe” limitations. In contrast, *Haploxeralfs* and *Haploxerepts* are soil Groups to which, to a greater degree, profiles with "light" or "moderate" limitations are associated.

3.2. Assignment of limitation degrees to climatic units

In the area of olive cultivation in the Madrid Region, it is particularly important to note the existence of minimum winter temperatures below the frequently established limit of –7 ºC, considered to be related to the damages of variable importance in plants and fruits. Also, late fall temperatures of a few degrees below zero occur frequently in different areas of the Region, especially in the Southeastern zone, being a negative influence on the ripening of the fruit. The absolute minimum temperatures in the period prior to 15 November are considered of special interest.

However, it is an extensive area in which there are remarkable climatic differences between different zones, which can be differenced by physiographic criteria (**Table 12**). In particular, such differences refer to the intensity and duration of the frost periods, among other parameters.

Table 12. Main limitations associated with climatic units within the Quality Mark (QM) “Olive Oil Madrid”

Climatic units within the QM and physiographic features	Climatic criteria and average values	Severity levels
Southwestern zone of the QM: Low slopes and valleys (450–600 m)	Average annual rainfall: 500–600 mm.	**Favorable**
	Mean minimum temperature observed in the coldest month during dormancy period: –1 ºC to –3 ºC	**Favorable**
	Minimum temperature attained in the period prior to November: 3 ºC –6 ºC	**Favorable**
	Minimum average temperature reached during the flowering period: 1 ºC –4 ºC	**Favorable**
	Minimum average temperature reached during the growth and ripening periods: 0 ºC	**Slightly favorable**
	Average values for relative air humidity in spring and autumn: < 60%	**Favorable**
	Sunshine: average annual values: > 2700 hours per year.	**Slightly favorable**
	Climatic limitations of this zone: Slight limitations	
Southern and Southwestern zone of the QM: Middle altitudes (600–700 m)	Average annual rainfall: 400–500 mm	**Slightly favorable**
	Mean of the minimum temperature observed in the coldest month during dormancy period: –4 ºC to –7 ºC.	**Slightly favorable**
	Minimum temperature attained in the period prior to November: 0 ºC –4 ºC	**Favorable**
	Minimum average temperature reached during the flowering period: –2.5 ºC to 1.5 ºC	**Unfavorable**
	Minimum average temperature reached during the growth and ripening periods: –5 ºC to 3 ºC	**Unfavorable**
	Average values for relative air humidity in spring and autumn: < 60%	**Favorable**
	Sunshine: average annual values: > 2700 hours per year	**Favorable**
	Climatic limitations of this zone : Severe limitations	

Southeastern zone of the QM: *Páramo* (high plateau) surfaces: 700–800 m	Average annual rainfall: 400–500 mm	**Slightly favorable**
	Mean of the minimum temperature observed in the coldest month during dormancy period: –6 ºC	**Slightly favorable**
	Minimum temperature attained in the period prior to November: 3 ºC	**Favorable**
	Minimum average temperature reached during the flowering period: 0 ºC	**Slightly favorable**
	Minimum average temperature reached during the growth and ripening periods: –2 ºC	**Unfavorable**
	Average values for relative air humidity in spring and autumn: < 60%	**Favorable**
	Sunshine: average annual values: > 2700 hours per year	**Favorable**
	Climatic limitations of this zone: Moderate limitations	
Southeastern zone of the QM: Lower terraces and alluvial plains: 500–550 m	Average annual rainfall: 400–450 mm	**Slightly favorable**
	Mean minimum temperature observed in the coldest month during dormancy period: –6 ºC to –8 ºC	**Unfavorable**
	Minimum temperature attained in the period prior to November: 0 ºC –1 ºC	**Favorable**
	Minimum average temperature reached during the flowering period: –1 ºC	**Unfavorable**
	Minimum average temperature reached during the growth and ripening periods: –2 ºC to –4 ºC	**Unfavorable**
	Average values for relative air humidity in spring and autumn: > 60%	**Unfavorable**
	Sunshine: average annual values: < 2700 hours per year	**Unfavorable**
	Climatic limitations of this zone: Severe limitations	
Southeastern zone of the QM: Middle slopes: 550–700 m	Average annual rainfall: 450 mm	**Slightly favorable**
	Mean minimum temperature observed in the coldest month during dormancy period: –6 ºC to –7 ºC	**Slightly favorable**
	Minimum temperature attained in the period prior to November: 1 ºC –2 ºC	**Favorable**
	Minimum average temperature reached during the flowering period: –1 ºC to 0 ºC	**Unfavorable**
	Minimum average temperature reached during the growth and ripening periods: –2 ºC to –3 ºC	**Unfavorable**
	Average values for relative air humidity in spring and autumn: < 60%	**Favorable**
	Sunshine: average annual values: > 2700 hours per year	**Favorable**
	Climatic limitations of this zone: Moderate limitations	

Southeastern zone of the QM: Higher terraces and alluvial plains (600–650 m)	Average annual rainfall: 400–500 mm	**Slightly favorable**
	Mean minimum temperature observed in the coldest month during dormancy period: –8 ºC to –9 ºC	**Very unfavorable**
	Minimum temperature attained in the period prior to November: –-1 ºC to 1 ºC	**Slightly favorable**
	Minimum average temperature reached during the flowering period: –3 ºC to –1 ºC	**Unfavorable**
	Minimum average temperature reached during the growth and ripening periods: –5 ºC to –4 ºC	**Unfavorable**
	Average values for relative air humidity in spring and autumn: > 60%	**Unfavorable**
	Sunshine: average annual values: < 2700 hours per year	**Unfavorable**
	Climatic limitations of this zone: Very severe limitations	

Southwestern zones of Madrid Region show the most suitable climatic characteristics for olive cultivation. By contrast, alluvial plains, especially those corresponding to the plains and terraces of the rivers Tajuña and Henares, constitute the areas with less climatic aptitude for the olive grove, due to a combination of a long frost period and high relative air humidity in spring and autumn. The plain and the slopes of the Páramo belong to the intermediate climatic suitability class.

In the context of the Quality Mark “Olive Oil Madrid”, it is currently considered of special importance to move the harvest season to November (before the frost season) in order to avoid frequent and/or intense frosts that usually occur in December. This advancement of the harvest implies, for practical purposes, prolonging the dormancy period of the tree. This supports, within the assessment process carried out in this work, the fact of considering the possibility of temperatures of –7 °C or lower in December or January as “unfavorable”, but not as “excluding”, especially when such temperatures occur in areas with generally low relative humidity values.

3.3. Suitability Categories assigned to Land Mapping Units

The allocation of Suitability Categories (orders, classes, subclasses and units) to each Land Mapping Unit (LMU), according to edaphoclimatic criteria, is summarized in the Table 13. According to the discrepant character, in terms of limitations, that is eventually found in different soil profiles corresponding to the same LMU, the table indicates the general assignation of Suitability Category to each LMU, and a summary of the particular assignations in specific cases within the units, given an idea of the diversity of the unit under study.

As for the evaluation of Land Mapping Units (LMUs), "Moderately suitable" (S2) and "Marginally suitable" (S3) constitute the most frequent Suitability Classes for olive grove in the Quality Mark “Olive Oil Madrid”. Units of Class S1 have not been defined in an olive grove area in Madrid Region.

Land Mapping Units dominated by *Haploxeralfs* (widespread in the Region) mainly show slight to severe limitations mostly derived from low AWCc as well as moderate limitations by low temperatures. On the other hand, LMUs with *Xerorthents* as dominant group reflect moderate and severe limitations associated to low AWCc and CEC, both generally as a consequence of coarse textures and low organic matter content, leading to "marginal suitabilities" as more common qualification. Poor drainage, low temperatures (frosts) and flooding are limitations that determine the qualification of "no suitable" for LMUs frequently characterized by *Xerofluvents* group. Land Mapping Units

Table 12. Main limitations associated with climatic units within the Quality Mark "Olive Oil Madrid"

Land Mapping Units (soil component)	General Suitability Category	Summary of particular suitability categories within the LMU
Ultic Haploxeralf /Typic Haploxeralfs /Typic Dystroxerepts	**S3 wmn-2**	S2 to N1 classes, dominating soil profiles with N1 (low AWC and CEC)
Ultic Haploxeralfs /Typic Dystroxerepts	**S2/S1 dm-2**	no discrepancies
Typic Haploxeralfs /Calcic Haploxeralfs /Typic Calcixerepts	**S3 wm-2**	S2 to N1 classes, dominating soil profiles with N1 and transitional S2/S3 and S3/N1 classes (mainly associated with low AWC)
Typic Xerofluvents /Aquic Xerofluvent /Typic Xerorthent	**N2 dm-1**	S2 to N2 classes, dominating N1 (deficient drainage)
Typic Xerofluvents /Typic Xerorthent /Gypsic Haploxerept	**N2 w-1**	no discrepancies
Typic Xerofluvents / Miscellaneous land type: water table	**N2 i-2**	no discrepancies
Lithic Xerorthents /Dystric Xerorthents /Typic Humixerepts	**N2 amnp-2**	no discrepancies
Lithic Xerorthents /Dystric Xerorthents /Miscellaneous land type: rock outcrops	**N2 pmnr-2**	no discrepancies
Dystric Xerorthents	**S3 emn-1**	N2 (intense erosion locally)
Dystric Xerorthents /Typic Xerofluvents	**S3 am-1**	no discrepancies
Dystric Xerorthents /Typic Xerorthents	**N1 wamd-1**	no relevant discrepancies; N1 and N2 soil profiles (very strong limitations because of low AWCc)
Dystric Xerorthents / Fluventic Dystroxerepts	**S3 anm-1**	S2 to N1 classes (N1 because of low AWCc)
Dystric Xerorthents /Typic Dystroxerepts	**S3/S2 wamd-1**	S2 to N1 classes (N1 because of low AWCc)
Dystric Xerorthents /Typic Dystroxerepts /Typic Xerofluvents	**S2/S3 wno-1**	no discrepancies
Aquic Dystroxerepts /Typic Dystroxerepts	**N2 d-2**	no discrepancies
Fluventic Dystroxerepts / Dystric Xerorthents / Typic Xerofluvents	**S3/S2 am-1**	no discrepancies
Typic Dystroxerepts /Ultic Haploxeralfs / Dystric Xerorthents	**S2 amn-2**	no discrepancies
Typic Dystroxerepts /Ultic Haploxeralfs / Dystric Xerorthents	**S2 amn-2**	N1 (limitations associated with low AWC and acidification)
Typic Dystroxerepts /Dystric Xerorthents	**S3/S2 amn-1**	S1/S2 to N1 classes (N1 because of low AWCc)
Typic Dystroxerepts /Dystric Xerorthents /Typic Humixerepts /Lithic Xerorthents	**S2/S3 amn-2**	S2 to N1 classes (N1 because of low AWcC)
Typic Calcixerept	**S3 wkm-1**	S2 to N1 classes, dominating soil profiles with N1 and transitional S2/S3 and S3/N1 classes (mainly associated with low AWCc)
Typic Calcixerept (stony phase)	**N2 w-1**	no discrepancies
Typic Calcixerept /Typic Haploxeralf /Calcic Haploxeralf	**S3 wm-2**	No relevant discrepancies, S3 to N1 classes, associated with low AWCc
Typic Calcixerept /Gypsic Haploxerept	**S3 wkm-1**	S2 to N1 classes, dominating soil profiles with N1 and transitional S2/S3 and S3/N1 classes (mainly associated with low AWCc)

(*) Miscellaneous areas are not included in this table. In all cases, such areas are evaluated as N2.

dominated by *Dystroxerepts* (Southwestern areas of the Region) show moderate to marginal suitabilities, being acidification and low AWCc the characteristic limitations. Land Mapping Units defined by *Calcixerepts* (Southeastern areas) are mainly characterized by severe limitations both climatic and edaphic (frost in vegetative period, low AWCc, Ca/K antagonism). In this case, such edaphic limitations are mainly related to the presence of massively carbonated subsurface horizons.

4. Conclusions

In this work, a Land Suitability Classification for olive crop has been applied on the basis of diverse Land Mapping Units defined and delineated by soil and climate criteria. Certain variations from a general scheme of a Land Suitability Classification have been implemented in order to emphasize the importance of soil profiles and meteorological stations as basic elements of the proposed methodology.

In the context of the Quality Mark “Olive Oil Madrid”, “Moderately suitable" and "Marginally suitable" constitute the most frequent Suitability Classes for olive groves.

Climatic limitations mainly derive from low temperatures in the dormancy and flowering periods, showing a marked divergence according to geographical areas. Thus, while in the Southwestern zone frost is of low intensity and in short periods, this parameter is of much greater importance in the Southern area of the Region and especially in the Southeastern zone, where it is combined with high relative air humidity, which is characteristic of low terraces and floodplains. This character is decisive in the classification as "Not Suitable" for low zones of the valleys of Tagus, Jarama and, especially, Tajuña rivers.

Low AWCc is the general edaphic reason for the assignment of “low suitability” to the established Land Mapping Units. Chemical factors as low CEC, acidity, Ca/K antagonism, high active lime or low organic matter content must also be taken into account in the definition of the Suitability for olive cultivation in specific areas. Some of them are susceptible to improvement to some extent by the addition of organic amendments and other practices of proper soil management.

This work also contributes to a general characterization of the soils in which olive cultivation is currently being developed in the Madrid Region, which is characterized by a large soil and climatic variety that is relevant to the requirements of the olive grove. Different soil taxa show contrasted characteristics with respect to Land Suitability.

This methodology is expected to work as a basis for the evaluation of olive cultivation in areas currently considered as marginal in terms of soil and/or climate, in order to contribute to an accurate selection of the most suitable areas for new plantations of rainfed olive groves.

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