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Doñana National Park (south-west Spain): geomorphological characterization through a soil–vegetation study

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The geographical history of the Doñana National Park during the Quaternary is viewed as a necessary background to understanding the actual morphology and principal processes. At present, the geomorphology of the Doñana National Park is classified into three morphogenetic systems: aeolian, estuarine and littoral. This paper describes the geomorphological classification of the aeolian system (the eldest one) down to the level of morphoedaphic elements, which are recognized through a soil classification and vegetation study.

Introduction

The Doñana National Park is situated on the right bank of the mouth of the Guadalquivir River in the south-west part of the Iberian Peninsula and occupies approximately 50,000 ha. From a geomorphological point of view, Doñana can be divided into three morphogenetic systems: estuarine (marsh), littoral (shoreline) and aeolian (dunes) (Siljeström & Clemente, 1987*a*). The aeolian system is formed by sands produced through erosion of the Plio-Quaternary coastal cliff. These sands are carried by littoral drift (Menanteau, 1981) and, later, are mobilized by the action of the wind. Three geomorphological units can be differentiated within this system: stabilized dunes, mobile dunes and marsh flooding limit (Fig. 1). These units have been studied using aerial photography at a scale of 1 : 10,000, doing a great number of boreholes and soil sample analysis. The soil is afterwards classified using the Soil Taxonomy System (Soil Survey Staff, 1975).

The climate shows the variability characteristic of a Mediterranean climate (Siljeström & Clemente, 1990). Even though the temperature is quite regular between years, the rainfall shows an irregular distribution. The average annual rainfall (518 mm) has little significance in soil genesis, because although some years exceed 700 mm, other years hardly reached 300 mm. The irregular rainfall distribution is apparent not only between years, but also during them. In fact, 50% of the total precipitation falls during winter, while, in summer, a level of 5% is seldom reached (Siljeström, 1985).

The winter is short and presents mild temperatures (seldom reaching 0°C) while the summer, long and warm, reaches temperatures over 40°C quite frequently. The extremely high temperatures in summer and scarce rainfall cause a deficit of water in summer, and

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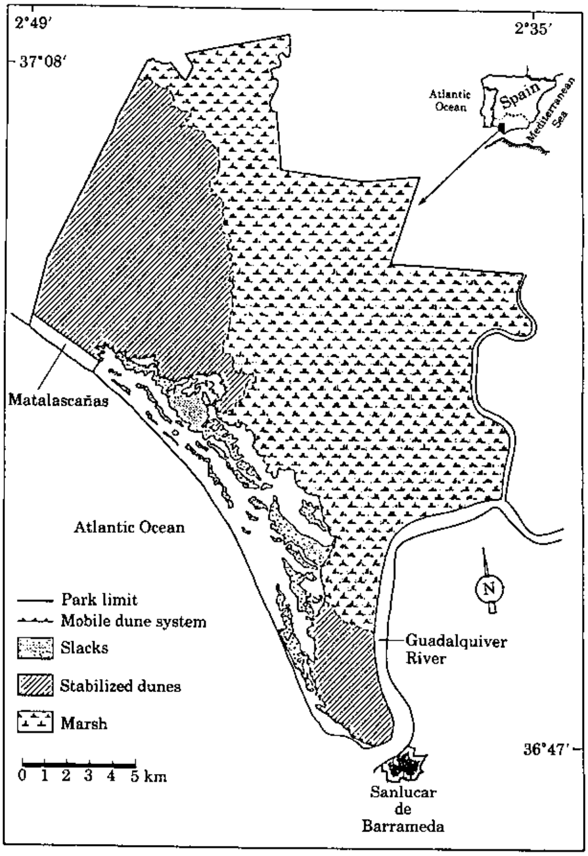

Figure 1. Doñana National Park.

rainfall that exceeds evapotranspiration occurs only during 3–4 months of the year. Based on this fact, the climate is classified as dry sub-humid with water excess in winter (Thornwaite, 1948).

Geological history

The Guadalquivir Valley is an ancient gulf which was previously a strait connecting the Atlantic with the Mediterranean during the Miocene period (Gignoux, 1960; Teran, 1967). In the Late Miocene (Tortoniense) a continuous subsidence of the depression of the Guadalquivir occurred, causing a major marine transgression during which the basal sandstone was deposited, followed by marly sediments.

During the Quaternary period there was a succession of climatic episodes clearly differentiated (Menanteau, 1981), although the best known belong to the Late Pleistocene or Würm. During this last glaciation, the climate in lower Andalusia was not very cold, as can be deduced by the presence of hazel and pine pollen in Würm III strata in the peatized layers at the base of the Asperillo Cliff (Caratini & Viguier, 1973; Vanney *et al.*, 1982), which constitute the south-west border of Doñana.

As a result of these climatic changes, there were great eustatic fluctuations and throughout the Pleistocene there was widespread regression, which resulted in a significant reduction in the depth of the gulf which was partially occupied by the marsh (Zazo, 1980).

At the end of the Pleistocene, one of the most important events was the Pre-Flandrian or Grimaldiense regression which occured at the end of the Würm III (some 18,000 years ago). According to various authors (Delibrias, 1974; Vanney *et al.*, 1979), this regression was about 110 m along the Atlantic coast and lengthened the continental shelf by approximately 40 km (Melieres, 1974; Baldy *et al.*, 1977).

The geomorphological evolution during the last 13- or 14,000 years has taken place due to a warming of the climate which became more accentuated 12,000 years ago, but because of the few data available it is supposed that during the Atlantic period (6000 years long) the climate was more humid than at present. As a consequence, there grew a dense forest (Horowitz, 1976), which progressively degraded until it disappeared in the Subboreal period as the climate permitted drier conditions which caused an upsurge in the aeolian activity. This activity (Pou, 1977) caused a series of dune fronts whose orientation suggests five changes in the direction of the dominant winds during the last 7000 years. After the glacial maximum of the Würm III began the Flandrian transgression, which caused, among other phenomena, the filling of the marsh. This transgression was very irregular (the sea rose 60 m in the first 8000 years — from 18,000 to 10,000 years B.P. and 40 m in the following 4000 years — from 10,000 to 6000 years B.P.). The sea level remained at −10 m from the one corresponding to the beginning of the Pre-Flandrian regression (Menanteau, 1981).

Finally, the first description of the studied area was given by Strabon (63 B.C.), who writes about the Guadalquivir River as flowing into a lagoon (Lacus Ligustinus), which resulted from the closing of an earlier bay by the advancing sand in the form of bars and spits (now supporting the present-day dune fronts, Clemente *et al.*, 1985).

The recent evolution of the coastline is strongly influenced by currents in a high-energy environment with significant movement of sediment. The principal current, with a NW–SE drift, carries sandy sediments from the weakly consolidated Würmian sand of the eroded coastal headland. To the south-east of Matalascañas, the headland disappears giving way to a low coast where the continuing accumulation of sand combined with the wind direction gives rise to the formation of small mounds. These mounds originate in the high part of the beach and grow towards the interior, where they form the mobile dune system (Siljeström & Clemente, 1990) in Doñana itself.

The best evidence for the geomorphological development of the littoral within the Doñana National Park is provided by the watch towers, built after 1590 by order of Felipe II for guarding the coast (Mora-Figueroa, 1978). A recession of the littoral of about 140 m to the north-west of Matalascañas can be measured, in contrast to the 163 m of beach widening to the south-east. This littoral drift is presently accentuated by human activities, including dredging, building of sea walls, etc.

The formation of a well-developed area of dunes in Doñana is the final step of the above processes, obliterating the marsh and fossilizing most of the residual forms from earlier phases in their advance.

Present-day geomorphology of Doñana National Park

Doñana National Park can be divided into three large morphogenetic regions depending on their origin: marine, marine-continental and continental, with three morphogenetic systems depending on the leading processes, respectively: littoral, estuarine and aeolian.

Using aerial photography and soil classification and situation in the landscape, a series of geomorphological units were identified. However, the precarious nature and youth of the littoral and estuarine systems do not permit further development of the forms nor the development of soils on it. For this reason, subdivisions of the recognized geomorphological units were not differentiated. On the other hand, the aeolian system

Table 1. *Division of recognized geomorphological units into subunits*

Geomorphological unit	Geomorphological subunit
Stabilized dunes	Dunes
	Eroded sand sheet
	Marismilla's strings
Mobile dune system	Mobile fronts
	Slacks
	Worms
Contact areas	Marsh flooding limit
	Permanent lagoons

shows a range of evolutionary forms owing to the existence of distinct dune ridges of different ages. Thus it is possible to divide the recognized units (stabilized dunes, mobile dune system and contact zones) into geomorphological subunits, shown in Table 1.

Stabilized dunes

The stabilized dunes can be found in two locations in the Park. The first one, in the north-west, occupies approximately 60% of the aeolian morphogenetic system and is an ancient dune system of variable potential, in which several dune phases can be distinguished. These dunes may be transgressive (Davies, 1980) or parabolic (Chapman, 1976; McKee, 1979). They are aligned, partially or totally flattened by water and wind erosion, but always with enough relief to identify a north–south orientation.

The factor which is responsible for the majority of the variation within this complex is the depth of the water-table, which is closely related to the topography (Allier *et al.*, 1974). Depending on this factor, and on the origin of the sediments, three large subunits can be separated: dunes, eroded sand sheet and Marismilla's strings.

The dunes belong to the highest and best preserved areas of the stabilized dunes, including slight depressions, which are vestiges of the interdunar valleys of the ancient system. With the exception of these small depressions, the water-table lies at more than 3 m deep, which, combined with a very permeable substratum, gives rise to a very characteristic vegetation adapted to extremely dry conditions (vegetal association *Rhamno oleoidi-Juniperetum lyciae*; Rivas-Martinez *et al.*, 1980), which impedes the mobility of the sand. Depending on the depth of the above-mentioned water-table, a series of characteristic soils, closely connected with the topography and vegetation may be distinguished, permitting their differentiation into smaller units, called morphoedaphic elements: dune top (Typic Xeropsamment), dune slope (Aquic Xeropsamment) with a vegetation represented by the *Halimio halimifolii-Stauracanthetum genistoidis* association, (Rivas-Martinez *et al.*, 1980) and dune bottom (Humaqueptic Psammaquent, Siljeström & Clemente, 1987*a*), with a vegetation characterized by the *Erico scopariae-Ulicetum australis* association (Rivas-Martinez *et al.*, 1980).

The eroded sand sheet is composed of two or three interior dune generations of little relief, eroded by water drainage and wind deflation (Vanney & Menanteau, 1979). The complex shows an erosion glacis, whose limits are the mobile dune system to the south, the marsh to the east and the Plio-Quaternary materials to the north (Fig. 1). Owing to erosion, the water-table is found nearer to the surface than in the dunes, appearing as a free water sheet in many places during the wet periods (winter).

The variable depth of the water-table, the preservation of the original vegetation (association *Oleo-Quercetum Suberis*, Rivas-Martinez *et al.*, 1980) in some areas and the presence of Plio-Quaternary sand in the edaphic layer causes wide variability in forms, soils and vegetation. This is reflected in the differentiation of a large number of morphoedaphic elements: mound top (Dystric Xeropsamment), mound slope (Aquic Dystric Xeropsamment) (both covered by the vegetal association *Halimio halimifolii-Stauracanthetum genistoidis*) and mound bottom (typic Humaquept, accompanied by the association *Erico ciliaris-Ulicetum lusitanica*), preserved forest (Histic Humaquept), temporary lagoons (Thapto Psammentic Ochraqualf covered during the dry season by the vegetal association *Trifolio resupinati-Caricetum chaetophyllae*; Rivas-Martinez *et al.*, 1980) (Siljeström & Clemente, 1987*b*) and the *Eucalyptus* sp. reforestation area (Thapto Alfic Xeropsamment) (Siljeström *et al.*, 1988).

The Marismilla's strings (following the local geographical name), placed in the south of the Park, are a series of parallel ridges in a NW–SE direction, and not higher than 10 m. These ridges alternate with small depressions which contain pools during the rainy periods, since they are found at practically the same level as the high tide (Menanteau, 1981; Clemente *et al.*, 1985). Its origin is the formation of bars and spits which favoured the filling of the marsh zone. This sand has got a distinct mineralogical (rich in $CaCO_3$) and granulometrical composition from that situated towards the north (mostly siliceous), and its morphology is characterized by curved structures in hook form, similar to the present-day 'Punta de Malandar' (Malandar Point, which forms the tip of the right margin of the Guadalquivir River mouth).

The presence of numerous bivalves in the bottom of the depressions seems to confirm the marine origin of these ridges which would have been extensions of sand banks through the joining of successive spits (Vanney & Menateau, 1979; Vanney *et al.*, 1979).

Towards the south, the strings become more spread out, and a slight deviation in the direction of the sand flow with the marine currents (from NW–SE to WNW–ESE) can be observed, producing a turn in the coast. This subunit has been divided into two morphoedaphic elements, namely, the high zone and the low zone of the strings, reflected in the moisture (%) and vegetation in each one. These parameters also affect the soil evolution, appearing as a Typic Xeropsamment under a vegetal cover of *Pinus pinea* L. in the dry places, and a Typic Haplaquoll which, covered by a vegetation of *Tamarix africana* Poir. and *Pistacea lentiscus* L., represent the more humid areas (Clemente *et al.*, 1985).

Mobile dune system

The second largest geomorphological unit is the mobile dune system. This occupies a narrow strip in the south-west of the Park, parallel to the littoral and has a length of about 25 km. It starts about 5 km from Matalascañas, and coincides with the disappearence of the stabilized dunes (which it partially covers), ending at the mouth of the Guadalquivir River with an advancing direction of SW–NE.

The disappearance of the stabilized dunes, buried by the progression of moving sand, seems to support the hypothesis of a tilting in the coast towards the east, probably produced by a subsidence in the area of the mouth of the Guadalquivir. This causes on one hand the stabilization of the dunes located to the west of Matalascañas (on the Asperillo Cliff), since they do not receive new sand because it cannot mount the unevenness of the cliff. On the other hand, the sea erodes the ancient dunes, which are later covered by new fronts forming the mobile dune system.

This system is formed by three or four well-defined fronts of varying heights and velocity, moving in the same direction as the predominant wind over a base of sand dampened by the water-table. Within this system three subunits have been distinguished: mobile fronts, slacks and 'worms' (named after their shape) (Siljeström & Clemente, 1990).

The mobile fronts are represented by the dunes which advance from SW to NE at a variable velocity, reaching 5 m $year^{-1}$ (Garcia-Novo *et al.*, 1975). These dunes are very variable in size and show an asymmetrical morphology: they have a flat deflation slope (3° or 4°) and a sharp advance slope which varies with height. As the height increases, so does the stability limit of the sand, with slope angles reaching 40° (Torres *et al.*, 1977).

The mobility of the substratum does not permit the differentiation of the mobile fronts into morphoedaphic elements. The vegetation, very scarce due to the mobility of the substratum, is represented by pioneer species, like *Ammophila arenaria* (L.) Link, or *Cyperus shoenoides* Griseb.

The slacks are interdunar valleys with a wet horizontal floor due to the proximity of the water-table. Therefore, the sand becomes 'hard' enough to permit the mobile fronts to move over them. When the dune has passed over, the sand remains moist by the capillary rise of the water. Thus, behind the train, a humid and almost horizontal surface appears giving birth to a slack, favouring the colonization by the association *Artemisio-Armerietum pungentis* (Rivas-Martinez *et al.*, 1980). The edaphic development in slacks, conditioned by the water-table depth and the vegetation, permits the differentiation of two morphoedaphic elements: dry slacks and wet slacks, characterized by Typic Xeropsamments associated with a vegetation of *Daphno-Juniperetum macrocarpae* the first ones, and Typic Psammaquents with the association *Holoshoeno-Juncetum acuti* (Rivas-Martinez *et al.*, 1980; Siljeström, 1985) the second ones.

The third subunit, worms, consists of a series of elongated, narrow sandy hillocks, parallel to each other, which appear windward of the permanent lagoons, as well as on the ground of some slacks (Garcia-Novo, 1979). Although their origin is very disputed, it seems that these formations are the remains of dune tails fixed by the water-table and vegetation, which causes the development of two morphoedaphic elements with their characteristic soils and vegetation: high worm (Aquic Xeropsamment covered by the vegetal association *Halimio halimifolii-Stauracanthetum genistoidis*) and low worm (Millic Psammaquent, accompained by *Agrostis stolonifera* L., *Juncus acutus* L. and *Scirpus holoshoenus* L.) (Siljeström, 1985; Clemente *et al.*, 1986; Siljeström & Clemente, 1990).

Contact areas

The great variety of factors which influence the contact areas among the above-mentioned units (stabilized and mobile dunes) and between them and the marsh, such as salts, iron, carbonates or organic matter accumulation and granulometric discontinuities, lead to the classification of these areas into two subunits: marsh flooding limit and permanent lagoons.

The first subunit, marsh flooding limit, is situated at the boundary between the stabilized sand and the marsh, forming a fringe which disappears towards the south, covered by the moving dunes in their advance over the marsh. It extends from north to south, varying in width from 200 to 1500 m and decreasing in altitude by 2 or 3 m.

This area is cut by a series of creeks which drain the stabilized sands. This implies a great dynamism in its morphology and soils, where many interdigitations (vertical, horizontal or both) between the fine sediments from the marsh (clays and silts) and the sandy ones from the adjacent region can be observed. Drilling has revealed these facts and, according to the predominance and the arrangement of these sediments, two morphoedaphic elements with their typical soils and vegetation are discerned: sandy area (Lithoplinthic Xeropsamment, covered by a dense vegetation of *Pteridium aquilinum* L. and *Quercus súber* L.) (Clemente *et al.*, 1981) and clayey area (Thapto Psammentic Pelloxerert), accompanied by the vegetal association *Galio-Juncetum acuti* (Rivas-Martinez *et al.*, 1980; Mudarra *et al.*, 1984; Siljeström & Clemente, 1987*c*).

The presence of very peculiar enclaves separate two other morphoedaphic elements in this subunit. First, the water-table appears in small and localized areas flowing upward and forming quicksand areas. These places appear associated with a *Trifolio resupinati-*

Caricetum chaetophyllae vegetation (Rivas-Martinez *et al.*, 1980), covering soils classified as Aeric Calciaquolls (Clemente *et al.*, 1988).

Second, in those areas surrounding the mouth of the sand-proceeding creeks into the marsh, a peat-bogged soil is formed (Hemic Hydric Medifibrist) (Siljeström, 1985; Siljeström & Clemente, 1987*c*), covered by the vegetal association *Scirpetum maritimi* (Christiansen 1934) R. Tx. 1937 (Rivas-Martinez *et al.*, 1980). This morphoedaphic element has been called creeks.

The second subunit occurring in the contact areas is represented by the permanent lagoons (Siljeström & Clemente, 1987*d*). Arranged like a rosary between the mobile dune system and the stabilized sands, they present a variable surface extension with shallow water, containing high values of suspended organic matter and peat-bogged rims (Allier *et al.*, 1974).

The water from the permanent or peridunar lagoons generally comes from the drainage of the aquifers of the mobile dune system at the base of the advancing fronts (Garcia-Novo *et al.*, 1975), and the surface drainage of the eroded sand sheet.

In spite of having the same origin, the water from the lagoons is different from that of the eroded sand sheet in its chemical composition and salinity (Hernando, 1978; Toja & Furest, 1981; Vela, 1984), in its phytoplankton (Margalef, 1976) and its zooplankton (Armengol, 1976).

Depending upon the length of time the water remains in the lagoons and, as a consequence, of the soil and vegetation development, two morphoedaphic elements have been differentiated, which are the peat-bogged rim (with an *Erico ciliaris-Ulicetum lusitanica* vegetal association growing on a soil classified as Mollic Psammaquent) and the lagoon bottom (with no vegetation and Typic Sulfaquent as representative soil) (Rivas-Martinez *et al.*, 1980; Siljeström & Clemente, 1987*d*).

Table 2. *Principal geomorphological subunits and morphoedaphic elements with their characteristic soils*

Geomorphological subunit	Morphoedaphic element	Representative soil
Dunes	Dune top	Typic Xeropsamment
	Dune slope	Aquic Xeropsamment
	Dune bottom	Humaqueptic Psammaquent
Eroded sand sheet	Mound top	Dystric Xeropsamment
	Mound slope	Aquic Dystric Xeropsamment
	Mound bottom	Typic Humaquept
	Temporal lagoon	Thapto Psammentic Ochraqualf
	Preserved forest	Histic Humaquept
	Eucalyptus area	Thapto Alfic Xeropsamment
Marismilla's strings	High zone	Typic Xeropsamment
	Low zone	Typic Haplaquoll
Moving fronts	Moving sand	—
Slacks	Wet slack	Typic Psammaquent
	Dry slack	Typic Xeropsamment
Worms	High worm	Aquic Xeropsamment
	Low worm	Mollic Psammaquent
Marsh flooding limit	Clay area	Thapto Psammentic Pelloxerert
	Sandy area	Lithoplinthic Xeropsamment
	Quicksands	Aeric Calciaquoll
	Creeks	Hemic Hydric Medifibrist
Permanent lagoons	Peat-bogged rim	Mollic Psammaquent
	Lagoon floor	Typic Sulfaquent

Conclusions

After the stabilization of the coastline towards the end of the Flandrian transgression, a strong coastal dynamic began which has led to the present-day modelling of the Doñana National Park.

The deposits which constitute the morphology of the area define two clearly differentiated zones: a sandy one (littoral and aeolian systems) and a mud-clay one (estuarine system).

The good conservation and longer evolution time of the aeolian system has caused a definite soil development in equilibrium with the environment, permitting the realization of a detailed geomorphological study. The above-mentioned study has shown, on the other hand, a close connection between the smallest landscape units and the soils developed on them. Based on this correlation, Table 2, containing the principal geomorphological subunits and morphoedaphic elements with their characteristic soils, has been established.

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