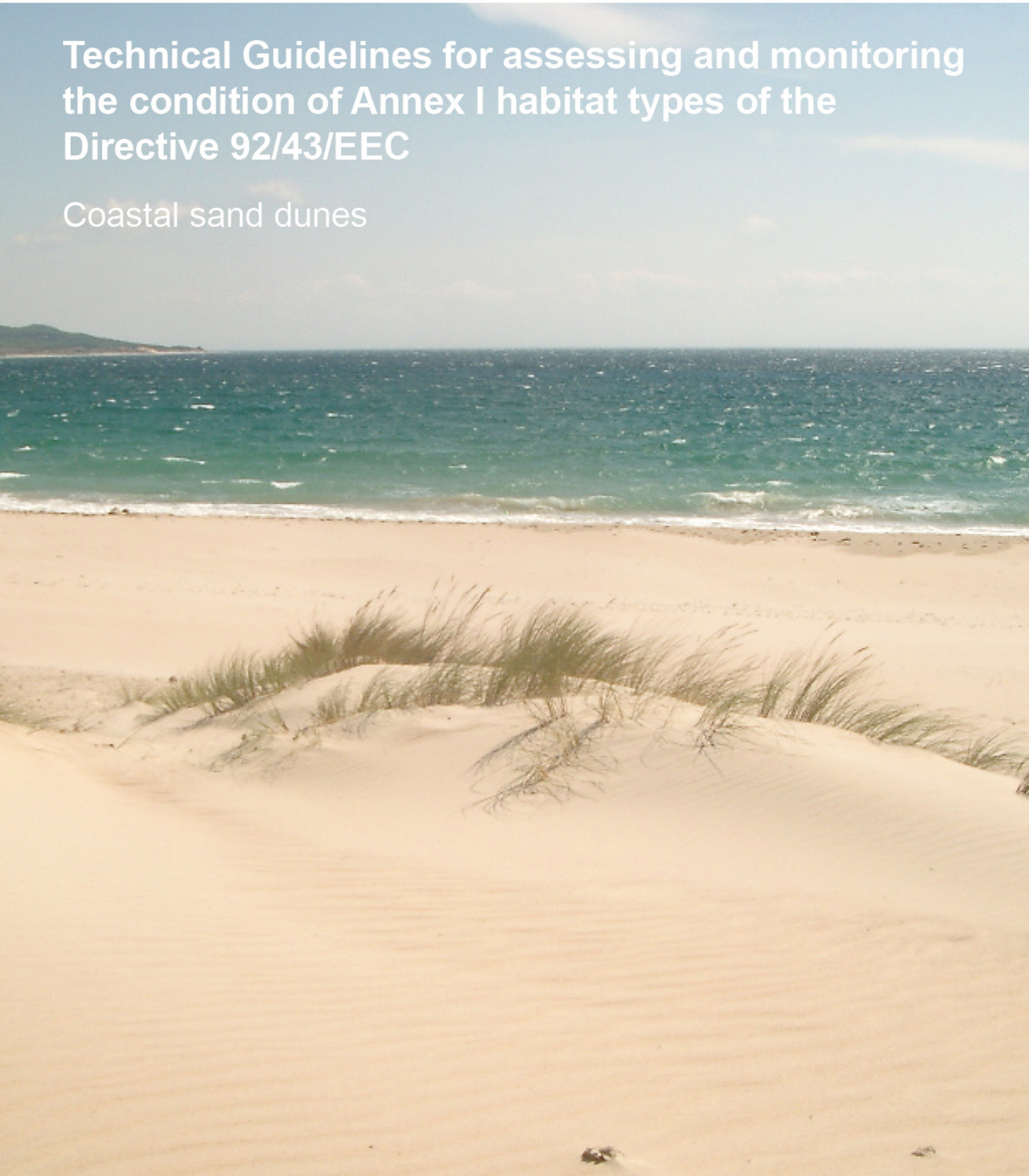
European Commission

Technical Guidelines for assessing and monitoring the condition of Annex I habitat types of the Directive 92/43/EEC

Coastal sand dunes



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Coastal sand dunes

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Contents

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Glossary and definitions

Habitats

Natural habitats: are terrestrial or aquatic areas distinguished by geographic, abiotic and biotic features, whether entirely natural or semi-natural (Habitats Directive).

Habitat condition: is the quality of a natural or semi natural habitat in terms of its abiotic and biotic characteristics. Condition is assessed with respect to the habitat composition, structure and function. In the framework of conservation status assessment, condition corresponds to the parameter "structure and function". The condition of a habitat asset is interpreted as the ensemble of multiple relevant characteristics, which are measured by sets of variables and indicators that in turn are used to compile the assessments.

Habitat characteristics: are the attributes of the habitat and its major abiotic and biotic components, including structure, processes, and functionality. They can be classified as abiotic (physical, chemical), biotic (compositional structural, functional) and landscape characteristics (based on the Ecosystems Condition Typology defined in the SEEA-EA; United Nations et al., 2021).

Species

Characteristic species: are species that characterise the habitat type, are used to define the habitat, and can include dominant and accompanying species.

Typical species: are species that indicate good condition of the habitat type concerned. Their conservation status is evaluated under the structure and function parameter. Usually, typical species are selected as indicators of good condition and provide complementary information to that provided by other variables that are used to measure compositional, structural and functional characteristics.

Variables

Condition variables: are quantitative metrics describing individual characteristics of a habitat asset. They are related to key characteristics of the habitat that can be measured, must have clear and unambiguous definition, measurement instructions and well-defined measurement units that indicate the quantity or quality they measure. In these guidelines, the following types of condition variables are included:

- **Essential variables:** describe essential characteristics of the habitat that reflect the habitat quality or condition. These variables are selected on the basis of their relevance, validity and reliability and should be assessed in all MSs following equivalent measurement procedures.
- **Recommended variables:** are optional, additional condition variables that may be measured when relevant and possible to gain further insight into the habitat condition, e.g. according to contextual factors; these are complementary to the essential variables, can improve the assessment and help understand or interpret the overall results.
- **Specific variables:** are condition variables that should be measured in some specific habitat types or habitat sub-groups; can thus be considered essential for those habitats, which need to be specified (e.g. salinity for saline grasslands, groundwater level for bog woodlands, etc.).

Descriptive or contextual variables: define environmental characteristics (e.g. climate, topography, lithology) that relate to the ecological requirements of the habitat, are useful to characterise the habitat in a specific location, for defining the relevant thresholds for the condition variables and for interpreting the results of the assessment. These variables, however, are not included in the aggregation of the measured variables to determine the condition of the habitat.

Reference levels and thresholds: are defined for the values of the variables (or ranges) that determine whether the habitat is in good condition or not. They are set considering the distance from the reference condition (good). The value of the reference level is used to re-scale a variable to derive an individual condition indicator.

Condition indicators: are rescaled versions of condition variables. Usually, they are rescaled between a lower level that corresponds to high habitat degradation and an upper level that corresponds to the state of a reference habitat in good condition.

Aggregation: is defined in this document as a rule to integrate and summarise the information obtained from the measured variables at different spatial scales, primarily at the local scale (sampling plot, monitoring station or site).

Abbreviations

EU**:** European Union

MS: Member State

EU Member States acronyms:

Austria	(AT)	Estonia	(EE)	Italy	(IT)	Portugal	(PT)
Belgium	(BE)	Finland	(FI)	Latvia	(LV)	Romania	(RO)
Bulgaria	(BG)	France	(FR)	Lithuania	(LT)	Slovakia	(SK)
Croatia	(HR)	Germany	(DE)	Luxembourg	(LU)	Slovenia	(SI)
Cyprus	(CY)	Greece	(EL)	Malta	(MT)	Spain	(ES)
Czechia	(CZ)	Hungary	(HU)	Netherlands	(NL)	Sweden	(SE)
Denmark	(DK)	Ireland	(IE)	Poland	(PL)		

SEEA EA – System of Environmental Economic Accounting- Ecosystem Accounting

Executive summary

Coastal dunes represent a unique interface between land and sea, forming dynamic and fragile habitats that fringe much of Europe's Atlantic, North Sea, Baltic, and Mediterranean coasts. These ecosystems are shaped by the continual movement of sand through wind and wave action, and support highly specialized biological communities adapted to often extreme and variable environmental conditions. Coastal dunes are integral for shoreline stabilization, protection against storm surges, and biodiversity conservation, but face increasing threats from human development, altered sediment supply and climate change, which together have accelerated habitat loss, fragmentation, and ecological degradation in recent decades.

These guidelines provide an integrated framework for assessing and monitoring the condition of coastal dune habitats listed in Annex I of the Habitats Directive, with focus on the two main groups—those of the Atlantic/North Sea/Baltic and the Mediterranean regions. The guidelines draw from extensive analysis of national approaches across EU Member States and highlight the diversity and complexity of dune systems, spanning from expansive, mobile Atlantic dunes to the often smaller and more fragmented Mediterranean types. This regional diversity translates into variations in dune morphology, vegetation composition, sediment dynamics, and susceptibility to disturbance, underlining the necessity of adaptable yet harmonized assessment methods.

Central to the guidelines is the recommendation to use a standardized suite of ecological variables that capture the key abiotic, biotic, and landscape-level characteristics of coastal dune ecosystem condition. Important abiotic variables include dune dimensions, sediment input and soil chemistry (such as pH and nutrient content), while biotic variables include the presence and abundance of typical and indicator species —including plants, bryophytes, invertebrates, birds, and reptiles—, presence of invasive or non-native species, vegetation cover (by type), flowering and regeneration rates, evidence of erosion (such as exposed roots), and the degree of natural succession. At the landscape scale, variables such as patch size, spatial configuration, habitat connectivity, and the extent of fragmentation or artificial stabilization are also addressed to assess the habitat condition.

The guidelines acknowledge the substantial variability in national monitoring practices, metrics, and threshold definitions, reflecting differences in both ecological and methodological context. To address this, these guidelines advocate for the harmonization of essential variables or indicators, reference values and data aggregation protocols, enabling reliable comparison of habitat condition across regions and over time. The adoption of thresholds for key indicators tailored to habitat type and regional conditions—such as dune height, nitrophilous species cover, degree of anthropogenic damage, and trends in habitat area—underpins consistent diagnostic and reporting frameworks.

To ensure robust and scalable monitoring, the guidelines recommend integrating conventional field approaches with advanced tools such as GIS, remote sensing, and digital modelling, thus enhancing both spatial coverage and data quality. Monitoring typically targets periods of peak ecological activity (often between spring and late summer) and is structured to capture both detailed site-level dynamics and supralocal patterns across habitat clusters. Emphasis is placed on the selection of sensitive bioindicator groups and functional species considering their diagnostic value

A cornerstone of these guidelines is the promotion of methodological harmonization at multiple levels —from data capture and variable selection to the aggregation and interpretation of assessment outcomes. By fostering consistent, objective, and sensitive monitoring protocols, the guidelines aim to achieve comparable assessments of habitat condition in the National Reports of Member States or at a biogeographical level.

1. Definition and ecological characterisation

1.1 Definition and interpretation of habitats covered

Coastal dunes are landforms composed of sand that accumulates along coastlines, which are located landward of the beach. They form in the maritime-land transition zone, in areas where there is a sufficient supply of sand and prevailing onshore winds, and have a great importance in the stability of the coast, playing a crucial role in coastal ecosystems and in their protection against storm waves (Hesp & Thom, 1990).

The environmental conditions in the areas occupied by coastal sand dunes are usually extreme and highly variable depending on their geographical location, orientation, distance to the sea and precipitation, which create different conditions for the biological communities they host (Davidson-Arnott et al., 2019).

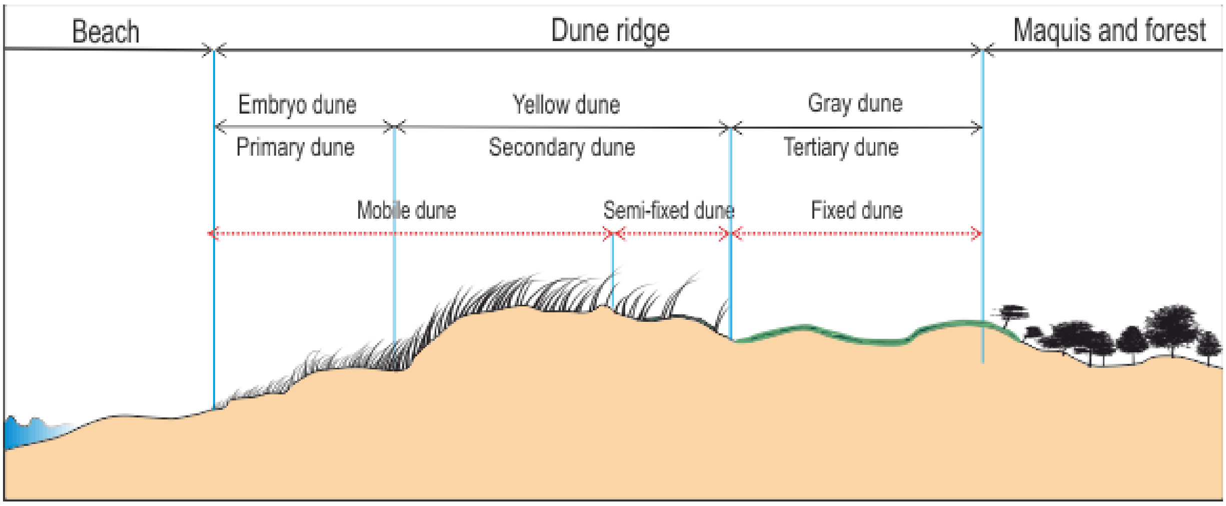
Coastal dunes harbor a highly specialized flora and fauna and are fragile ecosystems subjected to a strong sedimentary dynamic exerted by the wind and the action of the sea on a sandy and very little cohesive substrate. This natural dynamic equilibrium can be altered by degradation processes due to human land use, coastal defense measures and other activities carried out in coastal areas. Furthermore, port or coastal protection infrastructures interfere with coastal sedimentary dynamics, favouring erosion in many areas and gradually reducing coastal natural space (Martínez & Psuty, 2004).

Coastal sand dunes are formed from the sand that the waves and **currents supply** from the **coastal-marine environment** and deposit in the area of the high beach. The sea wind, since it acquires a certain speed (threshold of motion shear velocity, Bagnold, 1941) is able to transport the sand inland, which is deposited when the wind speed decreases and its carrying capacity is also reduced by friction with the roughness of the terrain and, especially with vegetation. Sand accumulates to create a dune system when the wind carrying the sand encounters an obstacle, such as driftwood, trash, or piles of seaweed, which makes that the speed of the wind locally decreases, the transport of the sand ceases and it is deposited (Delgado-Fernández & Davidson-Arnott, 2011).

The first zone where sand is deposited above the beach corresponds to the embryonic, or primary dunes, which are adapted to very specific physical characteristics and host a very special type of vegetation (Figure 1). As new sand is deposited by the wind on these primary or embryonic dunes, their physical characteristics gradually change, reducing the salinity, which allows the colonization by other species and transform them into secondary dunes that also receive sand input not only from the high beach area, but also from the embryonic dunes (Lammers et al., 2024). As new dunes form ahead of the previous ones, the characteristics of the secondary dunes continue to transform into tertiary dunes, in which the salinity and the wind contribution of sand is much lower and the substrate becomes more stable, top soil humus content is increasing, while calcareous influence is reduced (Hesp & Thom, 1990).

In temperate climates, as in the vast majority of European coasts, most of the sediments that reach the beaches are eroded from the high fluvial courses and transported by the rivers, so the dune systems are usually located near the river mouths. In dry climates, where rivers are unimportant, sediments can be of coral origin, or eroded from coastal cliffs, or come from other geological processes, such as volcanic supplies, or from the inner continental shelf during episodes of slow sea level rising. An important factor are also sea currents more or less parallel to coast lines which erode and transport sand, which is deposited in the "shade" of the current in the next bay, especially in the Baltic Sea, partially also in the island dynamics of North Sea islands.

Figure 1. Profile of a coastal dune system



Source: Ley (2012)

Dune habitats are distributed across all biogeographical regions in the EU, including the Atlantic, Continental, Boreal, and Mediterranean and Black Sea regions. Their occurrence is influenced by factors such as coastal geomorphology, climate, and human activities.

- **Atlantic Region**: dune systems in this region are often well-developed due to high wave energy and abundant sand supply. They support diverse plant communities and are crucial for coastal protection.
- **Continental Region**: dune habitats here may be less extensive but still play important ecological roles, particularly in areas with sandy and silty soils and low vegetation cover. They are especially abundant in the center of the Iberian Peninsula.
- **Boreal Region**: Dunes in this region are less common and often found in association with other coastal habitats, such as salt marshes and rocky shores.
- **Mediterranean Region**: this region supports a variety of dune habitats, including those with Euphorbia terracina, Juniperus spp., and sclerophyllous scrubs, reflecting the region's unique climatic and soil conditions.
- **Macaronesian region**: coastal sand dunes are less extensive in this region, where only a few habitat types (embryonic shifting dunes, white dunes, grey dunes, and aeolian sheets) occur in some islands.

The ecological diversity within dune habitats is significant, with each type supporting a unique set of species adapted to specific conditions. The variability within dune habitats is also notable, with differences in species composition, soil characteristics, and hydrology contributing to their ecological complexity.

Coastal sand dunes present some distinct characteristics in the various regions. For instance, Atlantic dunes are generally more extensive and well-developed compared to Mediterranean dunes. Atlantic coasts are affected by tides, which create a much wider portion of beach exposed to the aeolian deflation, producing much more sediment transport onshore. Besides, the Atlantic coast there are large sediment transport systems associated with important rivers, dealing to the development of great dune systems, stretching some kilometers inland. The Atlantic coast has some of the most extensive dune systems in Europe. Instead, Mediterranean dunes are typically narrower and more scattered compared to Atlantic dunes, due to the absence of tides and the much smaller, shorter and steeper rivers, which supply a limited amount of sediment, very often of coarse grain size, not able to produce dunes.

As regards their morphology and dynamics, Atlantic dunes are often parabolic in form and can be very dynamic systems. Mediterranean dunes are generally smaller, less mobile, and more fragmented due to human impacts. Many Mediterranean dune systems are narrow, with just a single foredune, resulting in compressed vegetation zonation.

Regarding climate and environmental factors, Atlantic dunes experience stronger prevailing westerly winds, and are exposed to more frequent sea storms and precipitation, which together with more frequent cloudy skies reduce evapotranspiration. All these factors influence vegetation colonization and growth, hence conditioning the formation and dynamics of the resulting dunes.

The plant communities also differ significantly between the two regions, with only a small set of shared species. Atlantic dunes show a more distinct and gradual vegetation zonation, showing clear successional stages from beach to inland areas (Fig. 1), with distinct zones of pioneer vegetation grading into grassland and scrub. Atlantic dune vegetation is generally more adapted to wind exposure and sand burial. Mediterranean dunes have less obvious zonation, with open vegetation transitioning more quickly to shrubland communities. Mediterranean dunes also tend to have more southern floral elements compared to Atlantic dunes, their plants show more adaptations to drought and heat stress, and endemic species are more common on Mediterranean dunes.

As regards human Impacts and conservation status, due to the contrasted climate prevailing on their respective coasts, Mediterranean dunes have also experienced greater degradation from tourism development compared to Atlantic dunes (Cooper et al., 2009). Atlantic dunes, while also impacted, often retain larger and more intact systems (Nordstrom, 2000).

Coastal dunes protected under the Habitats Directive and covered in these guidelines

Coastal dunes are currently protected by the Habitats Directive as natural habitat types of Community interest, which are threatened with disappearance in their natural range or have a reduced natural range due to their regression.

The Habitats Directive includes two main groups of coastal sand dunes, based on the region to which they belong (Atlantic, North Sea and Baltic coasts on the one hand and Mediterranean coast on the other hand), to their stage in the formation of the dune system (embryonic, shifting, fixed) and to the vegetation communities they host.

These guidelines cover all coastal sand dune habitats included in the Directive with the exception of wooded dunes that develop on sandy areas of dune origin but do not share the dynamic characteristics of coastal dunes; wooded dunes have similar characteristics to forest habitat types and are therefore covered in the guidelines on forest habitats (see Box 1).

Furthermore, inland dune habitats[1] included in the Habitats Directives are covered in the guidelines focusing on heath and scrub habitats or on grassland habitats, since they share similar characteristics and monitoring requirements with those habitat groups.

[1] The sub-group 23 Inland dunes in the Habitats Directive includes the following habitat types: 2310 Dry sand heaths with *Calluna* and *Genista,* 2320 Dry sand heaths with *Calluna* and *Empetrum nigrum* (both covered in the guidelines for heath and scrub habitats), 2330 Inland dunes with open *Corynephorus* and *Agrostis* grasslands and 2340 Pannonic inland dunes (both covered in the guidelines for grassland habitats).

Box 1. Habitat types included in the Habitats Directive that are covered in these guidelines (including an indication of those habitat type that are not covered)

21 Sea dunes of the Atlantic, North Sea and Baltic coasts

- 2110 Embryonic shifting dunes: Initial stages of dune formation, often found at the highest part of the beach where sand accumulates and pioneer species like *Elymus farctus* (*Agropyron junceum, Elytrigia juncea*) begin to colonize.
- 2120 Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes): dominated by marram grass, these dunes are mobile and constantly reshaped by wind and wave action.
- 2130 *Fixed coastal dunes with herbaceous vegetation (grey dunes): stabilized by a more diverse plant community, including grasses, herbs, and lichens, and are less mobile compared to white dunes.
- 2140 *Decalcified fixed dunes with *Empetrum nigrum*: decalcified dunes colonised by *Empetrum nigrum* heaths of the coasts. The term "fixed" should be taken to mean the opposite of "shifting".
- 2150 *Atlantic decalcified fixed dunes (*Calluno-Ulicetea*): found in regions with acidic soils, supporting heathland vegetation such as *Calluna vulgaris* (heather) and *Ulex europaeus* (gorse).
- 2160 Dunes with *Hippophae rhamnoides*: characterized by the presence of sea buckthorn, a shrub that stabilizes the sand and provides habitat for various fauna.
- 2170 Dunes with *Salix repens* ssp. argentea (*Salicion arenariea*): featuring creeping willow and other shrubby vegetation, often found in more sheltered dune areas.

Excluded (not covered in these guidelines):

- 2180 Wooded dunes of the Atlantic, Continental and Boreal region: supporting woodland vegetation, including trees like pine and oak, providing a different ecological niche compared to open dunes. This habitat type is covered in the guidelines on forests.
- 2190 Humid Dune Slacks: depressions between dunes that are seasonally wet, supporting a unique assemblage of moisture-loving plants. This habitat type is covered in the guidelines on 31 Standing waters.
- 21A0 Machairs (*in Ireland): complex habitat comprised of a sandy coastal plain with herbaceous vegetation, resulting partially from grazing and/or rotational cultivation. Only presented in Ireland and UK. This habitat type is not covered in these guidelines.

22 Sea dunes of the Mediterranean and Black Sea coast

- 2210 *Crucianellion maritimae* fixed beach dunes: fixed dunes present along the entire Mediterranean coast, with *Crucianella maritima* and *Pancratium maritimum*.
- 2220 Dunes with *Euphorbia terracina*: coastal dune grassland communities, with, among others, *Euphorbia terracina*.
- 2230 *Malcolmietalia* dune grasslands: grasslands dominated by annual species, typically found in Mediterranean region.
- 2240 *Brachypodietalia* dune grasslands with annuals: grasslands with a dominance of annual species, often found in Mediterranean dune systems.
- 2250* Coastal dunes with *Juniperus* spp.: featuring juniper species, these dunes provide important habitats for various fauna
- 2260 *Cisto-Lavenduletalia* dune sclerophyllous scrubs: Sclerophyllous scrubs dominated by *Cistus* and *Lavandula* species, found in Mediterranean regions.

Excepted (not covered in these guidelines):

- 2270 *Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*: coastal dunes colonised by Mediterranean and Atlantic thermophilus pines; including long-established plantations of these pines within their natural area of occurrence and with an undergrowth basically similar to those formations. This habitat type is covered in the guidelines on forests.

In addition to the above-mentioned dune habitats, these guidelines are also useful to address the assessment and monitoring of a habitat type which is closely linked to the dune complex, i.e. the **Annual vegetation of drift lines** (1210). This habitat type occurs in the highest part of the beach and can be associated with the embryonic shifting dunes (habitat type 2110). The Interpretation Manual of EU habitats describes the habitat type 1210 as “formations of annuals or representatives of annuals and perennials, occupying accumulations of drift material and gravel rich in nitrogenous organic matter (*Cakiletea maritimae* p.)”. According to the Manual, this habitat may develop on gravel or mixed gravel and sandy substrates (these mixtures are often very dynamic and variable) but such vegetation on purely sandy beaches should be regarded as habitat 2110 Embryonic shifting dunes if appropriate (EC, 2013). In fact, the characteristic plant species reported in the Manual for tor habitat type 1210 are very similar to those occurring in the embryonic shifting dunes, e.g. *Cakile maritima*, Salsola kali, *Euphorbia peplis*, *E. paralias* and *Eryngium maritimum*. Actually, the *Caikletea* vegetation given in the EU Interpretation Manual as typical vegetation is predominantly occurring on organic drift material on sand beaches and was included as Annex I habitat as most of this vegetation is highly threatened by beach tourism and beach cleaning. Gravel or mixed beaches have different vegetation and are covered by other habitat types as 1220 – Perennial vegetation of stony beaches, which is covered in another document (see Technical Guidelines for assessing and monitoring the condition of habitat type 1220 - Perennial vegetation of stony beaches).

1.2 Environmental and ecological characterization and selection of variables to measure habitat condition

1.2.1 Ecological characterization

Coastal dunes form when sand is deposited along the shoreline and subsequently dried out, allowing wind to transport it inland. The primary factors for their formation include:

- Sand Supply: An adequate supply of sand-sized sediment is essential for dune development.
- Wind Action: Onshore winds are necessary to move the sand from the beach to the landward areas.
- Obstacles: Natural obstacles such as vegetation, driftwood, or other debris slow down wind velocity, leading to sand deposition and the formation of incipient dunes.

The size and morphology of coastal dunes is dependent on the complex interaction between dominant winds, sediment supply, and the geomorphology of the nearshore and beach environment. As already mentioned, dunes can be divided into those that form from the direct supply of sediment from the beach face (primary dunes), and those that form from the subsequent modification of primary dunes (secondary and tertiary dunes).

Along these dune bands the vegetation is relatively homogeneous, although differences in exposition, salinity, ground water level and wind dynamics cause variations in composition and structure of the vegetation which are more important in larger dune systems.

The **embryonic shifting dunes**, or primary dunes show very specific physical characteristics: relatively constant granulometry, highly mobile substrate, very low fertility and high insolation. They are subject to frequent winds and hold high salinity, due to the sea occasionally contributed by the waves and from the sea spray, although salt concentration is lower than on the beach. In these areas, with basic sands since they are rich in carbonate and high salinity a very special type of vegetation develops (Gallego-Fernández & Martínez, 2011). These first mobile dunes are colonized by species that contribute to partially fix the sand, as *Elymus farctus (Agropyron junceum, Elytrigia juncea*) and other, starting the process of growth of the dunes that evolve towards the so-called secondary dunes. In general, the floristic composition of the primary dunes is variable and often can also host intermixed characteristic species of the beach or secondary dunes. Embryonic dunes initially form isolated, dispersed patches or minor accumulations in the high beach (*backshore* zone), acquiring different forms and dimensions, like small mounds, ramps, or terraces. Mounds can grow and join, conforming fields of small dunes, roughly parallel to the shoreline (Goldstein et al., 2017). Ramps and terraces directly connect to other pre-existing ridges of secondary dunes. When growing in vertical and horizontal dimensions, all these embryonic dunes create a new ridge of secondary dunes, or contribute to the widen and/or advance of the pre-existing secondary dune ridge seawards.

As new sand transported by the wind is deposited in the front of these primary or embryonic dunes, their physical characteristics gradually change, reducing salinity, allowing the colonization of other species and transforming into **secondary dunes or foredunes** that receive sand input both from the high beach area and from the embryonic dune (Perumal & Maun, 1999). Secondary dunes are mounds of sand of a certain height, exposed to the wind and, in normal conditions, they are out of reach of the sea. They have irregular shapes, with high peaks, hollows or depressions, plains and slopes, with a gentle slope on the side exposed to the wind and a steep fall on the opposite. Very often they develop an elongated shape, perpendicular to the prevailing winds and roughly parallel to the shoreline. Although these are **semi-fixed dunes**, although sometimes large parts of their area can be mobile. The vegetation cover is greater than in the embryonic dunes and they harbor a group of plants that hold the sand, tending to fix it by means of highly branched and creeping rhizomes, as *Ammophila arenaria*, which is responsible for the development of the dunes in height, acting as an active collectors of the sand carried by the wind and contributing to their continuous growth. Its great capacity for regeneration by large stolons allows a rapid colonization of areas with active sands. Psamophilous plants like *Ammophila arenaria* take part of the process of “ecological facilitation” (Huiskes, 1979; Brooker et al., 2008), by which the rests of a dead plant species (the “nurse”) positively impacts the growth and survival of another individual (the “beneficiary”; Lasso-Rivas, 2015).

In these areas, unlike the beaches and primary dunes, only the sea breeze arrives and, rarely, when the wind blows strongly from the sea, the foam can also reach these dunes. This, coupled with rain washing, contributes to reduce salt in the substrate, a freshwater lense is present and therefore the species presents are less halophilous. These conditions determine that the vegetation of these areas is more varied in species than in the embryonic dunes. Other properties of these sand dunes are: the lack of humus and reduced organic matter, and a rich content in calcium carbonates; in addition, they are very permeable as their sands are completely loose. The environment is usually also very dry and the vegetation in these dunes includes psammophilous, xerophytic species and few halophytic species.

As new sand is contributed onshore, the secondary dunes evolve into **tertiary dunes**, in which the salinity is much lower, since less salt comes from the sea and the precipitation gradually washes the salt from the ground. In addition, the wind contribution of sand is much lower and the substrate becomes more stable, thus less mobile, and holds increasing organic matter, with soil development and no longer supply of calcareous sand. However, as coastal dunes are a dynamic ecosystem, blowouts are locally present and can cause rejuvenation of soil and vegetation. These tertiary dunes are also called **grey, semi-fixed dunes**, consolidated or stabilized sands. Their plant communities are composed of psammophilous vegetation.

These consolidated dunes, like the secondary dunes, have an irregular shape, forming small elevations with strong slopes, peaks and gullies, although usually forming continuous ridges more or less parallel to the shoreline. Their lower salinity is one of the reasons that originates greater abundance and variety of plants. The vegetation that populates the tertiary dunes usually covers above 50 or 60% of their surface, causing them to be completely fixed, but never getting to form a closed vegetation as in the tertiary dune, next to this strip, and further inland from the coast.

These tertiary dunes are more sheltered, as the wind blows with less intensity than in the previous dune; they are more thermal because they are behind and, therefore, warmer. Their sands are still loose, therefore they remain somewhat permeable; they are no longer barely mobile and while the evaporation of water decreases, the moisture content increases in them. All this means that organic matter (humus), although still scarce, can appear in a superficial layer of very little thickness, and its incorporation into the substrate is carried out by means of microorganisms, whose number and activity are higher in these fixed dunes. Even so, this humus layer, is almost imperceptible in many places or even does not exist. Tertiary dunes often have some ericaceous dwarf shrub vegetation, besides grasses, sedges and other annual and perennial herbs.

This dune band presents much more variability in terms of flora and can include different communities depending on their distributions in various regions. Another characteristic of these dunes is the presence of mosses (e.g., *Tortula ruralis*), preferently in the north-facing slopes.

Depressions between successive ridges are common in well-developed dune systems. Their origin can be related to the advance of the secondary dunes landwards due to a scarce vegetation cover and strong onshore winds. As the foredunes move landwards they progressively transform into tertiary dunes while new secondary dunes are being generated in the seaward side, on the upper beach. This dune system in known as “transgressive dunes”. The space left between the tertiary and the secondary dune ridges forms a longitudinal depression, named “dune slack”. As all the dune ridges move landwards, new dune slacks are generated among consecutive ridges, and all the system slowly moves inland.

In other cases where there is a high supply of sediment to the coast, the shoreline advances seawards and the beach increases its width. This situation leads to the generation of new embryonic dunes in new places located seawards, leaving behind a wide space between these embryo dunes and the first consolidated foredune. As the embryo dunes grow to create a new foredune ridge, the pre-existing ridge of secondary dunes slowly transform into secondary dunes, without any displacement, just due to the advance of the shoreline seawards. Once completed the generation of the new foredune ridge, the space between the two first ridges constitutes the dune slack. Prograding coasts, characterized by a continuous, historical, advance seawards associated with an important sediment supply, can develop a significant number of parallel dune ridges, all of them separated by intermediate dune slacks.

These dune depressions can be affected seasonally by the water level, giving rise to wetlands, ponds and even small lakes, usually very fluctuant. Depending on the location of the wetlands (closer or distant from the shoreline), and the ground water oscillations, water arriving to these wetlands can be saline, from marine origin, or fresh, of continental origin. Interannual variations of salinity and humidity make these environments very unsteady, with a great variety of plants that can replace one another depending on the changing environmental conditions (Nordstrom, 2000).

Dynamics of coastal dunes

Overall, coastal dunes are very dynamic systems which develop at an interface terrestrial ecosystems and the sea. In this narrow band there is a huge energy exchange that determines the dynamics these systems experience.

Coastal sand dunes form where there is a readily available supply of medium to fine sediment (usually sand, sometimes silt, rarely clay) and they are located landward of the beach in the supratidal zone. The size of the sediment, duration, velocity, and direction of winds in the coastal zone, as well as the size and extent of vegetation, are fundamental factors that govern the size and shapes of dunes in coastal settings (Hesp, 2024).

Coastal dunes form from the sediment that waves and currents deposit in the beach. The wind carries this sand from the beach to the dune, where it is retained by vegetation, provided it has an adequate composition and coverage. During fair weather conditions, the base of the dunes is not affected by wave energy which dissipates on the beach face. During storms, the waves reach the upper area of the beach, causing erosion and the removal of significant volumes of sediment from the dunes in the part exposed to the sea. These unstable areas are mobilized quickly and dragged towards the sea, forming more or less extensive deposits in not very deep areas (winter profile bars) and/or transported longitudinally by longshore currents. These bars cause the wave to break, reducing the effect of the waves on the dune and protecting it from later storms.

When the time of the storms ends, in spring, these submerged sandy deposits are transported again by the waves on to the dry beach, where the onshore winds remove them again towards the dunes. The maintenance of these possibilities of exchange between the beach and the dune is fundamental for the equilibrium of the dune system (Hesp,1999). Much of the wave energy is dissipated by the constant mobilization of sediments, which is why the whole beach – dune system has an important protective role against marine erosion.

All this volume of sand, between the secondary dune, the embryonic dune, the high beach, the low beach and the submerged zone (up to the depth that is susceptible to be transported by the waves towards the coast) are therefore in a constant dynamic equilibrium in which a grain of sand, wherever it is in any place of this whole complex, belongs to the same sedimentary unit (Davidson-Arnott et al., 2019). This dynamic equilibrium of the whole beach - dune does not vary substantially in time, if it receives the contribution of sediment and the general energetic conditions do no change.

This is the normal dune dynamics in the European dunes, it is the natural process and it is the reason why the dune systems have a great natural regeneration capacity and why the artificial ecological restoration (stabilization) actions give these spectacular results at the short term.

When, due to natural or mainly artificial causes, the dune systems lose these dynamics, the dunes degrade. Tertiary dunes are colonized by shrubs and trees, losing their typical floristic composition, being replaced by species more typical of forest until they disappear. The primary and secondary dunes also lose plant diversity while the wind dynamics become less important, the transport of sand decreases, making these areas susceptible to the colonization of other species from other environments and invasive species (Arens et al., 2005).

The reduction of sedimentary material input by rivers due to the reduction of erosion by the revegetation of river basins and by the construction of reservoirs that reduce sediment transport through rivers also play an important role in the aging of European dune systems.

At present, many dune systems, especially in the north of the Atlantic coast, are facing problems of aging and biodiversity loss, also due to nitrogen deposition from acid rain caused by industrial processes in the past and by the emission of nitrogen compounds from agriculture and cattle ranching in modern times. These problems of aging due to overstabilization are not so important in Mediterranean dune systems, where nitrogen deposition is not so high and where tourism is a destabilizing factor that periodically, especially in summer, degrades the vegetation cover of the dunes.

The process of dune degradation has also been favoured by various human actions such as forest plantations on dune systems, especially those carried out with different pine species along many Atlantic, Baltic and Mediterranean coastal areas.

1.2.2 Main ecological characteristics and identification of variables to measure habitat condition

Coastal dune systems are dynamic and complex ecosystems characterized by a unique set of abiotic and biotic factors that shape their structure and function. The characteristic assemblage of landforms in dune systems, including their spatial sequences and temporal evolution, results from the interplay between physical processes and plant community development. This dynamic relationship shapes the unique morphology and ecology of coastal dunes over time. To effectively evaluate the state and trends of a dune system, periodic monitoring of key characteristics is essential. This monitoring provides insight into the environmental quality of the constituent habitats.

This section identifies and describes the main characteristics of dune habitats and the ecological processes that determine their condition, together with a selection of variables that can be used in the assessment and monitoring of those characteristics.

The presentation of the main ecological characteristics and the corresponding variables that can be used to measure habitat condition in this section follows the typology established in the framework for assessment of ecosystem condition defined under and in the UN System of Environmental-Economic Accounting— Ecosystem Accounting (SEEA EA; United Nations, 2021) [2], which is also adopted in the EU wide methodology to map and assess ecosystem condition.

This ecosystem condition typology classifies the ecological characteristics and variables into abiotic (physical and chemical) and biotic (compositional, structural and functional). In addition, characteristics related to landscape, that can be assessed at broader spatial scales, are also included.

Abiotic characteristics

A comprehensive assessment of the condition of dunes should encompass several key ecological characteristics and variables linked to climate, wind, effects of marine and coastal processes, morphosedimentary factors, topography, hydrology, nutrient availability and cycling, among other.

Key physical and chemical state characteristics and associated variables to assess dune condition are summarily described below and synthesized in Table 2.

Physical state characteristics and variables

Climate and microclimate characteristics: coastal dunes experience unique microclimatic conditions influenced by their proximity to the sea, exposure to wind and topography. Variables used to assess these conditions include temperature, precipitation, insolation and wind regime.

The European dune systems extend from the cold Scandinavian coasts to the hot and dry Mediterranean beaches, and due to strong gradients (exposure, distance to the sea, waves

[2] Ecosystem condition is the quality of an ecosystem measured in terms of its abiotic and biotic characteristics (United Nations, 2021).

or wind) there can be significant temperature variations; however, the average temperature range is relatively narrow, due to the presence of the sea that softens temperatures, and to the low altitude over which they develop (few meters above sea level).

The relative humidity in dune areas is relatively constant and high, with appreciable differences only between the Atlantic and the Mediterranean coasts. This climatic constancy is reflected in the relative similarity of the vegetation present in each of the different dune types (embryonic, secondary and tertiary), where a large proportion of species, especially the structuring species, is quite constant along all European coasts. Differences in exposure, water table and wind dynamics are responsible for the variations in vegetation composition and structure, especially in small dune systems.

Examples of variables to measure:

- Wind speed and direction
- Temperature and humidity gradients
- Precipitation patterns
- Salt spray deposition
- Radiation.

Physical characteristics related to morphosedimentary processes: coastal dunes are highly dynamic, with constant exchange of sand between dunes, beaches and submerged areas during storms and calm periods (see more details above in section 1.2.2 Dynamics of coastal dunes). This dynamic balance is crucial for dune health. When dunes stabilize, soil development processes occur, influencing vegetation succession and habitat diversity.

The geometry and topography of coastal dunes is usually characterized by a series of ridges and troughs parallel to the shoreline, with heights ranging from a few meters to over 30 meters in some locations (Hesp, 1999) or even more. The morphology of a given dune can change if the wind strength and direction vary substantially. Dunes exposed to two or more prevalent winds can experience important morphological variations along the year. The density of vegetation cover and the relative humidity are important factors in the mobility of dunes, due to the higher sand susceptibility to be blown out when the dune surface is dry and bare. Some parts of a dune ridge can move forward with respect to the ridge if the vegetation cover is not enough for preventing massive sand transport (Houser, 2013). In that case singular mobile dunes can form, with a number of morphologies (parabolic, linguoid, longitudinal ribbons parallel to the wind, etc.). If the mobile dunes invade zones with an irregular topography their morphology and dimensions can experience important modifications, giving rise to specific dune types like climbing dunes, echo dunes, nebkhas, etc. (Hesp, 2000).

Relevant morpho-sedimentary characteristics can be assessed and monitored through variables that measure the profile and physical dimensions of the dune habitats, which reflect the state of erosion-sedimentation cycles to which dune systems are subjected, especially in primary and secondary dunes. In any case, it is necessary to know the particular sedimentary dynamics of each dune system to be able to evaluate changes and alterations based on variables such as the width of the dune front or the dune profile.

Examples of variables to measure:

- Dune height, length and width
- Slope angles
- Presence and extent of different dune types (embryonic, mobile, fixed).

Granulometry: most coastal dunes consist of fine to medium sands (average size 1.60 to 2.65 ϕ, equivalent to 330 to 160 μm), although there is a fairly wide range within the same dune and between dunes of different coasts.

The granulometric ranges, within the sandy fraction, correspond to those of the beach, generally with a majority of the finer fractions since the wind is a selective dynamic agent of these minor fractions. However, intense winds are able to transport coarse sand and even small pebbles, and there may be little difference in the average sizes between the donor beach and the receiving dune. This highly selected granulometry is responsible for the high permeability of the substrate and the low moisture retention power in the soil, which is reflected in the aridity of dune systems.

Example of variables to measure:

- Sand grain size distribution in the dry beach
- Sand grain size distribution in the embryonic and mobile dunes.

Wind and marine erosion: the profile of the dune, together with the effects of marine and wind erosion produced in the dune, such as deflation corridors, blowouts, etc., are elements that fairly faithfully characterize the dynamic (erosion-sedimentation) state of the dune system. Coastal erosion can be associated to very different factors acting at different temporal scales: a single energetic storm, chronic sedimentary deficit, etc. It is important to reconstruct the tendency of the shoreline in the past decades, since very often this trend has direct consequences on the stability and continuity of the dune system (Labuz, 2016). The most used method is the comparison of remote-sensed images, commonly aerial photographs, where to draw the dune foot. Despite the uncertainties associated with this procedure in dunes (Del Río & Gracia, 2013; Smith et al., 2025), the results are very illustrative of the coastal trend, and a wide number of studies and methodological proposals prove the benefits of their application when trying to predict the near future extent and location of beaches and dunes (Dolan et al., 1991; Thieler et al., 2005; Mitri et al., 2020).

It is important not only to know the frequency of erosive events or the decadal tendency of the shoreline, but also the tendency and amount and effects of the coastal erosion to the most exposed dunes (mainly embryonic dunes and foredunes; Hesp, 2025). The exposition of plant roots in the primary ridge can be an indicator of prevalence of erosional conditions with respect to the natural recovery ones.

Example of variables to measure:

- Shoreline trend in the last decades
- Percentage of dune front with eroded slopes and scarps.

Hydrology: freshwater availability and groundwater dynamics significantly influence dune vegetation and habitat diversity.

Examples of variables to measure:

- Depth to groundwater table
- Soil moisture content and seasonal variability.

Chemical state characteristics and variables

Mineralogy and chemical composition of the substrate: in general, the sand composition of the dune is a function of the mineralogy from which the sediment comes, which they can be siliceous or carbonate. Siliceous sands come from granitic, volcanic or quartz minerals, while carbonates come from calcareous zones, although due to the presence of organic remains there is always a biogenic calcareous fraction. In addition, sand may contain small amounts of heavy metal minerals and on volcanic shores, sediments from basalts, andesites, pumites and other volcanic rocks. The most important consequence of the mineralogical composition of the sand is the acidity (pH) which in turn has implications on the availability and absorption of nutrients.

The calcareous sands of dune systems, as a result of washing and leaching, are decalcifying and acidifying, providing the substrate a more acidophilic vegetation. This process is slowed or reversed by the contribution of sand by wind.

Examples of variables to measure:

- pH of the dune soil
- Sand mineral composition and provenance
- Salinity (at different soil depths).

Nutrient availability and cycling: the mineralogical composition also determines the poor fertility of the substrate and the poor or no edaphic development. The substrate of dune systems is very poor in nutrients, which greatly limits the development of vegetation, especially regarding nitrogen and phosphorus. The marine influence (waves and tidal waves) maintains acceptable potassium levels. Nitrogen, in particular, plays a crucial role in dune ecosystem functioning and can be supplied by the sea spray (Zunzunegui et al., 2024).

The deposition of nitrogen by anthropic causes (from the burning of fossil fuels, NOx; and livestock and agriculture NHx) causes a strong impact in western European areas, which leads to excessive growth of tall vegetation and nitrophilous species that greatly reduce biodiversity, eventually displacing many plant and animal species, especially in tertiary dune systems.

Examples of variables to measure:

- Nitrogen fixation rates
- C/N ratio
- Litter proportion in the dunes and decomposition rates
- Organic matter content in soil.

Biotic characteristics

The biotic components of dune habitats contribute to soil formation and stabilization. Plant roots help bind the sand, while organic matter from decaying plants enriches the soil, promoting further vegetation growth.

Compositional state characteristics

Compositional state characteristics describe the composition of ecological communities, including the presence/absence or abundance of individual species or taxonomic groups (e.g. birds, invertebrates), or the diversity of species or groups at a given location and time.

The vegetation covering the dune systems is a very valuable indicator for assessing the status of habitats. Vegetation is a fundamental element in the formation and development of dune systems. A complete list of species characteristic of the different coastal dune habitats in Europe and Mediterranean countries can be found in Marcenò et al. (2018). The ability of vegetation to fix wind-carried sand depends on vegetation coverage and its morphological and physiological characteristics.

Characteristic species: The dune species have acquired adaptations to the ecological conditions that exist in the dune systems, such as abrasion by sand, salinity, insolation, low water retention in the soil, etc., which makes these plants exclusive to the dune systems (Favennec, 2007). Dune habitats typically host specialized vegetation adapted to sandy, nutrient-poor soils and high salinity. Common species include grasses (e.g., *Ammophila arenaria*), shrubs, and many herbaceous plants. These plants play a crucial role in stabilizing the sand and preventing erosion.

Along the European coasts the vegetation is quite homogeneous, because it develops at similar altitude (few meters above sea level); temperatures also remain in a narrow range and the plant communities do not show great differences and genetic exchange between adjacent and relatively close dune systems. However, the vegetation composition in dune systems in northern Europe and the Mediterranean has some particular features.

Embryonic dunes have as characteristic species *Elytrigia juncea*, with two subspecies: *boreoatlantica* in the north and *juncea* in the south and Mediterranean coasts, sharing some typical species of the high beach such as *Cakile maritima*, *Salsola Kali, Chamaesyce peplis, Honckenya peploides, Polygonum maritimum,* etc. and also some species of the secondary dune, such as *Ammophila arenaria*. The secondary dunes, dominated by *Ammophila arenaria*, *Eryngium maritimum, Calystegia soldanella, Sporobolus pungens, Pancratium maritimum*, etc. also can share some species from the embryonic dunes, such as *Elytrigia juncea*. Tertiary dunes have much more variety of plant species and communities.

The composition of each dune habitat may be assessed based on a list of characteristic species and some countries have developed such lists of species for their dune habitats (e.g. Oosterlynck et al., 2020 in Flanders; Goffé, 2011 for the Atlantic coast of France; Krause et al. 2008 in Germany, etc.).

Vegetation zonation: the gradients of environmental conditions with respect to the distance to the sea are significant, resulting in a distribution of vegetation from the high beach to the tertiary dune in strips parallel to the coast. Dune ecosystems often exhibit distinct zones based on plant species and their tolerance to environmental conditions such as wind, salt spray, and moisture. The foredunes are usually dominated by pioneer species, while more stabilized areas may support a greater diversity of flora.

Fauna: dune habitats support a variety of invertebrates, including insects and crustaceans, which are integral to the food chain. These organisms contribute to soil aeration and nutrient cycling. Birds, mammals, and reptiles are also common in dune ecosystems. Many species rely on dunes for nesting and foraging. For instance, certain birds may use the open sandy areas for nesting, while others may seek shelter in the vegetation. Dune habitats provide critical resources and shelter for various species, they serve as important stopover points for migratory birds and habitats for endangered species. Concerning typical animal species, the situation is quite different within the dune habitat types. Primary or embryonic dunes on the beach are of special importance for breeding birds, for example *Charadrias hiaticula* and *C. alexandrinus*, and for invertebrates mainly beetles (*Carabidae*), spiders and very few highly specialised invertebrates form other groups. In *Ammophila* secondary dune habitats soil nesting psammophilous *Hymenopptera* are an additional larger group of typical invertebrates. Very species rich in invertebrates are all more developed dunes including grey dunes, decalcified dunes or dune shrub habitats. Here not only soil living invertebrates as predators, but also the main pollinator groups such as wild bees, hoverflies, butterflies and other Diptera groups are species rich, with less wind exposition and a higher plant diversity.

Species richness: is a common biodiversity indicator used in ecosystem condition assessment (Rendon et al., 2019). However, it may not be an accurate indicator of ecological integrity as it only provides a small part of the information that describes the concept of biodiversity (Alexandrino et al., 2017; Fleishman et al., 2006; Hillebrand et al., 2018).

Although species richness is an important variable of ecological status, degradation at a given point may not lead to net changes or even increase, of species richness if some are replaced by generalist species that are most often found in degraded areas (Devictor et al., 2007). Consequently, the relationship between species richness and ecosystem condition would depend on the species selected as an indicator of this variable.

Invasive alien species: Coastal dune ecosystems are mainly located in temperate-climate zones, whose characteristics facilitate the establishment of tropical and subtropical species with a high invasive potential. These are very dynamic ecosystems, especially the high beach and active dune, with a large area lacking vegetation and subject to very restrictive environmental conditions. Under these conditions, dune ecosystems are highly susceptible to being invaded by invasive alien species. Various factors such as wind, burial, erosion, high nutrient availability and often human pressure facilitate, in dune systems, the opening of areas of bare soil that are more easily colonisable.

Alien plant species are an agent of change and a threat to indigenous biodiversity, being able to displace native species from their ecological niches by transforming some of the environmental conditions, which some of the native species may not be able to assimilate.

Examples of variables to measure:

- Characteristic species presence and abundance
- Herbaceous or shrub/tree cover
- Species richness
- Presence of entomofauna (coleopters, butterflies, etc.): predatory groups, pollinator groups, phytophagous groups, specialised psammophilous fauna
- Presence or proportion of invasive or alien species.

Structural state characteristics

Vegetation cover and density: structural state characteristics are primarily related to the local amount of vegetation of dune ecosystems, including vegetation density and cover. Their advantages include the ease of implementation, the possibility of statistical treatment and comparison with other habitat occurrences and samples over time.

Examples of variables to measure:

- Vegetation cover and density
- Cover of characteristic species or communities
- Proportion of bare sand.

Functional state characteristics

Functional state characteristics describe the biological, chemical and physical interactions among different ecosystem elements that influence their status. They relate to ecosystem functions and relevant ecosystem processes and can also be linked to disturbance regimes. Characteristics that concern specific functional groups of species, which perform ecosystem functions (e.g., producers, pollinators, nitrogen fixers, predators, decomposers, etc.), could be considered as functional state characteristics (UN, 2021).

Health status, flowering and fructification: flowering and fructification rates of plants can be used as an indicator of dune habitats condition. Sediment supply as well as threats and alterations can affect the dune condition. Poor condition and lack of flowering are usually indicative of lack of sediment supply. The assessment shall include an evaluation of the robustness of the stems and the presence of degenerate dead material in the species: *Elytrigia juncea* and *Leymus arenarius* in the case of embryonic dunes and *Ammophila arenaria* and *L. arenarius* in mobile dunes (Ryle et al. 2009). Grazing status (both by sheep, goats), but often also by introduced rabbits largely changes plant species composition and invertebrate communities in dune ecosystems.

Example of variables to measure:

- Proportion of surface altered by trampling
- Grazing status
- Diffuse contamination from litter or polluted water.

Landscape characteristics

Landscape characteristics include characteristics of ecosystem assets that are quantifiable at larger spatial scales (landscape) but that have an influence on their local condition. Examples are metrics that quantify how an ecosystem asset is connected to other ecosystem assets of the same ecosystem type, how close ecosystem assets are situated from certain pressures, such as intensive agriculture, or how the condition is influenced by other assets (UN, 2021).

The size of the habitat patch as well as the habitat fragmentation and connectivity are typical landscape characteristics.

Size of the habitat patch: dune ecosystems are highly dynamic and one of the main indicators of their state is the temporal morphological evolution they have experienced in recent decades or years, as well as the variations they currently experience. Monitoring their morphology and surface can use a methodology that combines field work with the use of remote sensors, mainly aerial photographs. Historical data can provide information on the evolution of the ecosystem in recent years.

If the coast receives sediment in a stable and continuous way, the different types of coastal habitats, including dunes, will develop naturally (without human intervention). However, if there is a sediment deficit, beaches, dunes habitats and marshes will recede and erode, and can even disappear.

There are numerous methods for the delimitation of the surface of dune habitats (Garzón & Garrote, 2004). This process involves mapping and drawing the boundaries that differentiate the various types of boundary habitats. The boundaries between different habitat types are not always well defined and identification is complex, which should always be supported by field visits.

Automatic and (semi)automatic mapping methods using remote sensing images might provide good opportunities to map large scale versus small scale variety of habitat types (vegetation mosaics). A project will start soon in France to develop a remote sensing technique to map dune habitats through mainland France every six years (Margaux Mistarz, pers. comm.)

Dune connectivity and fragmentation: fragmentation involves the division of continuous dune habitats into smaller, isolated patches, often due to human activities and land-use changes. If the connection among contiguous habitats favours their self-enrichment, the opposite of habitat connectivity in dunes is fragmentation, which has far-reaching consequences for biodiversity, ecosystem functioning, and resilience to disturbances. Dune fragmentation is primarily driven by anthropogenic factors: urban expansion in coastal areas, tourism infrastructure, roads, and recreational use can cause physical fragmentation of dunes.

The resulting fragmented landscape is characterized by: isolated dune patches surrounded by modified matrices (e.g., urban areas, infrastructures), increased edge effects, making the remaining dune habitats more vulnerable to external disturbances, altered microclimates and sand dynamics within the fragmented dunes. The fragmentation of dune systems has several ecological consequences:

- Altered species composition: fragmentation can lead to changes in plant communities, often favouring the establishment of exotic species.
- Reduced genetic diversity: isolated dune populations may experience decreased gene flow, potentially leading to genetic bottlenecks and reduced adaptive potential (Massó et al., 2016).
- Disrupted ecological processes: fragmentation can affect key processes such as dispersal, recruitment, and pollination, which are crucial for maintaining healthy dune ecosystems.

- Increased vulnerability to disturbances: Fragmented dunes are more susceptible to erosion, storms, and other environmental pressures (Molina et al., 2023).

Example of variables to measure:

- Distance among dune systems
- Degree of fragmentation of the dune ridges (number, dimensions, temporal trends)
- Completeness of the typical zonation of dune habitats
- Fragmentation by anthropic structures.

Table 2. Framework for the ecological characterisation and examples of variables to measure forest habitat condition

Ecological characteristics	Types	Description of associated variables	Examples of variables
Abiotic characteristics	**Climate and microclimate characteristics**	Climatic variables influencing dune generation and vegetation growth	- Wind speed and direction - Temperature and humidity - Precipitation - Salt spray, radiation
	Physical state characteristics	Dimensions Sedimentary dynamics (marine/aeolian)	- Length, width, height, slope angles - Dune types - Accretion/erosion rate - Granulometry - Mineralogy - Shoreline trend, dune erosion - Groundwater table, soil moisture
	Chemical state characteristics	Nutrients Chemical composition	- Nitrogen concentration - Nitrogen deposition - pH of soil - Salinity - C/N ratio
Biotic characteristics	**Compositional state characteristics**	Composition / diversity of ecological communities (Flora and fauna)	- Characteristic vascular plant species presence and abundance - % of surface invasive species - Entomofauna - Species richness and abundance of specialised psammophilous invertebrates - Nesting density of typical bird species - In grey dunes, dune heathland and dune shrubs: species diversity of main pollinator groups, phytophages and predatory groups.
	Structural state characteristics	Vegetation cover and density	- Herbaceous cover - Shrub/tree cover - Vegetation succession/transition - Proportion (%) of bare sand.
	Functional state characteristics	Biological, chemical, and physical interactions between the main ecosystem compartments. Disturbance regimes, threats and alterations.	- Flowering and fructification rates of plants - % of surface altered by trampling - % of surface under grazing pressure - Diffuse contamination from litter - Diffuse contamination from polluted water

Ecological characteristics	Types	Description of associated variables	Examples of variables
Landscape characteristics		Metrics describing mosaics of ecosystem types at coarse spatial scales, habitat connectivity	- Distance among dune patches - Degree of fragmentation - Habitat fragmentation by infrastructures (roads, etc.) - Completeness of typical dunal zonation - % dune area affected by coastal stabilisation or defence measures

1.3 Selection of typical species for condition assessment

Although the Directive uses the term 'typical species', it does not give a definition that can be used in reporting on the conservation status of habitats. The term 'typical species' is part of the definition of Favourable conservation status for a habitat type give in Article 1(e): 'The conservation status of its typical species is favourable as defined in (i).'

The assessment of typical species is however included as part of the assessment of the Structure and functions parameter. The selection of 'typical species' for Article 17 reporting should reflect favourable structure and functions of the habitat type (EC, 2023).

Typical species should include species which are good indicators of favourable habitat quality, and species sensitive to changes in the condition of the habitat (e.g. 'early warning indicator species').

Typical species should provide additional information to assess the habitat condition. Therefore, as a general rule, it is recommended not to use characteristic and dominant species as typical species, as far as these are already assessed as part of the compositional or structural characteristics of the habitat.

Typical species may be drawn from any species group. In addition to vascular plants, which are often selected, consideration should be given to selecting lichens, mosses, fungi, and different animal groups. Many essential functions, such as pollination, predation and regulatory groups, phytophagy and litter decomposition, rely mainly on invertebrates, and their exclusion may lead to incomplete function assessments.

The set of typical species for habitat types should cover all the area and diversity (all subtypes) of each habitat type. Moreover, typical species can vary across the habitat range, different species may be present in different parts of the range of a habitat type or in different subtypes (EC, 2023).

These lists often contain rare species, so it is advisable that the list has enough species indicative of good habitat condition in the dune systems.

It is also advisable to consider different relevant functional groups for the selection of typical species, considering their possible role as bioindicators and their sensitivity to changes (see some examples in Table 3 below).

Table 3. Examples of typical species useful for monitoring dune habitats (other than vascular plants)

Species Group	Ecological notes – bioindication	Sensitive to changes in quality
Bryophytes and lichens	*Tortula ruralis* (Star moss) for fixed dunes *Lichens mainly of the genus Cladonia, for example Cladonia foliacea* for dune heath or grey dunes	indicate stable conditions in fixed dunes.
Insects	*Hipparchia semele* (Grayling butterfly) for fixed dunes *Cicindela maritima* (Coastal tiger beetle) for mobile dunes	Sensitive to changes in vegetation structure and microclimate
	Ground-nesting psammophilous bees and wasps	Sensitive to disturbance by human activities and frequentation, changes in vegetation cover and microclimate
	Main pollinator groups (Wild bees, hoverflies, butterflies)	Sensitive to changes in flowering phenology, vegetation composition and climate change
Birds	*Oenanthe oenanthe* (Northern wheatear) for fixed dunes *Charadrius alexandrinus* (Kentish plover) for embryonic dunes	Sensitive to disturbance by human activities and frequentation
Reptiles	Lizards	Sensitive to disturbance by human activities and frequentation

Criteria for Selecting Typical Species

The selection of typical species for assessing the condition of dune habitats involves identifying species that are reliable indicators of habitat quality and sensitive to environmental changes. These can include key species, rare species, etc. The following criteria can be used to select these species:

- **Regular occurrence and high constancy***:* Species must be consistently present across the habitat type and demonstrate high constancy, meaning they are commonly found in various locations within the habitat and over time and are specific to the habitat. As indicated above, an up-to-date list of diagnostic plant speciesl of coastal dunes in Europe and Mediterranean can be found in Marcenò et a. (2018).
- **Indicator of favourable habitat quality***:* Selected species should be indicative of favourable habitat conditions. Their presence and abundance should correlate positively with the overall quality of the habitat, reflecting its optimal state.
- **Sensitivity to environmental changes***:* Species should be sensitive to changes in habitat conditions, acting as 'early warning indicators'. These species should respond quickly to both positive and negative changes in the environment, allowing for timely detection of habitat degradation or improvement.
- **Ease of identification and monitoring***:* Species that are relatively easy to identify and monitor are preferred. This ensures that assessments can be carried out efficiently and consistently by different observers.
- **Representation of different functional groups**: the selection should include species from various taxonomic and functional groups (e.g., plants, invertebrates, lichens) to provide a comprehensive picture of habitat condition.

- **Native status**: Typical species should generally be native to the habitat type and region, as they have evolved alongside the ecosystem and are more likely to reflect its natural state.
- **Conservation status**: While not a primary criterion, the inclusion of species of conservation concern can add value to the assessment, providing information on both habitat condition and species conservation.

Recommendations for Selecting Typical Species

- **Literature review:** Conduct a thorough review of scientific literature, habitat descriptions, and existing monitoring protocols to identify species commonly associated with the dune habitat type.
- **Expert consultation:** Engage with local and regional experts in dune ecology to gather insights on potential typical species based on their field experience and knowledge.
- **Field surveys:** Perform comprehensive field surveys across a range of dune habitats in different conditions to identify species that consistently appear in well-preserved areas.
- **Statistical analysis:** Analyse species occurrence data to determine which species show the highest constancy and fidelity to the habitat type.
- **Indicator value assessment:** Evaluate the potential indicator value of candidate species by assessing their sensitivity to known pressures and threats affecting dune habitats.
- **Pilot studies:** Conduct pilot studies to test the practicality and effectiveness of monitoring the selected typical species in different dune habitat subtypes.
- **Periodic review:** Establish a process for periodically reviewing and updating the list of typical species to account for ecological changes and improved knowledge over time.

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2. Analysis of existing methodologies for the assessment and monitoring of habitat condition

This section presents the results of the review and analysis of some national methodologies for assessment and monitoring of dune habitats condition from EU MS. Among the 27 members, only 21 have coastlines, and among costal countries, 14 MSs have developed some methodology for the assessment and monitoring of dune habitats under Article 17 of the Habitats Directive.

The assessment of coastal dune habitat condition relies on a range of variables that aim to capture the key ecological characteristics and processes of these dynamic ecosystems. This review analyses the variables, metrics, and measurement methods used across different European countries to evaluate dune habitat condition, considering their alignment with the ecological characterization described in section 1.2.

2.1 Variables used, metrics and measurement methods, existing data sources

A description of the main variables used in the methodologies considered in this analysis is presented below and a summary overview is provided in Table 4. More detailed information about the variables used in the EU Member States is presented in the Annex.

The variables and the characteristic they measure are classified according to the Ecosystem Condition Typology of the Framework for Ecosystem Accounts (UN, 2021), which distinguishes the following types of variables: abiotic (physical, chemical), biotic (compositional, structural, functional) and landscape.

Abiotic variables

Physical variables

Physical variables are only measured in few of the methodologies analysed. The **dimensions of the active dune system**, specifically its **length and width**, are measured to assess it geomorphological dynamics. These variables can indicate the potential for dune migration and the extent of active sand movement. Longer and wider dunes typically have more significant interactions with wind and water, affecting their shape and stability. These variables are considered for instance in the methodologies available from Spain (Aranda et al, 2019) and France (Goffé, 2011) although the latter is a simplified method to assess the conservation status of three dune habitats at the Natura 2000 site scale and for the Atlantic coast only.

The **height** of dunes within a system is measured in several methodologies, as those available from Greece, Italy, Latvia and Spain (Dimopoulos et al., 2018; DAP, 2023; Aranda et al., 2019). This variable provides insights into the erosion-sedimentation dynamics of the system, as well as on the overall topographic variability of the habitat. Substrate erosion/accumulation processes are monitored in Italy through the use of graded rods driven into the ground (Angelini et al., 2016)

Wind erosion is assessed in some of the methodologies, for instance in Spain by estimating the percentage of eroded slopes (Aranda et al., 2019) or in France by expert assessment of the degree of wind erosion on large transect (Goffé, 2011).

Some of methodologies considered in this analysis include the assessment of **substrate and soil features**, e.g. sand grain size in Romania (Trif et al., 2015) and soil thickness for 2140 in Denmark (Fredshavn et al. 2022).

Chemical variables

As with physical variables, chemical variables are not commonly found in the methodologies considered in this analysis.

Several **chemical elements** that influence the **nutrient status**, including Nitrogen, Phosphorus, Calcium, Potassium, C/N ratio, etc., are measured in some of the methodologies analysed. **Soil pH** is also measured in the methodologies available from Belgium, Denmark and the Netherlands.

Biotic Variables

They include three groups of variables, regarding composition, structure and function of the dune ecosystem (Table 4). As ***Compositional variables***, the presence and abundance of **characteristic/ typical/ key/ dominant species** is assessed in almost all the MS, based on lists of species available for each habitat type. **Animal species** are also included in some national methodologies, including species from several groups: beetles, reptiles, birds and even small mammals that can be found in dune habitats. On the other hand, **invasive, non-native**, **nitrophilous** and other **negative indicator** species are also recorded in several MSs to assess the habitats condition.

Among the **structural variables**, the total cover of vegetation, of characteristic species or certain types of vegetation (herbaceous, psammophilous, woody species, mosses and lichens) are included in many of the methodologies analysed, as shown in Table 4. On the other hand, the cover of invasive, alien species and other species indicative of disturbance, as nitrophilous species, are also often recorded in the assessment of dune habitats in several MS.

Functional variables are only included in some of the methodologies analysed and cover aspects such as flowering and fruiting of positive indicator species, shrub regeneration and natural vegetation dynamics. Plants with exposed roots are used in one methodology as indicator of dune erosion processes. Rabbits are also included in one methodology, which as this species can cause vegetation loss, affecting dune stability and plant composition.

Landscape characteristics and other variables

The area or extent of the habitat patch is measured in at least four methodologies (BE, ES, IT, RO) in order to follow the evolution of the habitat in the locations being monitored.

The **coastal trend** is measured in two MSs using historical data, remote sensing, and field surveys, to understand changes in sediment deposition and erosion patterns on dune systems.

Fragmentation is assessed in some of the methodologies analysed using landscape metrics and spatial analysis tools to measure the extent and distribution of fragmented patches, or by identification of anthropic infrastructure that cause fragmentation (roads, constructions, parking areas, etc.).

As regards **other variables that indicate habitat degradation** or alteration, various **signs of damage or alteration effects** by different human activities, e.g. trampling, vehicle access, parking, recreational activities, etc., are frequently assessed in the methodologies available. The **percentage area affected by human activities** and by **solid waste and garbage** is also measured in some of the methodologies considered in this analysis. Finally, **grazing** impact is assessed in one of the methodologies, as overgrazing can lead to habitat degradation.

A synthesis of all the variables used by the different MSs is presented in Table 4. Further details, including metrics and measurement methods, are provided in the Annex..

Table 4. Summary of variables (groups) in national methodologies

Ecological characteristics	BE	BG	DE	DK	ES	FR	GR	IE	IT	LT	LV	NL	PL	RO
1. Abiotic characteristics														
1.1 Physical state characteristics														
Dimensions of the dune system (length, width, height)	■				■	■	■		■		■			
Relief, micro-topography			■											■
Erosion (marine erosion, wind erosion)					■	■							■	
Bare sand cover (%)				■				■			■	■		
1.2 Chemical state characteristics														
Soil pH	■			■								■		
Chemical elements and nutrients (N, P, Ca, K, C/N ratio	■			■			■					■		
2. Biotic characteristics														
2.1 Compositional state characteristics														
Characteristic/typical/positive indicator species	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Animal species (entomofauna, reptiles, birds, small mammals…)	■				■	■			■	■				
Invasive/ non-native/, ruderal, nitrophilous species		■			■	■		■	■	■	■		■	■
2.2 Structural state characteristics														
Cover of characteristic/ typical/ indicator species				■		■	■		■	■	■	■		■
Cover of herbaceous vegetation						■					■			
Cover of woody species				■		■								■
Cover of mosses and lichens, mosaics of mosses and lichens		■		■					■	■	■			
Cover of invasive, alien, nitrophilous species				■		■			■	■	■		■	
2.3 Functional state characteristics														
Flowering and fruiting of indicator species					■									
Shrub regeneration, Juniper regeneration								■					■	
Shrub regeneration, Juniper regeneration										■			■	
3. Landscape characteristics														
Extent/area of the dune system, patch size, distance between patches	■				■				■			■		■
Degree of fragmentation		■			■									
Coastal trend					■									
Coastal defences- changes to the sediment cycle				■				■						

Ecological characteristics	BE	BG	DE	DK	ES	FR	GR	IE	IT	LT	LV	NL	PL	RO
4. Other (degradation)														
Proportion of area (%) with negative anthropogenic impact, disturbance, damage (trampling, infrastructure, vehicles, waste…)					■	■		■			■			
Presence and intensity of anthropic disturbance by paths, urbanization, sediment extraction and other activities.					■			■	■	■			■	■

References: BE: Oosterlynck et al., 2020; Van Calster et al., 2020. BG: MOEW, 2013. DE: Krause et al., 2008. DK: Fredshavn et al., 2022; Aarhus Univerisity, 2021. ES: Aranda et al., 2019. FR: Goffé, 2011. GR: Dimopoulos et al., 2018. IE: Delaney et al., 2013). IT: Angelini et al., 2016. LT: GTC, 2015. LV: DAP, 2023. NL: BIJ12, 2021. PL: Główny Inspektorat Ochrony Środowiska, 2010; Lemke D. 2015. RO: Trif et al., 2015.

2.2 Definition of ranges and thresholds to obtain condition indicators

This section provides a review of approaches and methods used in the national methodologies analysed to establish thresholds in order to determine whether the measured variables indicate good or poor habitat condition. Thresholds are not always available to assess the condition for each variable and when they are provided, the methodologies do not always specify how those threshold values are determined.

Many methodologies include variables related to the presence, abundance and cover of typical/characteristic species, or vegetation types, and thresholds can be established through expert opinion and considering data from reference sites in good condition.

For instance, in the methodology available from France (Goffé, 2011), the following thresholds are used in the assessment and monitoring of various dune habitats:

- Cover of herbaceous vegetation: For white dunes, >75% cover is considered optimal, 50-75% moderate, and <50% poor condition.
- Cover of woody species: Thresholds vary by habitat type, but generally <5% cover indicates good condition, 5-20% moderate, and >20% poor condition for grey dunes, high cover of woody species is however positive in dune scrub habitats such as 2160, 2170 and high cover of ericaceous dwarf shrubs in dune heathland habitats such as 2140, 2150.
- Cover of nitrophilous species: <10% cover indicates good condition, while >10% suggests degradation.
- Dune width: Thresholds vary by dune type and region, e.g. >5m for embryonic dunes, >40m for white dunes, and >100m for grey dunes indicate good condition.
- Erosion indicators: Qualitative scales (e.g., no erosion, moderate erosion, severe erosion) are often used, with thresholds based on the presence and extent of erosional features.
- Coverage of "heavy disturbance/damage" (e.g., urbanisation, infrastructure): A common threshold is <5% coverage indicating good condition, 5-20% moderate impact, and >20% severe degradation.
- Diffuse damage (e.g., trampling, recreational use): Often assessed qualitatively (negligible, moderate, severe) based on expert judgement and site-specific factors.

Other examples are available for other variables, e.g. from the Spanish methodology (Aranda et al., 2019), as the following information:

- Dune height: >4 meters indicates favourable condition, between 2-4 meters is inadequate, and <2 meters is considered bad.
- Overall dune complex width: >100 meters indicates favourable condition, 50-100 meters is inadequate, and less than 50 meters is bad.
- Surface area of the dune system: is favourable when >500 hectares, inadequate when 50-500 ha, and bad when <50 ha
- Coastal trend over the last 10 years: is considered favourable when it is >5.0 m/year, inadequate when 1.0-5.0 m/year, and bad when <1.0 m/year
- Fragmentation of the dune system: is considered favourable when there is no fragmentation, inadequate when the degree of fragmentation is 25-50%, and bad when >50%
- Presence of invasive species: the absence of invasive species indicates favourable condition, their presence is inadequate, and their dominance is bad.

The methodology available from Flanders (Oosterlynk et al., 2020) provides a set of thresholds for the different biotic variables. For those variables that measure presence or abundance, abundance classes have been designated based on the monitoring scale method (INBO protocol SVP405) and are scaled to a plot of 1 ha. Originally developed for measuring species, the abundance classes are applicable for other variables:

- Absent, absence of a species or other variable;
- Very scarce: species (or other indicators) that are only present with 1 to 4 individuals and covering 5%;
- Scarce: species (or other indicators) that occur by only 4 to 9 individuals and that are covering <5%;
- Sparse species (or other indicators) that occur in small numbers (10-20) and that have not a significant cover (<5%);
- Numerous: species (or other indicators) that are numerous (21-100) but their coverage is <10%.

For those variables that measure coverage, whether it is coverage of a certain species or a disturbance, the same threshold values are used. These values only discriminate between favourable or unfavourable condition. The methodology establishes threshold values of 10%, 30%, 50% or 70% depending on the cases, as explained below:

- 10% is set as the limit value when a low coverage is already indicative of bad condition, e.g. for some disturbance indicators.
- 30 or 50%: many habitat types are considered to be in unfavourable status when the key species no longer have the main share, and there is a mix with species indicating e.g. grassing, afforestation, coarsening, etc. In such cases, a limit of 30 % cover of disturbance indicators is set as the limit between favourable and unfavourable local condition. For species that have naturally a significant cover, 50% is set as the threshold value.
- 70 % is set only for certain species or group of species. A threshold value for disturbance can be set at 70% for them to consider the habitat in bad condition. It can also be set as the minimum coverage required for a favourable condition, e.g. 70% ground cover of stand-specific tree and shrub species in forests.

As regards spatial cohesion, the methodology acknowledges the lack of both the basic data and the reference framework to determine limit values for shape or distance of the habitat clusters. Two limit values are specified for each habitat type, which are used in the calibration model as follows: one for the surface at which at least 75% of the potentially present faunal target species are covered (so-called A status), and one for the lower limit at which 50% of the potential fauna target species present have sufficient area available (so-called B status). The A status was tested against the surface of the complete functional habitat cluster, i.e. including all related biotopes. The consideration for the B status only takes place on the surface of the habitat type itself within such a functional cluster.

Example of threshold values for the spatial cohesion variable for a few habitats (Oosterlynck et al., 2020):

Habitat type	B-status area (ha)	A-status area (ha)
2130	5	50

In the Bulgarian methodology, threshold values are indicated for each variable but it is not indicated how these are calculated. Some examples are given below for the habitat 2120:

- Presence and cover of ruderal or invasive species: Favourable condition (FV) – Ruderal and/or invasive species cover up to 10% of the area of the monitored polygons; Unfavourable-inadequate (U1) – Ruderal and/or invasive species cover 10.1% to 20% of the area; Unfavourable-bad (U2) – Ruderal and/or invasive cover more than 20.1% of the area of the monitored polygons.

In the methodology available from **Germany**, a threshold/range is given to each variable to determine three categories: A = excellent conservation status, B = good conservation status, C = medium to poor conservation status. These thresholds are adapted to each variable group. For instance, as regards the completeness of the typical habitat structures and completeness of the habitat typical species inventory, then following thresholds are used: A= available, B= largely present and C= partially present. For impairments: A=none/very little, B=low to moderate and C=strong (Krause et al., 2008).

2.3 Aggregation methods at the local scale

The aggregation of indicators at the local scale for condition assessment of dune habitats involves combining various measured variables into an overall evaluation of habitat condition. Methods for this aggregation vary widely, ranging from strict one-out all-out principles to more flexible majority rules or additive approaches. Some methodologies also assign different levels of importance or weights to individual variables. Some specific examples of the member states' methodologies analysed are presented below.

For the aggregation of variables at local level in **Flanders** (Belgium) a common approach for all habitats is used, which involves the implementation of weighted aggregation and a majority rule (Oosterlynck et al., 2020). The approach was applied to the Article 17 report on the conservation status of the habitat types for the period 2013-2019, more specifically for the specific structure and function section. A weighting of the various indicators as "important" or "very important" was applied and the following decision framework was used:

- (1a) at least one Very Important indicator scores unfavourably (the Very Key indicators follow the one-out-all-out rule) → local status of the spot is unfavourable.
- (1b) none of the Very Important indicators score unfavourably → step 2 applies as follows:
    - (2a) half or more of the indicators score unfavourably →local status of spot is unfavourable.

- (2b) less than half of the indicators score unfavourably → local status of spot is favourable.

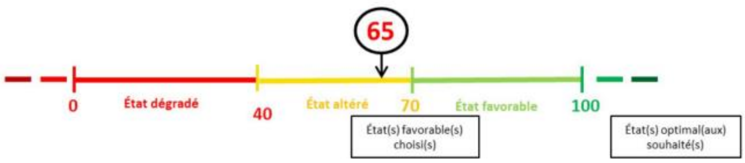
In the methodology available from **Bulgaria**, the overall condition at the monitoring plot/station is favourable when all variables are assessed as "favourable" (a maximum up to 25% of the parameters can be assessed to have insufficient information available). In case the assessment is "unfavourable – bad" for just one variable, the overall assessment becomes unfavourable – bad. Unfavourable – inadequate status is determined by any other combination of parameters.

In **Denmark**, a favourable status presupposes that all the conditions that are important for the habitat are present in the same place. For some indicators there can be a large natural variation between plots, and for these indicators the station's mean value is used as the value of the sample field instead of the measurement on the individual sample field. This applies, for example, to the degree of coverage of some individual species where there is great variation between the sample fields within a station.

In **France**, the same aggregation method is applied for all habitats, which is based on a 0-100 score (from bad to good condition) and the F-U1-U2 scale, but it only applies at the Natura 2000 site scale. For each indicator (variable), a score is attributed according to threshold values. A final score is obtained by subtracting all of these scores from 100. The overall condition is obtained by transferring that score onto an axis representing a gradient that can be divided into different levels of condition or status (favourable, altered, degraded).

Figure 2. Aggregation method applied for all habitats in France

Indicators	Threshold values (or modalities)	Note
A	0 < A < 3	0
	3 < A < 6	-5
	6 < A < 9	-10
B	100 % > B > 80 %	0
	80 % > B > 20 %	-10
	20 % > B > 0 %	-20
C	C > 10	0
	C < 10	-15
	Final note	100 - 0 -20 -15 = 65



Source: Maciejewski, 2024

In **Germany**, a common approach is applied to all the habitats. Three groups of variables are used to assess: 1) completeness of the typical habitat structure; 2) completeness of the typical species composition; 3) degree of impairment or degradation of the habitat. Each variable is assessed according to thresholds in three possible classes: A - excellent, B-good and C-moderate condition. The results of the evaluation of the individual variables are summarised by means of an accounting matrix to an overall evaluation for each group. Then, an overall condition at each sampling plot is obtained by applying the following rules: 1A, 1B and 1C results in B; double entries usually determine the overall assessment, e.g. 2A and 1B results in an overall rating of A, but 2A and 1C results in B. If there is a C rating, an overall rating of A is no longer possible.

In **Greece**, typical species and structure and function parameter are assessed separately. Typical species in each sampling locality are assessed based on their abundance and vitality and according to threshold values. As regards structure and function, a list of specific indicators for each habitat type are assessed at each sampling plot and the overall assessment is based on the proportion of indicators that are present in each sampling locality from the total number of indicators for each habitat type, applying the following thresholds (Table 5; Tsiripidis et al., 2018).

Table 5. Values of indicators of conservation degree applied in Greece

Conservation degree	Proportion of indicators marked as present
Favourable (FV)	≥ 50%
Inadequate (U1)	< 50% but ≥ 25%
Bad (U2)	< 25%

Source: Dimopoulos et al., 2018

Integrated assessment at the local level is done after combining the assessment of the two sub-criteria (typical species and structure and functions) as shown in Table 6.

Table 6. Assessment of the conservation degree of habitats at the local level in Greece

Conservation degree	Combinations of conservation degree of sub-criteria
Favourable (FV)	Typical species and structures and functions FV
Inadequate (U1)	Typical species and/or structures and functions U1, but none U2
Bad (U2)	Typical species and/or structures and functions U2
Unknown	Typical species and/or structures and functions Unknown, but none U2

Source: Dimopoulos et al., 2018

In the **Irish** methodology, aggregation at the local level is generally based on the number of assessed variables that fail to reach the good status, where No failures indicate favourable condition, 1-2 failures determine unfavourable condition and 3 failures determine bad condition.

In **Poland**, the assessment of the 'specific structure and functions' is based on the assessment of particular indices described in detail for each habitat type and is done by expert assessment. The overall assessment is equal to the lowest assessments of particular parameters, as indicated below (Mróz, 2017):

- three FV assessments (or possibly two FV assessments and one XX assessment) → overall assessment FV
- one or more U1 assessments and no U2 assessments → overall assessment U1
- one or more U2 assessments → overall assessment U2.

In **Spain**, the variables are assessed using quantitative values and thresholds for determining their condition (good, medium, bad) and a rescaling is applied based on the distance of the measured values to the thresholds established. Then, aggregation at the level of sampling plot is done calculating an index, which can consider a weighting of the different variables.

2.4 Aggregation at biogeographical scale

The aggregation of local habitat condition assessments to obtain an overall evaluation at the biogeographical scale is a critical step in reporting under Article 17 of the Habitats Directive.

Overall, most MSs follow the recommendations from the Art. 17 reporting guidelines for the period 2013-2018, which establish that "if 90% of habitat area is considered as in 'good' condition, then the status of 'structure and functions' parameter is 'favourable'. If more than 25% of the habitat area is reported as 'not in good condition', then the 'structure and functions' parameter is 'unfavourable-bad'".

Some MSs have also considered the aggregation of the results obtained in the measurement of individual variables at biogeographic level, which also makes it possible to determine the status for each variable and therefore know what variables are in good or not good status. (e.g. in Belgium, see Paelinckx et al. 2019).

It must however be stressed that reporting the habitat structure and function according to Article 17 requires to determine the proportion of the habitat area that is in good or not good condition, which implies the need to provide data aggregation that is useful for that reporting.

It should also be taken into account that some variables must be measured at larger scale than the plot scale.

2.5 Selection of localities

The selection of localities for monitoring dune habitats requires careful consideration of habitat representativeness, spatial coverage, and statistical robustness. By employing systematic and stratified random sampling methods, ensuring adequate replication, it is possible to obtain a comprehensive and reliable assessment of habitat condition. When analysing the national methodologies available for assessment and monitoring of dune habitats, particular approaches have been identified, which are described below.

In **Bulgaria**, a random representative sample of polygons is identified, which must cover a minimum of 5% of the area of a deductive GIS model. The polygons from this 5% representative sample are selected based on expert analysis.

The methodology available from **Germany**, considers that the nine coastal dune habitats are stages in a succession process and in their natural state they are part of a closely connected habitat complex that is continuously changing with the natural dynamics of the coast. The dune systems on the North Sea coast are subject to larger dynamics than those of the Baltic coast. In the large intact dune systems that are still entirely under the influence of natural processes of accumulation and erosion (principally in the core zones of the national parks), the condition of all the dune habitats should be assessed as a whole, considering that each dune habitat is in a dynamic relationship to the others, and the relative areas of each are continuously changing. In these areas, the dune habitats should be assessed together within a distinct area that contains the habitat complex; at most, the area should encompass an island or a section of coastline. Within this area, the components and development of each dune habitat should be assessed in relation to the whole, using whatever methods are most suitable (e.g. aerial photos in combination with vegetation transects). If all the habitats are present and the natural dynamics are intact, all habitat types should be assigned to condition A. In areas where coastal defences and other constructions have significantly restricted the natural dynamics of the dune complex, the individual habitat types should be assessed separately. Even if the typical habitat characteristics are still present, the habitat condition should be downgraded if the pioneer habitat stages are absent, and the assessment should consider the condition of the whole habitat complex in order to judge the representativeness of the habitat in that place (Krause et al., 2008).

In **Denmark**, the monitoring network has been laid out with a view to reflecting the geographical spread and variation of the individual habitat types. The distribution of the monitoring stations reflects their distribution in the two biogeographical regions, and the overall distribution of the locations has been done so that half lie within - and half lie outside Natura

2000 areas. At the monitoring stations, a 10 m reference grid is laid out on the areas to be included in the station, and the sample plots are laid out at random intersections in the grid.

In the methodology available for the selection of localities in **Spain** (Gracia et al., 2019), 11 criteria for the selection of monitoring areas are suggested, although it is not necessary for the area to meet all the criteria, which are indicated below in order of importance, the first three being those that each selected site must necessarily present:

1. Representativeness within the Natura 2000 Network and the Networks of protected areas.
2. Statistical significance. A minimum number of monitoring locations is necessary so that the evaluation can be extrapolated from local to regional level.
3. Number of types of habitats of community interest present in the location.
4. Range/Occupied surface area.
5. Representative presence within the coastal province.
6. Threat status (danger of disappearance) and conservation status. Includes habitat types with a certain degree of degradation or threat, which have a current tendency to decrease or have had a historical trend in this sense.
7. Reference ecosystems.
8. Ecological significance and national/community uniqueness.
9. Environmental-ecological diversity.
10. Distance to other monitoring points.
11. Representativeness within the administrative autonomous communities.

In particular, taking into account that several habitat types of community interest as estuaries, beaches, dunes and marshes usually appear together forming complexes in the landscape, those areas that present the highest number of types of habitats of community interest will be considered.

Using the above-mentioned criteria and based on an inventory of the main types of coastal habitats, a number of monitoring areas are proposed for each of the major groups of coastal ecosystems. A total of 40 dunes systems in Spain have been thus selected as monitoring localities. The monitoring Localities should be ecologically representative and accessible, covering full habitat diversity, and should include both well-preserved and degraded habitats across geographic regions. Monitoring should aim to reflect the geographical distribution and variation within habitat types, with stations distributed to cover both inside and outside Natura 2000 areas. Coastal dune habitats being dynamic, with natural processes affecting their structure, monitoring should consider the interconnectedness of dune habitats, using methods like aerial photography and vegetation transects.

In **Greece**, monitoring localities were selected based on sampling localities included in IDHTACI project (1999-2001), and the need to assess the conservation status of habitat types in sites where the number of existing sampling locations was insufficient. All habitat types are usually assessed in the 10 km EEA reference grid, except for some habitat types, including 2230 and other dune habitats which are proposed to be assessed in the 5 km EEA reference grid.

In **Ireland**, a sample of 40 sand dune sites was selected by NPWS from the 181 sites identified during the Coastal Monitoring Project (CMP) (Ryle et al., 2009). The sites were chosen to be representative of the range of habitat types and geographic locations of sand dune systems in Ireland and they contained a substantial proportion of the total national area for each habitat as assessed during the CMP, ranging from 19% for 1220 Perennial vegetation of stony banks to 95% for 2170 Dunes with creeping willow (Delaney et al., 2013).

In **Latvia**, given that beach and dune habitats form a single complex and are distributed in strips along the coast, it is recommended to combine their monitoring. A combined route-point-transect method should be used. The planning of the monitoring areas shall be based mainly on the routes established in the previous monitoring period, optimising their number and location according to the occurrence of the monitored habitat, influencing factors, accessibility and other aspects. A route (or several routes) shall be established along the coast (parallel to the coast) within and outside Natura 2000 sites. The route shall cover the majority of each coastal habitat to be monitored in the area. The length of a single route shall be approximately 500-1000 m.

The route map marks the points where the expert must first identify which habitats are present perpendicular to the shoreline (seaward-landward) and which of these are to be monitored. In each habitat strip, a habitat questionnaire is completed using transects (parallel to the coastline) 50 m long and 10 m wide. Where the habitat is narrower than 10 m, the transect shall include the full width of the habitat. If the transect size is less than 50x10 m, the length and width of the transect shall be indicated in the notes to the questionnaire.

In **Lithuania**, monitoring of habitat areas is carried out in selected monitoring squares with an average area of about 100 km2, which were used for Annex I habitat types inventory work across the country. Monitoring is carried out in 64 monitoring squares, which make up ca. 10% of the number of squares covering the territory of the country. The monitoring sites, or polygons, are distributed proportionally among designated monitoring squares. The monitor organizer selects specific locations within these squares, considering factors such as previous results and habitat protection status. The distribution of monitoring sites within each square is balanced between protected areas (including Natura 2000 sites) and unprotected areas.

In **Romania**, the monitoring guidelines recommend using selective sampling with a minimum of 7 survey plots/transects distributed both within and outside protected natural areas where habitats have been identified, without specifying whether this minimum number refers to a local, regional, or national distribution of vegetation samples. The area of each sampled plot varies between 1 and 100 square metres (1x1, 1x10, 2x5, 10x10). The suggested field sheet will be completed for each sample area surveyed. Correspondences between vegetation types (vegetation associations) will be established using the national vegetation inventory and description monographs.

In **Poland**, monitoring localities are selected by expert choice.

2.6 General monitoring and sampling methods

Field surveys form the backbone of most assessment methodologies, typically involving a combination of:

1. Transect-based sampling: Transects perpendicular to the coastline are widely used to capture the full dune zonation (Bauer et al., 2025).
2. Plot-based vegetation sampling: Fixed or random plots within each dune habitat type for detailed floristic and structural assessments.
3. Mapping of visible pressures and disturbances.

In general, monitoring involves filling out questionnaires for habitat structure, functions, and impact assessments, and observations are typically conducted from May to October, with optimal monitoring times in July and August.

Remote sensing and GIS analysis are increasingly used to complement field data, particularly for assessing landscape-scale variables and changes over time (Gonçalves et al., 2018). Existing habitat maps, where available, provide valuable baseline data.

Some countries (e.g., Belgium, Netherlands) have established detailed monitoring networks with fixed plots that are resurveyed at regular intervals, providing robust trend data.

In **Italy**, Angelini et al. (2016) suggest conducting vegetational surveys in 1x1 meter plots along permanent transects that are positioned perpendicular to the coastline. This method ensures a systematic evaluation of plant communities in relation to coastal dynamics. To monitor substrate conditions, it is advised to use graduated rods inserted into the ground. These rods serve as effective tools for tracking processes of erosion and substrate accumulation over time, providing valuable insights into the stability and changes within the dune system. For measuring the occupied area, high-resolution aerial photography with a minimum resolution of 1 meter is proposed. This aerial data should be complemented with field surveys to ensure precise measurements of habitat extent and distribution. By integrating these methodologies, researchers can achieve a thorough understanding of the ecological dynamics at play in coastal dune ecosystems.

The **Irish** monitoring methodology uses 2 x 2 meters (or 1m x4m in linear habitats) monitoring stops distributed according to stratified random sampling to maximize representativity, and field data are supplemented using aerial imagery for some variables. This should be reflected in the text. Some variables are assessed on sample sites (e.g. characteristic vegetation communities, positive and negative indicator species, artificial coastal stabilization) while others are more appropriately assessed at a regional or national level (e.g. sea level rise, storm frequency).

In **Flanders**, the sampling protocol involves using GPS navigation to locate the centre of the sampling test area, which serves as the starting point for plot layout. A north-south axis is established, and two 6-meter ropes with pre-marked distances are used to create a precise rectangular plot. The plot is oriented along the north-south axis, with bamboo poles placed at specific distances (2.12m, 3m, and 4.24m) to mark the corners. This method ensures consistent plot size and orientation across sampling sites, allowing for accurate comparisons of vegetation and habitat characteristics. Additionally, a larger circular plot with an 18m radius is mentioned for certain measurements, to be conducted after the primary vegetation recording is completed.

In **Bulgaria**, the general sampling methods and protocols used to address dune habitat condition involve a targeted approach focusing on selected habitat polygons. The assessment process is flexible, allowing for two main strategies. Firstly, field observations and measurements for conservation status assessment can be conducted simultaneously with mapping or model verification activities. Alternatively, when more comprehensive data is required, the assessment can be carried out independently. This separate assessment is particularly valuable in scenarios where there is a high likelihood of potential threats and impacts materializing, or when the habitat characteristics exhibit significant heterogeneity.

In **Denmark**, monitoring stations often encompass multiple habitat types due to the mosaic nature of the landscape. At each station, the sampling methodology typically includes 10 randomly distributed sample plots, with a circular area established around each plot. For most habitats, this circular area has a radius of 5 meters. Importantly, each circular area can be associated with only one habitat type per monitoring year. Monitoring activities are carried out from May to October, allowing for optimal data collection during the growing season.

In **France**, in the national methodology applied in Natura 2000 sites, a systematic sampling approach is proposed to cover the entire dune system as comprehensively as possible. This is achieved using "Large Transects" (LTs), which are 50 meters wide and positioned perpendicular to the coastline_to capture the greatest environmental differentiation and characterize the well-defined vegetation belts typical of dune ecosystems. LTs are systematically laid out along the dune system, with distances between each transect ranging from 500 to 1000 meters. A permanent line is established within each LT for measuring criteria and indicators that assess the conservation status of the non-forested dune system. This method provides insights into both floristic composition and vegetation structure, facilitating regular monitoring of changes over time. Surveys are organized by habitat within each LT, with all defined criteria assessed for each habitat type. For indicators measured at the plot level, subjective sampling is conducted in representative areas of each habitat. This comprehensive approach allows for detailed assessments of dune habitats and supports long-term monitoring of environmental changes (Goffé, 2011). A minimum number of 10 LT should be carried out for a site with a surface area of 1000 ha. Concerning the number of plots within these LT, they recommend a minimum of 1 to 2 plots minimum per TL for embryonic and white dunes, and 3 plots per LT for grey dunes.

A national monitoring protocol is being developed for dune habitats In France, which requires using a transect every 5-6 km of dunes along the coastline and perpendicular to it, with permanent and systematic frequency plots along the transect. The operators will be able to set additional plots along the transect if they want. In the plots, some structural and compositional variables will be monitored. The sedimentary dynamics will be also monitored at the plot scale and at larger scale. Explanatory variables (climatic variables and atmospheric nitrogen) will be used to link structure, composition and environmental conditions (Margaux Mistarz, pers. comm).

In **Lithuania**, the monitoring process focuses on assessing habitat structure and functions using a transect method. Typically, a transect measures 200 meters in length and 10 meters in width, covering an area of approximately 2000 square meters. This transect is positioned in a representative location within the monitoring site. For smaller polygons, the transect size is adjusted to fit the available area while maintaining the standard dimensions as much as possible. In some instances, particularly for very small or uniquely shaped habitats, the transect may encompass the entire polygon area. Field surveys are ideally conducted from early June to late July. The monitoring method involves completing four questionnaires at each site: general site information, impact and threat assessment, floristic phytosociological characteristics (with three descriptions per polygon) and habitat structure and function monitoring for specific habitat types. The monitoring plan spans 12 years, including two reporting periods for conservation status assessments under the Habitats Directive. Each monitoring square is observed at least three times during this period, covering a total of 16 squares every twelve years.

According to the **Latvian** methodology, beach and dune habitats should be monitored using a combined route-point-transect method. Monitoring areas will be planned based on routes established in previous periods, optimizing their number and location according to habitat occurrence, accessibility, and other factors. Routes, approximately 500 to 1000 meters long, will run parallel to the coastline and cover the majority of the coastal habitats. In each habitat strip, a habitat questionnaire will be completed using 50-meter long and 10-meter wide transects. If a habitat is narrower than 10 meters, the transect will encompass its full width. For small and rare habitats, additional points may be added for characterizing typical structures and species. Monitoring should ideally occur in July and August, with September as an option. Most coastal habitats require monitoring at least once every six years, while highly variable habitats exposed to coastal processes may need assessments every two years or more frequently after significant disturbances. During monitoring, it may also be necessary to clarify habitat polygon boundaries on the map.

For **Romania**, the monitoring guidelines recommend employing selective sampling by establishing a minimum of seven survey plots or transects, distributed both within and outside protected natural areas where habitats have been identified. However, the guidelines do not specify whether this minimum number pertains to local, regional, or national vegetation distributions. Each sampled plot varies in size from 1 to 100 square meters (e.g., 1x1, 1x10, 2x5, 10x10 meters). A field sheet is recommended to complete for each surveyed sample area. Additionally, correspondences between vegetation types (vegetation associations) could be determined using the national vegetation inventory and descriptive monographs.

Finally, in **Poland**, the monitoring protocol involves establishing a fixed transect measuring 200 x 10 meters, which can be adjusted in length if necessary. The transect is located using

GPS coordinates and is typically oriented parallel to the shoreline. Phytosociological relevés are conducted at three points along the transect: at the beginning, in the middle, and at the end. If a continuous 40-meter transect cannot be established, three separate slacks may be sampled instead.

2.7 Other relevant methodologies

Methodologies available from UK have established reference values for favourable condition in various dune habitat types, as described in Box 1 below.

Box 1. Example of key criteria defined for favourable condition of coastal sand dune features

Source: *Common Standards Monitoring Guidance and Internal Natural England targets for tailoring the Favourable Conservation Tables for SSSIs* (JNCC, 2004; compiled by G. Weaver)

For a whole site:

- less than 10% of any dune site should retain dune scrub woodland into the long term
- an 'active dune zone' should be present along 95% of the dune frontage, subject to local natural coastal processes and sediment supply.

For strandline/embryo/mobile dunes, 'favourable' condition includes:

- native scrub should be rare or absent from any dune site's mobile dune grassland
- non-native scrub should be rare or absent, with invasive non-native species absent
- up to 50% of any dune site's mobile dunes should constitute bare sand.

For fixed dune grassland, 'favourable' condition includes:

- between 5% and 10% of any dune site's fixed dune grassland should have native scrub either scattered or in small clumps
- non-native scrub should be rare or absent, with invasive non-native species absent
- native scrub should be rare or absent from any dune site's semi-fixed dune grassland
- between 5% and 20% of any dune site's fixed dune grassland should constitute bare sand
- fixed dune grassland should have 30-70% of its sward comprising short turf 2-10 cm tall.

For dune heath, 'favourable' condition includes:

- between 5% and 20% of dune heathland should have native scrub either scattered or in small clumps
- non-native scrub should be rare or absent
- between 5% and 20% of any dune site's dune heath should constitute bare sand
- all growth phases of heathers should be present (pioneer/building/degenerate/dead phases)
- some acid grassland presents as mosaics providing a contrasting structure.

New technologies, including remote sensing, are increasingly used in the monitoring of habitats and ecosystems. A novel initiative in Latvia implements comprehensive monitoring and assessment of sand dune habitats using remote sensing data and national registers (Dainis Jakovels et al. 2022). It covers various aspects such as the use of laser scanning data for landform analysis, monitoring humidity status using Sentinel-2 spectral data, and detecting, for example, parameters such as sand blowing/accumulation, sand cover detection, and the identification of individual sand dunes. The methodology emphasizes the need for feasibility studies to determine the suitability of remote sensing data for assessing specific characteristics of sand dune habitats, such as dune hills extraction, pine identification, and land cover classification. Other similar methods were introduced in Lithuania by Cesnulevicius et al. (2018).

Nevertheless, limitations must be noted in spatial resolution for identifying individual plants or vegetation groups and the requirement for high-resolution drone data for detailed evaluations. It also addresses the importance of terrain analysis from laser scanning data for automatic extraction of landforms and monitoring changes in terrain over time.

In summary, the methodology provides a detailed framework for utilizing remote sensing data and national registers to monitor and assess changes in dune habitats, emphasizing the importance of accurate data collection, analysis, and interpretation for effective environmental monitoring and conservation efforts.

2.8 Conclusions

The complexity of dune ecosystems and the variability in their characteristics have resulted in a lack of a universally accepted method for assessing dune condition, making global evaluation of their conservation status highly challenging. This complexity is further compounded by disparities in methodologies applied across different countries, variations in conceptual definitions of conservation status (such as in the selection of typical species), and the subjectivity introduced by expert opinions. Despite these challenges, various countries and regions have developed their own approaches to evaluate and monitor these dynamic coastal features.

The analysis of existing methodologies for assessment and monitoring of coastal dune habitats in the EU shows important differences in the specific methods used but also some common approaches.

While the reviewed methodologies cover a wide range of relevant variables, some gaps and areas for improvement are evident:

- Functional indicators: Many approaches focus heavily on compositional and structural variables, with less emphasis on direct measures of physical variables and ecosystem functions.
- Measurements and assessments of different functional animal species groups, mainly invertebrates such as soil predators, main pollinator groups etc. are largely missing.
- Standardization: There is considerable variation in the specific metrics and measurement methods, as well as in the establishment of thresholds across different countries and regions, making cross-border comparisons challenging.
- Objective results: The assessments are heavily influenced by expert judgments in some member states, resulting in subjective assessment that make them hardly comparable.
- Temporal dynamics: Given the naturally dynamic nature of dune systems, capturing temporal variability remains a challenge in many assessment schemes.
- Emerging threats: Some methodologies may need updating to better capture the impacts of climate change, such as changes in storm frequency or sea-level rise.

With regard to general sampling methods, there is room for harmonisation in the use of transects and square plots for vegetation sampling, satellite images, aerial photographs and drones for monitoring changes, measurement of dune dimensions, analysis of dune dynamics and vegetation, monitoring erosion and sand deposition, and landscape analysis to assess habitat fragmentation and connectivity.

The European dune systems are some of the most threatened habitats due to their intrinsic fragility at the marine-terrestrial interface and the significant tourist pressure they face. There is a recognized need to develop new, more objective methods to refine habitat assessment and monitoring protocols while harmonizing criteria and concepts among professionals conducting assessments. Moreover, the multidisciplinary nature of dune systems requires the selection of variables and methods from different disciplines to study these habitats, where the analysis of sedimentary dynamics studies to understand dune system development and evolution needs to be coupled with vegetation surveys to assess floristic composition.

3. Guidance for the harmonisation of methodologies for assessment and monitoring of habitat condition

3.1 Selection of condition variables, metrics and measurement methods

As shown in the previous section, there are quite some differences in the specific variables, metrics, and methodologies used by the various EU Member States to assess the condition of coastal dune habitats. Common procedures would be desirable to obtain comparable assessments across habitats and Member States. To harmonize the selection of condition variables for the assessment and monitoring of coastal dune habitats, several general principles should be considered:

- Any habitat type can be described with a set of key characteristics, irrespective of its location in different MS; each of these characteristics can be measured with relevant variables.
- There are contextual factors operating in the different MSs, which may determine the values of the variables that determine whether the habitat is in good or not good condition.
- For a given habitat, the final assessment of habitat condition, based on the relevant variables associated with key characteristics of the habitat, should be equivalent for the different MS, after accounting for the contextual factors of each MS.

Moreover, the harmonization of the use of relevant variables requires a set of common requirements:

- For any coastal dune habitat, the main characteristics must be measured in all MSs using a set of common variables, applying the same measurement procedures.
- The description of the condition variables, metrics and measurement procedures must therefore be clearly defined and perfectly understandable so that they can be applied in all the MSs.
- The number of common condition variables should be the minimum needed to determine the habitat condition. For particular habitats, there may be also specific variables that apply to those habitats.
- The common variables should meet the criteria of validity, reliability, availability, simplicity and compatibility (Czúcz et al. 2021).
- Common training on the measure of the condition variables should be programmed for experts from the different MSs in order to achieve full harmonization.

This section presents a proposal for a common set of variables, recommended metrics, and measurement procedures for all dune habitat types, classified as follows:

- **Essential** condition variables describe essential/key characteristics of the habitat, reflecting its conservation quality, and should be assessed in each MS, following equivalent procedures.
- **Specific** condition variables, which should be measured on some specific habitats or in some contexts but are not required in all the cases.
- **Recommended** condition variables, which are recommended to be measured whenever possible to obtain further insight or complementary information on the condition of the habitats and may be especially relevant in certain situations or circumstances.

In addition to these condition variables, other **descriptive or contextual variables** are also proposed for monitoring. These variables do not directly determine the condition of the habitats but are useful for the habitat characterization in the monitoring locations.

The assessment of and monitoring of the main dune characteristics should consider the key factors that involve morphological and sedimentary changes (morpho-sedimentary factors) in dunes, their exposure to and impact from coastal and marine processes (marine and coastal incidence factors), the wind dynamics responsible for the creation and growth of the dunes (wind incidence factors), the plant development and general ecological maturity of the system (ecological and plant cover factors), as well as human actions that cause degradation or destruction of the dune system (Gracia et al. 2009)

Table 7 presents a proposed list of essential, specific and recommended variables to assess habitat condition in coastal dune habitat habitats, which are explained further below. The list is based on the main characteristics of coastal dune habitats described in Section 1.2, information provided by Member States on habitat condition assessment (see section 2), and available literature on coastal dune habitats. The proposed metrics and measurement methods are designed to be easily and reliably obtained, primarily at the monitoring or sampling plot level.

The characteristics and proposed variables are classified according to the Ecosystem condition typology from SEEA-Ecosystem Accounting (United Nations, 2021).

The main abiotic variables refer to the dimensions of the dunes that inform about the dynamics (erosion-sedimentation processes) and some relevant chemical variables that are useful to understand their nutrient status and possible deterioration of the natural conditions.

The proposed variables for describing biotic characteristics include the presence and abundance of characteristic species (vascular plants) for each habitat type, as well as the presence of some animal species that can reflect favourable condition, the total cover of vegetation and the presence and cover of negative indicator species (non-native, nitrophilous species).

Some variables are assessed on the basis of sample sites (e.g. characteristic vegetation communities, positive and negative indicator species), while others are more appropriately assessed at a wider scale, e.g. on the whole dune system (e.g. coastal trend). Some of the variables (e.g. dune morphology) are best measured over long periods and at wide scales. At a local scale, dunes receding or growing seaward may be part of normal sedimentary cycles. However, detecting changes in dune morphology that indicate a change in natural erosion-sedimentation processes caused or not by human action enhancing erosion and preventing accretion, may be addressed in the condition assessment of dune habitats at the appropriate scale.

Table 7. Proposal of essential, specific and optional condition variables for coastal dune habitats, including metrics and measurement procedures

App.: Application of variables: Essential (E), Specific (S), Recommended (R), Descriptive (D).

Characteristic type	Variable	Metrics	Measurement procedure	Appl	Effect on habitat condition	Observations
3.2 Abiotic characteristics						
Physical characteristics	Dimensions: (1) width (mean), (2) length, (3) height	m	Aerial photography, Remote sensing,	E	Positive	Measure the entire dune system and each habitat type, to detect changes and evaluate trends/ evolution over long periods. Difficulties in identifying the limits of each habitat type of dune (embryonic, secondary...)
	Sediment input	m3/year/length of coastal section (e.g. 100 m)	Graduated rods, GPS monitoring, use of UAV	R	Positive	Graduated rods is an effective method in the short term, while for longer-term assessments other topographic methods are more adequate, like GPS monitoring or the use of UAV for the elaboration of detailed DSM
	Erosion signs: vertical scarps showing exposed roots of plants, mass movements (overhangs and sand tongues)	Number of vertical scarps with exposed roots of plants.	Quantification on exposed face of primary or secondary dunes - Plot survey	R	Negative	Temporary erosion signs can be natural in stormy periods but if prolonged in time, these signs can indicate an alteration of the natural sedimentation-erosion dynamics of the dune
Chemical characteristics	Nitrogen content	mg/kg	Analysis from plot samples	E	Negative	Soil test kits
	Acidity	pH	Analysis of plot samples	E	Fit to habitat characteristics	Soil test kits. Considering pH requirements, detect and assess changes
3.3 Biotic characteristics						
Compositional	Characteristic species - vascular plants	No. of characteristic species from a reference list	Count of characteristic species - Plot survey	E	Positive	List of characteristic species for each habitat in each region or locality (as appropriate) should be developed
	Fauna (invertebrates, birds, reptiles, small mammals)	Number of characteristic invertebrates (functional groups) presence of species, signs or remains	Plot survey/ Field work	E	Positive	Ground beetles, Hymenoptera and other psammophilous invertebrates, pollinators, reptiles, amphibians, birds, small mammals

Characteristic type	Variable	Metrics	Measurement procedure	Appl	Effect on habitat condition	Observations
Compositional	Non-native plant species (incl. alien species)	number of species	Plot survey	E	Negative	Non-native species in the area that can become invasive; also invasive exotic species. Regional lists of as potential non-native and harmful species in dune habitats should be developed.
	Non-habitat - harmful species	number of species	Plot survey	E	Negative	Species that have colonised the habitat but are not characteristic for it, which come from other habitats, usually grasslands but also trees species (Alnus) and cause damage and alteration of the habitat structure
Structural	Vegetation cover / bare soil cover	% cover	Plot survey, aerial photographs	E	Positive	Specific ranges for each habitat type to be established; may also vary depending on environmental conditions and over time (for example, due to storms, strong winds, etc. etc.)
	Harmful species cover (including nitrophilous)	% cover	Plot survey	E	Negative	Complementary to compositional variable on invasive species
	Invasive species cover	% cover	Plot survey	E	Negative	Complementary to compositional variable on invasive species
	Shrub cover	%	Plot survey	S	Positive/ negative depending on habitat type and specific % ranges of cover	For tertiary dunes and dunes with scrub and woody vegetation (2130, 2140, 2150, 2160, 2170, 2250)
	Moss and lichen cover	%	Plot survey	S	Positive	Relevant for fixed dunes (e.g. 2130)
Functional	Pollinators	Presence, nr of species	Time based Plot survey, eventually insect traps	S	Positive	List of typical pollinator species to be developed, relevant for all dune types, excluding early stages (2110, 2120) and dense shrub vegetation (2160, 2170, 2250)
	Psammophilous predators	Presence, nr. of species	Plot survey, pitfall traps	R	positive	
	Ground-nesting hymenoptera	Nesting density and species nr.	Plot survey	S	positive	Relevant for all dune types, excluding early stages (2110, 2120) and dense shrub vegetation (2160, 2170, 2250)

Characteristic type	Variable	Metrics	Measurement procedure	Appl	Effect on habitat condition	Observations
	Damage/human-driven impact: trampling, garbage, litter	% surface affected	Qualitative: aerial photo (at supra-local scale, dune system), field survey	E	Negative	Trampling caused by people, animals and vehicles. Accumulation of human waste (artificial objects
	Beach cleaning	% of the beach affected	Qualitative: aerial photo, field survey	E	Negative	Maintenance activity for tourist uses
3.4 Landscape						
Landscape features, fragmentation, impacts	Completeness of dune zonation, habitat heterogeneity	Nr of dune bands present along a dune system, from the seaward edge to the landward side.	Aerial photography, Remote sensing, Assessed at supralocal scale	E	Positive	The completeness of dune zonation aims to assess the continuity or presence of a complete and connected dune system with all its dune bands. A complete dune system requires sufficient space that has not been invaded
	Habitat patch size	Patch size: m2, ha	Aerial photography, Remote sensing.	E	Positive	Assessed at supralocal scale. Measured for the whole dune system and for each dune habitat type
	Continuity of dune system along the coast/ degree of fragmentation	Distance between patches (m)	Aerial photography, Remote sensing.	E	Positive	Assessed at supralocal scale Measured on the entire dune system.
	Effects from constructions and infrastructure development that directly affect the dune	% of affected surface (local plot)	Qualitative: aerial photo (at supra-local scale, dune system), field survey	E	Negative	Access to beaches, parking lots, promenades, kiosks, urbanized areas
	Coastal trend	m/year, width gained or lost	Aerial photography, Remote sensing,	E	Negative	Assessed at the scale of the entire dune system. Regression implies reduced sedimentary input
	Alterations outside the dune area that interfere with the sedimentary dynamics of the dune	Presence and type of alterations	Aerial photography, maps, field survey. Assessed at supralocal scale	D	Negative	Identify the existence of breakwaters, coastal defence, dams, etc. that can affect the sedimentary dynamics of the dune system

Abiotic variables

Physical variables

Dimensions: length, width, height

All transverse coastal dunes, whatever their type, have a very characteristic geometry, derived from their vertical growth and their low horizontal migration on a human scale (McKee, 1966). The morphological variations of the dune complex involve parameters such as its length, the width of the active dune system, the height of the dunes (modal and maximum), the average slope of the dunes of the active system, or the volume of sand present in the complex. Dunes do not grow indefinitely, however. With constant wind flows and supplies, an equilibrium form is reached, so that the sand leaves the dune at the same rate as it enters it (Gracia et. al. 2009).

The surface and width of the dune system are variables that provide information on the resilience of the dune system. The larger the dune assembly and, therefore, the greater the amount of sediment, the more effective the system will be against large coastal storms (Carter 1988).

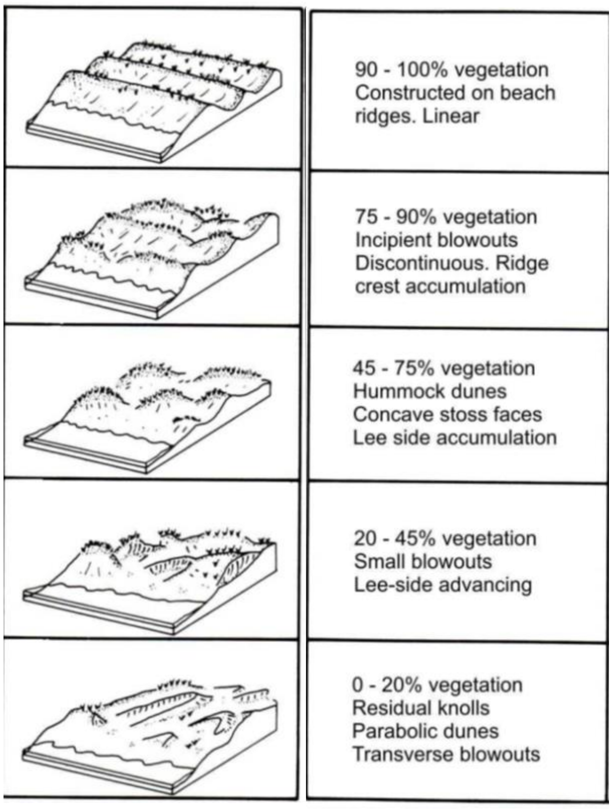
In large dune systems that can be considered regional references for their size, variety of habitat types and state of conservation the width of the dune systems is usually equal to or greater than 500 m, while their length often exceeds 2,000 m. These dune systems contain a wide variety of interconnected habitat types, with a complex dynamic that changes the percentage occupied by each habitat within the dune system over time (Gracia et. al. 2009).

The **length and width** of the dune habitats can be estimated on a topographic map, but it is preferable to measure these variables from aerial photographs or satellite images, since the boundaries of the dune system are much better identified. Remote sensed images are especially useful in order to plan a long-term monitoring of the habitat changes through time. Previsions based on historical trends can be unreal by only using maps as historical sources, since very often new commercial maps trace or simply reproduce the limits represented in previous editions, without any updating. For measurement of dimensions, Google Earth tool can also be useful.

The length of the dune ridge along the area where it is in direct contact with the beach should be measured. In the case of the width of the active system, it should be measured from the line where the first grey spots or patches of vegetation appear, to the limit where the dunes are fully covered and fixed by vegetation. The measurement shall be made in a direction perpendicular to that of the first active ridge. For the case of the width of the dune system, several measures are proposed along the entire surface, since the width can vary considerably between zones and thus obtain an average of all of them. It is recommended that the same criteria be used for each measurement over the whole monitoring period, so that the error induced in the measurement is minimized to the maximum extent. Whenever possible it is recommended to also make measurements in situ with GPS to detect possible errors, if the dimensions of the system allow.

As regards the **height**, a dune system with potential for development would be one in which the first dune ridges vegetated with *Ammophila arenaria* have average heights of no less than 0.5 m and preferably greater than 1 m (Gracia et al., 2009). As Ley et al. (2007) indicate, the capacity of vegetation to retain available sediment determines, among other factors, the increase in sediment volume and the potential growth in height of dune ridges. Once the vegetation is no longer effective as a wind screen, the sedimentary structure stabilises its height and begins to advance towards land. Taking into account this interrelation between geomorphology and vegetation, it is necessary to take into account the type of vegetation installed on the coastal dune, since it will determine the development and morphology of the sedimentary structure (Figure 3). As a rule, the density of the vegetation cover, the type of vegetation and the height of the dune determine the surface extent of sand deposition in the foredune.

Figure 3. Classification of coastal dunes based on the percentage of vegetation cover



Source: Adapted from Carter, 1988

The modal height, maximum height and average slope measurements of coastal dunes should be made in the field. It is recommended to make a representative number of height measurements of the dune summits, preferably by dynamic GPS, along the entire dune system, especially in the most dynamic areas of the system

Sediment input

It must be reminded that dunes form when the volume of sand entering the sedimentary system is greater than the volume of sand leaving it. This excess of sand is transported by the wind with a selection of sizes according to the wind intensity and the dunes are usually located outside the action of ordinary storms. When there are extraordinary storms, the sand is eroded and transported towards the submerged beach, which dissipates the energy of the waves and prevents further erosion. Then, in calm moments, the sand is returned to the emerged beach, ending the cycle that characterises the sedimentary balance of the beach. In periods of recession such as the present one, with a widespread deficit of sediments along the world coasts, in calm moments, the profile cannot be reconstructed due to a lack of sediments, so the beach becomes narrower, the dunes lower and narrower (Gracia et al., 2019).

There are several factors that control the morphological balance of dunes. The most important ones, according to Lancaster (1985), are: the possibility of sand supply and the characteristics of the wind regime, although grain size, sediment classification and vegetation cover may be locally significant. The sediment supply also depends on the shape and width of the beach, the nature of the aerodynamic flow crossing the beach and the vegetation (Short & Hesp, 1980). The sedimentary contribution to the dune depends on the erosive or cumulative state of the beach, as well as the grain size or the volume of available sand, often linked to the number of bars on the beach. The inter- and subtidal bars constitute the best natural defence of the beaches against the action of energetic waves. In addition, the remobilisation of the sediment of the bars by the swell waves facilitates the transport of sand to the beach, and therefore, the supply of sand to the dunes.

Sediment input can be quantified with a simple method (Wilson & Skyes, 1999). It consists of nailing a series of graduated rods, usually thin metal bars with measuring marks along their length. They are usually buried in the sand until they are firmly attached and stable. The depth at which they are buried and the distance between them may vary depending on the specific measurement objectives and the conditions of the beach in question. The arrangement and density of the rods should be uniform to provide a representative monitoring of the area. This method is very effective for the quantification of the amount of disturbance depth in beaches at the short term (days to weeks), while for longer-term assessments (months, years) other topographic methods are more adequate, like GPS monitoring (Gracia et al., 2005) or the use of UAV for the elaboration of detailed DSM (digital surface models; Gonçalves et al., 2018).

Erosion signs

The geomorphology of the sandy coast can be affected by significant erosion processes linked to other factors that are difficult to quantify (frequency of storms according to wave height intervals, frequency of high-energy phenomena compared to the natural rate of sedimentary recovery of the beach, etc.). Therefore, it is appropriate to evaluate on the ground the erosive effects of the energetic waves, which are especially evident in the breaks of the first dune ridge (secondary dunes), which often produce overflows or spills towards land (*overwash*). These breaks give rise to cuts in the dune ridge, which make it easier for the following storms to concentrate their energy in these weaker areas, where plant colonization and the generation of dunes is very difficult (Van Wiechen et al., 2023). In fact, the first evidence of the erosive action of the waves is the formation of **vertical scarps** on the exposed face of the first dune ridge (secondary dunes). These scarps usually show exposed roots of the pioneer plants, as well as signs of mass movements (overhangs and sand tongues), result of the gravitational instability caused by an excessive slope, as a consequence of the basal excavation and undercutting by the waves during episodes of maritime storms. The secondary dunes affected by this process need a long period of time for their recovery, while the embryonic dunes, which could have been swept away by the waves responsible for the erosion, have a faster recovery speed. The existence of exposed roots on the windward slope of the secondary dune indicates the predominance of erosive processes over the cumulative processes due to sand retention by plant roots. It is, therefore, an indicator of the sedimentary deficit of the dune system, which may lead to its disappearance over time.

Dune morphology influences aeolian sedimentation, creating areas of deflation or dune erosion (**blowouts**), as well as areas of wind speed decline and sedimentation. The presence and development of blowouts breaks up the dune system and makes it more vulnerable. In addition, deflation basins are forms derived from the punctual erosion of the dunes, so their proliferation is indicative of a predominance of sand loss that can lead to the fragmentation of the dune system. The alternation of erosion and sedimentation areas favours the formation of small isolated sand mounds or accumulations (*hummocks*), which lead to a significant fragmentation of the dune system. When wind erosion is concentrated in specific points, deflation corridors are excavated, whose growth in number and size also contributes to the progressive fragmentation of the dune system: they increase the fragility of the dune ridge when breaking points occur in the continuity of the front. In this way, the aeolian erosion processes become more intense. The development of the dune system requires an efficient aeolian transport from the dune front towards the interior. On the other hand, for the aeolian accumulations to form dune ridges, they must be consolidated with the growth of vegetation. As a consequence, over time, the aeolian system will grow, both due to the advance of the dune front towards the sea and due to the decrease of blowouts, variables that are indicative of the evolution of the dune system (Gracia et al. 2009).

It is important to note that when assessing coastal dune habitats, care must be taken for not misinterpreting natural processes and intrinsic characteristics as indicators of poor condition. Factors such as the extent and mobility of dunes, erosion and deposition patterns, and the size of dune systems are all part of the natural functioning of these dynamic ecosystems. These elements contribute to the overall dynamism, large-scale mobility, and connectivity between sites, which are crucial for the health of coastal dune systems. When assessing habitat condition, it is essential to distinguish between natural processes and human-induced impacts. For instance:

1. Size: The size of a dune system should not be considered a negative factor unless there is clear evidence of human-induced coastal squeeze or other artificial restrictions.
2. Erosion and accretion: These are natural processes in dune systems. Only when erosion is enhanced or accretion is prevented due to human activities should they be considered negative factors.
3. Sediment movement: This is a crucial part of dune dynamics and should be viewed neutrally unless artificially impaired.

For all these reasons, treating natural or intrinsic values such as local erosion or smaller site size as negative indicators could be counterproductive to conservation goals and might lead to misallocation of resources.

Chemical variables

Nitrogen content in soil

Nitrogen concentration in soil is an important variable for determining the state of dune systems. N is an essential nutrient for the development of all known life forms. The duality of reactive N as a contaminant and fertilizer is what makes the deposition of N as a source of pollution so particular (LeBauer & Treseder, 2008; García-Velázquez & Gallardo, 2017). The release of this element into the atmosphere results in a systematic loss of biodiversity at all trophic levels (primary producers, consumers, decomposers) and biological groups (micro-organisms, plants, animals), as well as a disruption of a large number of ecological interactions that ensure the smooth functioning of ecosystems (Tylianakis et al., 2008; Baron et al., 2014), so much so that it is considered as the main agent of change in ecosystems associated with the emission of polluting gases (Gruber & Galloway, 2008; Bobbink et al., 2010).

Anthropogenic emission of nitrogen is the result of burning fossil fuels, mainly in the form of oxidised N (NOx; e.g., industrial or associated activities to the fleet), or agricultural and livestock activities, typically in the form of reduced N NH_3 (Ochoa-Hueso et al., 2017). Once released into the atmosphere, these nitrogen compounds take part in a series of complex chemical and physical processes until they are finally deposited in terrestrial and aquatic ecosystems through mechanisms called "dry deposit" and "wet deposit" (Hertel et al., 2011).

Dry deposition is the direct entry of gases and particles into ecosystems by depositing on their various surfaces or being absorbed (in the case of gases) through plant stomata; whereas the wet deposit is an input associated with atmospheric precipitation, through processes of "washing" of air pollutants occurring both inside and under clouds. Atmospheric N deposition occurs near emission sources, but it may also be transported in the atmosphere and deposited in remote areas where it can often be the main source of N in those ecosystems limited by N (Bleeker et al., 2011).

In the dune systems, N deposition is currently a serious problem in northern and northwestern Europe. Deposition stimulates the growth of especially tall grass species. For example, in the Dutch coastal dunes (Figure 4) nitrogen levels reached up to 40 kg/ha/year in the 1980s. Since then, the situation has gradually improved to 15-20 kg/ha/year (Figure 5), still above the critical load for limestone dunes (15 kg/ha/year) and acid grey dunes (10 kg/ha/year) (Kooijman et al., 2017). Furthermore, Ammonium is directly toxic to lichen and mosses and may alter the cryptogam composition completely. In the Mediterranean regions, N deposition is expected to increase significantly, in areas which together hold a high percentage of global biodiversity despite their small geographical extent (Phoenix et al., 2006). N deposition also causes increased growth of algae responsible for the fixation of bare sand.

Figure 4. Estimated nitrogen surplus for the year 2005 across Europe

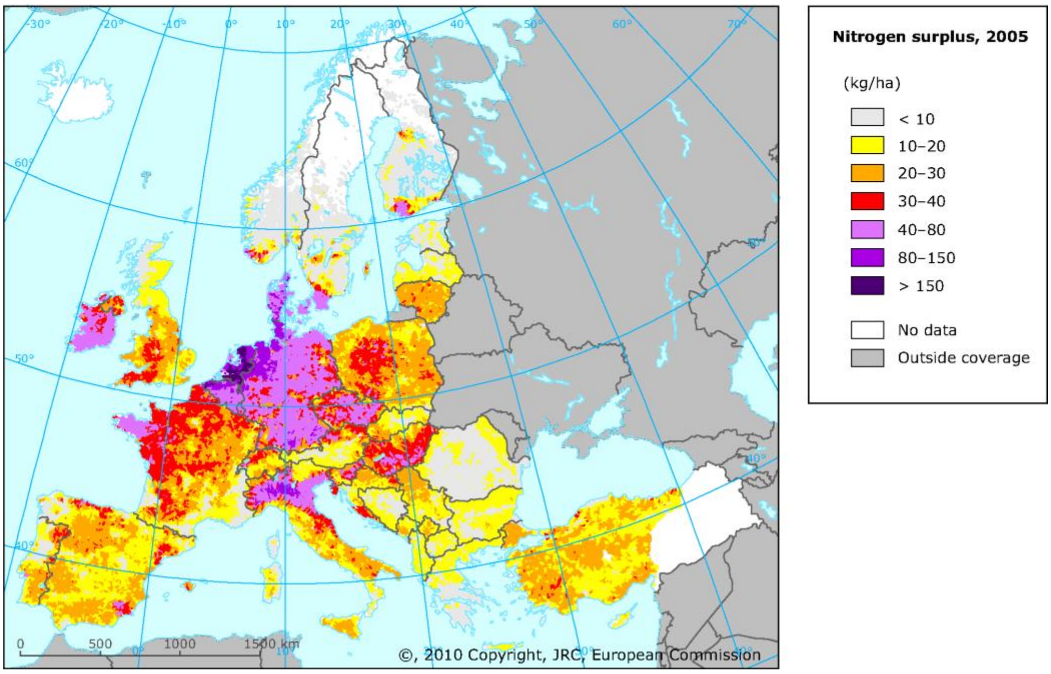
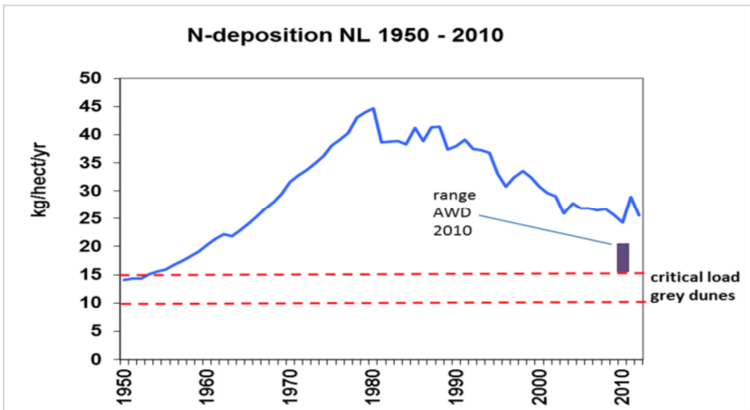


Figure 5. Estimated nitrogen surplus for the year 2005 across Europe



The consequences are an acceleration of vegetative succession which in calcareous dune areas is reflected in the invasion of shrubs at the expense of the area of dune grassland, which manifests itself not only in the reduction of the area of grey dunes, but also in the deterioration of quality and diversity. Several species characteristic of dune grasslands have declined and, apart from the flora, also have disappeared species characteristic of the fauna in many coastal dune areas, such as the Grey Collared (*Oenanthe oenanthe*) or butterflies like *Argynnis Niobe* (Van Til et al., 2019).

Atmospheric deposition is the process by which materials (particles and gases) are transferred from the atmosphere to land or water surfaces. On the one hand, atmospheric deposition depends on the concentration of pollutants in the air at a given time, which is in turn conditioned by the location and activity of the sources (urban centres, industries, natural sources, etc.). On the other hand, atmospheric conditions determine the reactivity of pollutants and their deposition and displacement speed.

There are several methods for determining the concentration of Nitrogen and ammonia, including rapid test kits (checkers), photometric methods, volumetric methods or selective ion electrode methods. There are now several easy-to-use ammonia and nitrate meters with more than sufficient accuracy to monitor these parameters. Some of these meters are multiple, that is, they measure several parameters at the same time, which is useful to have a complete information of the overall chemical characteristics of the areas to be monitored.

Acidity (pH Value)

Simple soil properties measurements include soil pH. In most European dune systems, when sand is pushed out by the surf onto the beach, it has a pH above 7. Over a long period of time, the calcareous material is leaching and the sand becomes acidic and vegetation also begins to change. Knowing the soil pH, allows you to choose different management techniques or restoration actions. Some dune systems, especially in northern Europe have naturally acidic soils due to the chemical properties of sand.

Chemical analysis of soil samples in the laboratory is usually quite expensive. An alternative is to use easy-to-acquire rapid test kits. The sample is usually obtained in sand at 0 - 15 cm depth (pH of soil at bulk 0-15 cm depth, measured in deionized water). Monitoring of soil chemical properties including measurement of nitrogen content and pH can be performed every six years.

Biotic variables

From an ecological point of view, the dune system is composed of a succession of interconnected vegetation bands. The maintenance and development of dune habitat types depend on the continuity of the plant successions and the connection between them. Variation in the vegetation cover is a good indicator of the environmental health of dune habitats, which makes advisable to monitor this variable, as well as the type of plant species that cover the various dune habitats present in the dune system.

Compositional and structural variables

Presence and abundance of plant species

The main structural component of habitats is vegetation, which also determines many functions in particular dune habitats. The plants growing in a dune system are a useful ‘sentinel’ for changes happening on the site. Their abundance changes from year to year depending on the weather, but they also reflect what is happening in the soil and respond to longer-term influences such as climate or nitrogen deposition. For example, this might show up as an increase in nitrogen-loving species over time, a decrease in wetland species in dune slacks that are slowly drying out, or increasing numbers or spread of invasive species (Jones et al., 2021).

The presence and cover of exotic species is an indicator of ecological degradation of the dune complex. Exotic species do not help dune development, can favour the erosion of the first dune ridge and displace other species that are beneficial for the development of the habitat.

The proposed monitoring (see section 3.5) is to be carried out on plots integrated in transects perpendicular to the coastline covering all habitats included in the dune system, and if possible, also including habitat 1210 (Ephemeral vegetation on accumulated marine litter) if it is represented in the area under study.

On all habitats, the following plant species should be considered:

- Characteristic species, those that define a particular habitat.
- Non-native species (but not invasive)
- Invasive species (non-native species that are invasive)
- Undesirable species (native at regional level, but characteristic of other habitats).

The number of species from relevant reference lists should be recorded. Regional or local lists of coastal dune characteristic species (vascular plants, lichens and mosses, animal species) for each habitat type, as well as potential non-native and harmful species, should be developed. This will allow to interpret changes in vegetation over time, e.g. when new pressures can become important at the site.

This method provides information about vegetation composition, species diversity and richness, presence and proportion of key and indicator species such as pioneer, dune-builder, stabilizer, nitrophilous and exotic species.

UAS (Unmanned Aerial Systems) and colour orthophotos (like those available at Google Earth visor) can be used to identify the state of vegetation cover in dunes and its evolution, and even to differentiate habitats through the application of indexes (Talavera et al., 2022).

Animal species

The presence of different types of fauna (invertebrates, reptiles, birds) in the dune system is an indicator of its ecological richness and good condition. As already mentioned, primary or embryonic dunes on the beach are of special importance for breeding birds and for invertebrates, including beetles, spiders and highly specialised invertebrates from other groups. In secondary dune habitats soil nesting psammophilous Hymenopptera are a group of characteristic invertebrates.

Grey dunes, decalcified dunes or dune shrub habitats are species rich in invertebrates, including soil living invertebrates as predators and also the main pollinator groups such as wild bees, hoverflies, butterflies and other *Diptera* groups. Pollinators and Some reptile and mammal species can also be considered characteristic of certain dune habitats. Lists of characteristic animal species should be developed for each habitat type and region or locality, as appropriate. The detection of invertebrates and reptiles, as well as coastal bird nests, can be carried out by visual inspection of the dunes, which can also allow the identification of rabbit burrows.

Functional variables

Pollinators and other invertebrate species

Pollinators, as well as psammophilous invertebrate predators and ground nesting Hymenoptera are proposed as functional variables as they indicate proper functioning of some dune habitats, excluding early stages (2110, 2120) and dense shrub vegetation (e.g. 2160, 2170, 2250).

Damage/human-driven impacts

Trampling can affect the condition and proper functioning of dune systems. The transit of visitors and vehicles through the dune system causes the destruction of pioneer plants through trampling, proliferation of waste, compaction of the sand, etc. The deterioration of the embryonic dunes is proportional to the pressure of visitors, especially during the summer season. The vehicles that travel through the active dune system compact the sand and difficult its transport by the wind, destroy the vegetation, prevent the formation of embryonic dunes and favour the appearance of water erosion phenomena. Although to a lesser extent, the movement of horses also causes compaction of the sand, death of vegetation, etc.

Among other effects of human-driven impacts, accumulation of **solid waste, garbage and litter** indicates deterioration and pollution of the dune system.

The surface affected by trampling caused by visitors, vehicle and horse traffic, as well as the cover of garbage and litter accumulated on the dunes can be estimated visually in the field or by aerial photography at the scale of the dune system.

Beach cleaning. On the neighbouring beach, the source of sand for the dune system, the embryonic dunes, from which the main ridges are fed, can be destroyed by cleaning work during the bathing season, or by the installation of temporary infrastructures. Beach cleaning often eliminates part of the pioneer plants that give rise to the embryonic dunes, as well as other plant obstacles that nucleate or capture sand, such as the mats of *Posidonia* accumulated on the dry beach. This activity can affect the natural dynamics of the dune system and its effects mostly concentrate in the summer season, which is the time of the year when the sand is drier and looser, and therefore, when the dunes could develop greater wind activity (Gracia et al., 2019). The area affected by beach cleaning can be estimated by visual inspection during filed surveys or by aerial photography at the scale of the dune system.

Landscape variables

Completeness of dunal zonation

The existence of a complete a connected sequence of dune bands indicates habitat heterogeneity and good condition of the dune system, which requires sufficient space that has not been invaded or altered. It can be assessed at landscape or high spatial scale by aerial photography or remote sensing.

Habitat patch size

The patch size (total and for each dune habitat type) should be measured by aerial photography or remote sensing for the whole dune system and for each dune habitat type in the system to detect possible changes that indicate reduction and deterioration or increase and recovery or improvement of the habitat condition at the relevant scale.

Continuity of dune system/degree of fragmentation

The degree of dune fragmentation is proposed as a landscape variable that can be assessed by measuring the number of fragments and distance between the remaining fragments or patches of the former dune system. The assessment should be done using aerial photography or remote sensing at the scale of the dune system.

The extent of the dune patch and the number of fragments can be measured by remote sensing, aerial photography, or UAVs (Gonçalves et al., 2018; Grottoli et al., 2021). Scalable aerial photography-based programmes that enable measurements can be used for this purpose. Measurements of these variables shall be carried out every six years or when a new photogrammetric flight is obtained. UAVs can be programmed under demand (area covered, frequency of surveys, resolution of the data, etc.). Yearly assessment could be recommended for a adequate assessment of the number and size of patches, since most changes take place during the energetic winter season (Bastos et al., 2024).

Area occupied by constructions and infrastructure that directly affect the dune.

Permanent infrastructures, such as walkways, footbridges, parking areas, establishments selling and/or renting various products, affect the natural dynamics of the active dune system, since they prevent the growth and progress of active dunes, are generally accompanied by total or partial elimination of dunes close to the infrastructure, often cause pollution or discharges, etc. The effect of such infrastructures and activities can be assessed at the scale of the dune system by estimating the percentage cover of the affected area during field surveys or using aerial photography.

Coastal trend

The medium-term trend of the beach-dune system determines the future of coastal dune complexes. It is therefore essential to know the coastal trend (progress or retreat) in recent years, as well as the evolution of sedimentary contributions to the beach.

Lack of sediment and inadequate coastal management is a key problem for dunes' conservation. The main sources of sand in the past were firstly fluvial supply, and secondarily marine reworks of fluvial and glacial sediments on the sea bed and finally the erosion of coastal cliffs on soft materials. These sand sources are much less important today, due to a number of human activities like the occupation of drainage basins, blockage of fluvial transport by dams, diversion of water discharges by irrigation practices, blockage of coastal longshore sand transport by groynes and harbours, etc. (Regard et al., 2023; Lentz et al., 2024).

Coastal trend is proposed as a descriptive variable that provides information on the sedimentary contribution to the coastal system, which is a major factor for dune formation and maintenance. The advance of the coasts is the result of a surplus of sediment and results in wider beaches, which increase the space available for the development of embryonic dune habitats. It has been shown that the retreat of the coast increases coastal vulnerability (Bertacchi et al., 2016; Prisco et al., 2016). To be able to manage dune systems properly, it is necessary to have knowledge of the processes that occur in them and of the effects that human actions have on their morphology and stability.

It is recommended that a detailed geomorphological assessment study be carried out at each dune site, or group of sites, to determine the most appropriate monitoring strategy. In determining the impact of the intervention, it is important to define the geographical scale at which it will be carried out. The interactions that determine the geomorphology of dunes and beaches are very complex, operating on a wide range of time and space scales (Gracia, 2022). In addition, slight modifications of factors (natural or anthropogenic) can cause coastal dunes to evolve into a different morphological state from which they may or may not recover. This highlights the fundamental importance of understanding the conceptual model of a dune system.

These studies should try to more accurately quantify the volumes of beach sand and dunes present over different reference levels, historical evolution, rates of recent morphological change and degree of mobility of the sand. These assessments should also take into account the nature of morphology and process regime in intertidal zones, near the coast and adjacent offshore to develop predictive models of the likely three-dimensional evolution of each beach dune system in the short, medium and long term. The scale of the required study will vary significantly from area to area, depending on factors such as dune size and habitat importance (Pye et al., 2020).

As a result of sediment entering the beach and subsequently into the dune system or its exit, there is a change in position of the water line towards land (marine transgression) or towards the sea (marine regression). The evolution of this line therefore indicates whether the beach-dune sedimentary set is winning or losing sand. This line is measured by aerial and orthophotos currently in the regional and national databases. They provide the possibility of recognizing processes that have taken place at specific dates, facilitating the recognition of evidence of sedimentary activity and events of variable magnitude on coastal land. By comparing images, it is possible to recognize the coastline and changes in environments, although a certain amount of errors and uncertainties must be taken into account and quantified (Del Río & Gracia, 2013).

The assessment consists of comparing the coastline through vertical aerial photographs. This is done by establishing a reference line parallel to the coast and at some distance from land (500 m to 1 km), passing through fixed and easily identifiable control points. From this line, perpendicular transects are drawn at regular intervals, separated at a variable distance depending on the size of the dune system to be evaluated, being common 50 m in Mediterranean dune systems (Prisco et al 2016), or 200 m, or 500 m in large dune systems. Measurements should be taken from the baseline to the coastline, identified as the water/land contact, which is not always easy to define (Boak & Turner, 2005).

The trend of the coastline over the last ten years should be measured by comparison of aerial photographs covering approximately this period or as close as possible. The photographs should be georeferenced. The measurement will be made perpendicular to the coastline along representative transects, separated from each other by a maximum of 50 m. Each transect will be identified in each of the photos from fixed, invariant points located towards the mainland and which allow the measurement line to be correctly located and oriented, so that it is the same from one flight to the next. In each transect, the distance in metres from a reference point that is identified in all the photos and the coastline will be measured.

Once the coastlines at different dates have been obtained from the digitalization of the indicators, the comparison between them and the quantification of the change rates can be carried out using a GIS (Ojeda et al., 2002). For the monitoring of this parameter, it is recommended to use the "Digital Shoreline Analysis System" tool from ArcView, which is a stand-alone application associated with a GIS that calculates the change in coastline or boundary over time. DSAS allows you to calculate exchange rate statistics from multiple historical positions on the coast. It provides a system for setting measurement transects, performs rate calculations and other types of information associated with exchange rates (Oyedotun, 2014).

A new estimate of the coastal trend should be made at least six years after the last measurement, depending on the availability of new aerial photos.

Other anthropogenic alterations outside the dune area that affect its sedimentary dynamics

In recent decades, human actions have caused very important modifications in the sedimentary balance of the coastal environment, which contribute to accelerating coastal erosion and make it more vulnerable to any natural risk. The human actions that have the greatest impact on the modifications of coastal areas are the construction of dams in rivers that retain river sediments, thereby reducing the amount of materials that reach the sea, the extraction of sediments from the beach itself and the construction of artificial structures (ports, breakwaters, etc.). The sea level rise due to global warming must also be added as a relevant external factor.

The effects of the reduction in sediments due to retentions in the reservoirs have been clearly observed in some areas, such as in the Nile Delta after the construction of the Aswan Dam, where a significant retreat of the shoreline has been detected for decades (Stanley, 1996). Something similar happened in the beaches of the Ebro Delta, where a decrease of sediment supply in the Ebro River due to the construction of reservoirs, caused, since the middle of the 20th century, a retreat of the coastline that has been estimated at 22 m/year (Jiménez & Sánchez-Arcilla, 1993). This resulted in the almost total disappearance of the mobile dunes of the Fangar Peninsula (Rodríguez Santalla, 2000), and could result in the complete erosion of the whole San Antonio Island by 2050 (Aranda et al., 2022).

The construction of marine defences can affect sediment supply by limiting erosion and interrupting coastal drift which carries sediments in a predominant direction. Hard defences, such as walls or breakwaters, can increase the loss of sand from beaches by reflecting wave energy and thus increase sediment loss (Molina et al., 2025). The most significant alterations are caused by breakwaters perpendicular to the coast, because they are a barrier to the sediments carried by the longitudinal current. In this way, breakwaters (or any work perpendicular to the coast) cause an induced accumulation of sediments on one side of the obstacle and accelerated erosion on the other side. Large port works have caused the greatest alterations, although the action that small breakwaters can have on certain beach sectors should not be ruled out. The larger the obstacle, the greater the distortion caused and it will affect a larger area of beach (Gracia et al. 2009). Longitudinal breakwater defences are also rigid structures that can substantially modify the profile of the beach (Molina et al., 2019). Coatings (usually stone or concrete) can also lead to the fossilization of dunes behind them by disconnecting beach and dune systems.

Dredging of sand in specific coastal areas also leads to the retreat of the sandy coast in nearby areas. Offshore dredging can also affect sediment supply by interrupting shore-normal sediment movement (Pye et al., 2020). There are also much wider scale effects on sediment supply resulting from alteration of estuary systems, reclaimed land and drains.

There is no sufficiently developed methodology for measuring this type of change, which could however be proposed as a descriptive or contextual variables to be assessed through consultation with experts in various disciplines (geologists, engineers, biologists, etc.).

3.2 Guidelines for the establishment of reference and threshold values, and obtaining condition indicators for the variables measured

The measured values of the condition variables need to be compared with reference values and critical thresholds to assess the condition of each variable. A reference level is the value of a variable under reference conditions, against which it is meaningful to compare past, present or future measurements. The difference between a variable's measured value and its reference level represents its distance from the reference condition.

Reference levels should be defined consistently across different variables within a given ecosystem type, and for the same variable across different ecosystem types. This ensures that derived indicators are compatible and comparable, and that their aggregation is ecologically meaningful (United Nations, 2021).

Reference levels are typically defined with upper and lower values reflecting the endpoints of a condition variable's range, which can then be used in re-scaling. For instance, the highest value may represent a natural state, while the lowest value may represent a degraded state where ecosystem processes fall below the threshold required to maintain function (Keith et al., 2013, in UN, 2021). For example, pH values in some ecosystems clearly indicate whether biological life can be sustained, while soil nutrient enrichment beyond a certain threshold can lead to the loss of sensitive species.

Establishing reference values and thresholds is essential for determining whether habitats are in good condition or have become degraded. Reference values represent the desired state of an ecosystem, typically reflecting intact or minimally disturbed conditions. These values serve as benchmarks for assessing habitat condition.

These guidelines do not aim to prescribe specific threshold values. Rather, they outline the main criteria and provide guidance for establishing reference values that support the determination of good or not-good condition, while accounting for the ecological variability of habitats across their range.

With regard to the variables, the harmonization of reference values and thresholds should consider a set of **common requirements**:

- For a given habitat, the final assessment of its condition and trend over time – based on the reference values and thresholds of the variables characterising the habitat – should be equivalent across Member States, after accounting for the contextual factors specific to each MS (e.g., climate).
- Thresholds, limits, and reference values should be tested using sufficiently robust datasets that represent the full range of habitat conditions, from degraded to high-quality sites.
- Thresholds must account for the natural variability of habitats across their range. Consequently, different threshold or reference values for the same habitat type may be appropriate in different MSs or in different regions within a single MS
- Establishing reference values requires information external to the evaluated site, which can provide insight into the condition of the habitat and be translated into variable values that characterise that condition.
- Reference values should meet the criteria of validity (ecological relevance), robustness (reliability), transparency, and applicability (Czúcz et al., 2021, Jakobsson et al., 2020).
- Each MS should provide a clear, justified, and comprehensible description of the methodology used to establish threshold and reference values for each variable.
- The methodologies should be designed for regular evaluation and improvement, based on the best available scientific knowledge. Any modifications made – and their implications for past monitoring data – must be communicated transparently.
- A reference library and indicator thresholds should be developed for different habitat types across regions, taking into account their ecological characteristics and natural variability.
- Joint training or guidance on setting threshold and reference values should be offered to experts from the different MSs in order to achieve ensure harmonised approaches.

Several approaches have been recognized for estimating reference values to assess habitat condition (Stoddard et al., 2006, Jakobsson et al., 2020, Keith et al., 2020). These can be broadly synthesised into six categories: (1) absolute biophysical boundaries, (2) comparison to reference empirical cases - i.e., areas or communities considered to be in good condition, (3) comparison to undisturbed cases, (4) modelling and extrapolation of variable-condition relationships, (5) statistical assessments, and (6) expert judgement.

All approaches should be grounded in scientific literature. Methods that use values from a single baseline year as a reference for good condition are not recommended, as the selected year may not reflect favorable conditions, and historical data may be unreliable or incomplete (Jakobsson et al., 2020). The use of historical period (e.g., pre-industrial) as a reference state, as proposed by Stoddard et al. (2006) and Keith (2020) aligns with the baseline approach but also overlaps with comparisons to undisturbed cases (see below). If conditions during a specific baseline year are well documented as favourable, they may be useful for trend analyses. Likewise, where historical pristine conditions are clearly documented, they may serve as valid reference states under the undisturbed comparison approach.

Absolute biophysical boundaries

These refer to situations in which observed values of variables exceed the physical and chemical limits (e.g., pH, bare soil cover, critical loads for eutrophication or acidification) or biotic limits (e.g., presence of alien species) that define the habitat. When such limits are exceeded, the habitat cannot be in good condition (Jakobsson et al., 2020). These thresholds therefore indicate negative impacts on the favourable condition of the habitat.

Advantages: This approach provides robust and transparent criteria that are clearly linked to the ecological integrity of the habitat.

Disadvantages: It is applicable to a limited number of variables, typically those with direct negative impacts on habitat condition.

Comparison to empirical cases considered to be in good condition

This approach is based on identifying areas or communities considered to be in good condition (Stoddard et al. 2006, Jakobsson et al. 2020, Keith et al. 2020). These serve as reference cases from which the reference values can be derived. Therefore, their careful selection – and the availability of a sufficient number of such cases – is essential for ensuring the reliability of the reference value estimates (Soranno et al., 2011). While this method may appear straightforward, it is often limited by the scarcity of suitable sites, especially in landscapes that have been historically modified.

Advantages: Providing that sufficient data from high-quality cases are available, this approach offers empirical validity and reliability by directly linking variable values to habitat condition.

Disadvantages: Methodological challenges arise due to the difficulty of identifying a sufficient number of suitable reference sites in historically altered environments.

Comparison to cases with a natural disturbance regime

This approach is closely related to the previous one, based on the assumption that most human-induced disturbances reduce habitat quality. This assumption is generally valid in human-modified landscapes and can be linked to historical reference conditions when human pressures were less pronounced (Stoddard 2006). However, disturbances that are part of a natural disturbance regime may actually indicate naturalness and thus good habitat condition. In fact, a certain level of disturbance can be beneficial, supporting microhabitat formation, enhancing biodiversity, and promoting regeneration of habitat-characteristic species (Keith et al., 2020).

Historical reference criteria may include the absence of human intervention or management, as found in “primary” forests (sensu Sabatini et al. 2017), and are often directly connected to climax communities such as old-growth or primeval forests (Wirth et al. 2009, Burrascano et al. 2013, Buchwald 2005), which are typically assumed to be in good condition. However, in regions with long-standing anthropogenic pressure, it may be difficult to identify unaltered or naturally disturbed habitats for certain types (Keith et al. 2020). Additionally, defining the undisturbed state based on a relatively short time period may overlook disturbance legacies that persist over longer timescales (Alfaro-Sánchez et al. 2019).

Advantages: This approach provides transparent and empirically grounded criteria for defining reference conditions and can benefit from large-scale information on disturbance and land-use history.

Disadvantages: The assumption that any disturbance reduces habitat quality may not always be valid. Moreover, identifying sufficient undisturbed or naturally disturbed reference areas can be challenging for some habitat types.

Modelling the relationships between variables and condition

This approach assumes a relationship between variable values and habitat condition. When determining threshold and reference values, models that describe these relationships share a conceptual basis with methodologies based on dose-response curves. Such models assume that certain cases of good condition correlate with specific levels of a condition variable.

The advantage of modelling is that it allows reference values to be inferred where empirical examples of good condition or undisturbed condition are lacking. In these situations, information from known empirical examples can be extrapolated to other contexts, such as locations along a climatic gradient.

Various modelling procedures are available. Functional relationships – linear, saturated, or humped – can be applied (Stoddard et al. 2006, Jakobsson et al. 2020). For instance, deadwood volume in pristine forests can be modelled along productivity gradients to establish reference values in climatic conditions where unaltered forests no longer exist (Jakobsson et al. 2020). Correlative climate niche models can also be used to estimate the suitability of species sets (i.e., variables that characterise the habitat) at different points along the climatic gradient (Jakobsson et al. 2020).

Although these approaches offer a functional basis for establishing reference values, they involve several assumptions that often require expert judgement. It is also possible to create models in which condition is inferred from variables other than the condition variable itself – for example, biodiversity-related condition variables may be inferred from pollution levels. However, this approach should be used with caution to avoid tautological inferences involving variables that reflect pressures.

Advantages*:* Modelling approaches are flexible, transparent, and encompass a variety of procedures based on functional relationships between variables and condition (validity), drawing on scientific knowledge from multiple disciplines. They can also be applied to obtain reference values when empirical examples of good or undisturbed condition are lacking.

Disadvantages: The information available to build models is often insufficient or unreliable for many variables. Outputs are highly sensitive to the chosen modelling procedure and underlying assumptions, and expert judgement is ultimately required at multiple stages of the modelling process.

Statistical assessments

This approach is based on quantitative data from databases, such as habitat inventories, which report the distribution of variables within a given habitat. It assumes that higher values of certain variables correspond to good condition when a positive relationship exists, and vice versa. For such variables, high percentile values or confidence intervals (e.g., 95%, Jakobsson et al. 2020), or differences from the maximum observed values (Storch et al. 2018), may be used.

For variables with a negative impact on habitat condition, low (e.g., 5%) or minimum values are applied, while for variables that show a hump-shaped (non-linear) relationship with condition – peaking at intermediate values (e.g., gap occurrence, browsing) – a combination of high and low percentiles may be used.

This approach is particularly suited to variables obtainable from forest inventories (Storch 2018, Pescador et al. 2022), and is useful when empirical examples of good condition are lacking. However, it may provide limited insight into the state of habitats that are in poor condition throughout the entire assessed territory. In other words, this approach is not directly based on reference situations of good condition, but on statistical inferences subject to the constraints of the sampling used to build the reference database.

Advantages: This approach can be applied with reasonable ease by users with statistical training. It is transparent, replicable, and minimally subjective.

Disadvantages: The existence of appropriate, quantitative datasets representing the reference state is essential for this method. Its reliability depends on the distribution of condition classes (from bad to good) in the dataset and on how well this distribution corresponds to empirical situations of good condition. As a result, it may lead to under- or overestimation of good condition and may be less reliable for habitats that are poorly represented in the dataset.

Expert judgement

Setting of reference values and thresholds based on expert judgement is common practice, particularly where other sources of information are lacking – for instance, in certain non-abundant habitats where experts have developed empirical knowledge of habitat condition. However, this approach is often criticised for its limited transparency, and the level of expertise may be insufficient in some cases. For this reason, it is sometimes considered a last-resort option for many variables.

Nonetheless, for certain variables – such as assemblages of characteristic species, successional stages, the presence of microhabitats, or regeneration characteristics – expert judgement may be appropriate for establishing thresholds and reference values. In other cases, it can also serve as a complement to other approaches.

In all situations, it is advisable to apply expert judgement through protocols based on consensus and consultation with multiple experts of comparable experience. This should include clear procedures (e.g., standardised questionnaires) and transparent documentation of how conclusions were reached (Stoddard et al. 2006). A further limitation is the lack of available experts for certain habitats, which can hamper the correct application of this approach.

Advantages: This approach is easy to apply and is commonly used.

Disadvantages: It entails a high degree of subjectivity and low transparency, which limits replicability and reliability. Its use may also be constrained by the scarcity of suitable experts for particular habitats and Member States.

Given the uncertainties involved in setting reference levels, a combination of approaches is generally recommended to improve reliability. The approaches described are not mutually exclusive, and are often applied in combination. For example, expert judgement is typically required when defining reference cases for good condition or when making modelling decisions about the relationship between variables and condition. Similarly, modelling-based approaches can complement those based on empirical cases of good or undisturbed condition and may also be integrated with statistical methods.

Habitat condition assessments are based on determining whether the variables used indicate good or not good condition. However, it is common practice to define more than two categories for each variable – e.g., good, medium, and bad – as observed in the analysis of methodologies used by MSs. The criteria for assigning these condition categories vary depending on the characteristics of each variable. For example, categorical variables may involve thresholds such as “no alien species allowed”, while quantitative variables may follow linear or non-linear relationships with condition (Jakobsson et al. 2020).

This classification of variable values – whether quantitative or categorical – into condition categories (e.g., good, not good; or good, medium, bad) corresponds to the scaling process needed for joint evaluation through aggregation procedures, as described in the following section. Condition categories can be translated into numerical values (e.g., good = 2, medium = 1, bad = 0|. Alternatively, where quantitative values for the variables are available, these can be directly standardised for use in aggregation.

Owing to the different metrics and magnitudes used for the variables that characterise habitats, the values obtained from their measurement require some form of standardisation – e.g., through re-scaling – in order to build indicators that combine multiple variables. In habitat condition assessments, each characteristic and its associated variable is likely to be measured in a different unit. These values are normalised using reference levels and reference conditions, allowing comparison across variables. Measurement values are scaled in relation to their reference levels, thereby normalised to a common scale and aligned direction of change. They can then be combined to form a composite index or used to obtain an overall condition result through appropriate aggregation approaches (see further details in Section 3.3. on Aggregation).

Thresholds, limits and reference values must be tested against sufficiently broad data sets, covering the full range of habitat conditions – from degraded to high-quality examples.

It is important to note that many methodologies emphasize the need for adaptive thresholds:

- Regional variation: Thresholds often need adjustment based on biogeographic region, local climate, and dune system type.
- Natural dynamics: The inherently dynamic nature of dunes means that some indicators (e.g., bare sand coverage) may have wide natural ranges.
- Climate change considerations: There's growing recognition that reference conditions may need to account for ongoing and projected climate changes.

3.3 Guidelines for the aggregation of variables at the local level

The aggregation of condition indicators typically involves the integration of the measured variables into a single composite score or index that defines the overall state. The choice of aggregation method for combining these partial assessments into an overall evaluation has been widely discussed within the scientific community, as it can significantly influence the final outcome. Various approaches can be used to integrate the values of measured variables into an overall index reflecting the condition of habitat types at the local scale (e.g., monitoring plot, station, or site).

Applying appropriate aggregation approaches is essential for categorising condition at the local scale as good or not good, since the proportions of habitat type area in good/not good condition is the key information needed for evaluating the conservation status of structure and functions at the biogeographical level.

3.3.1 Overview of aggregation methods

Based on the literature (e.g., Langhans et al. 2014, Borja et al. 2014), two main aggregation approaches can be distinguished: the one-out, all-out rule (minimum aggregation) and additive aggregation (e.g., addition, arithmetic mean, geometric mean). Further information on aggregation approaches and methods is provided below.

Minimum aggregation, or the One-out, all-out rule

For the minimum aggregation, the aggregated value is calculated as the minimum of the values of the measured variables.

The one-out, all-out (OOAO) rule has been recommended for assessing ecological status under the Water Framework Directive (CIS, 2003). The principle behind this minimum aggregation method is that a water body cannot be classified as having good ecological status if any of the measured quality elements fail to meet the required threshold. This is considered a precautionary and rigorous approach, but it has also been criticised for potentially underestimating the true overall status.

A precautionary OOAO approach is also used in the aggregation of parameters when assessing conservation status under the Habitats Directives, the IUCN Red List of Species and the IUCN Red List of Ecosystems.

Conditional rules

Conditional rules require that a certain proportion of variables meet their respective thresholds in order for the overall assessment to achieve a good condition rating. For example, the overall status may be considered as not good when a specific number of variables fail to meet their thresholds.

Simple additive methods and averaging approaches

Simple additive methods calculate an aggregated value as the sum of the *n* values (*vi*) of the variables.

Averaging approaches are among the most commonly used methods for aggregating indicators. These include straightforward calculations such as the arithmetic mean, weighted average, median, or combinations thereof, to produce an overall assessment value.

Weighting

Differential weighting of indicators may be applied when calculating sums, means, or medians. The choice of weighting system should reflect the relative importance of each indicator in determining the overall condition of the ecosystem. Ideally, the approach should be supported by a clear scientific rationale and informed by input from ecologists with expertise in the relevant ecosystem types.

However, a robust basis for assigning weights is not always available. In such cases, weighting often relies on expert judgment, which can be subjective, as expert opinions may differ considerably.

Normalization of variables values (rescaling)

In the assessment of habitat condition, each characteristic and associated variable is likely to involve the use of different measurement units. To ensure comparability, the measured values of variables are often normalised to a common scale (e.g., 0 to 1 or 0 to 100). This involves rescaling the raw data based on reference values or thresholds that define the boundary between good and not good condition for each variable. By rescaling the condition variables, indicators are standardised to the same scale, making it possible to aggregate them into condition indices that reflect the overall condition at a given plot or location.

Figure 6. Example of deriving condition indicators by rescaling the values obtained for variables, based on upper and lower reference levels.

$$Condition\ indicator = \frac{(V-VL)}{(VH-VL)} \quad \text{[Equation 1]}$$

Where:

- V is the measured/observed value of the variable,
- VH is the high condition value for the variable (upper reference level),
- VL is the low condition value (lower reference level).

Source: Vallecillo et al, 2022

3.3.2 Proposal for the aggregation of measured variables

A quantitative aggregation method should be applied to integrate all essential and specific variables measured to assess the habitat condition. The method should be applied consistently across the habitat range in order to obtain comparable results. The main steps for aggregation are described below.

Step 1 – Normalisation of the variables

The quantitative values obtained for each variable should be normalised by rescaling based on reference values (as described above). The value of each variable will be thus in the range from 0 to 1.

Step 2 – Aggregation of normalised variables

The aggregated value is then calculated by the aggregation of the normalised values of the variables. For the sake of simplicity, and considering the difficulties to suggest a more complex method or index, we describe here a preliminary proposal for aggregation based on the arithmetic mean with normalisation of the values obtained for each of the measured variables, which could be used to determine the habitat condition at the local scale, as summarised in the following equation:

$$Local\ condition = \sum_{1}^{n} v_i / \mathrm{n}$$

Where n is the number of variables, and v_i is the rescaled value of the corresponding variable (between 0 and 1). The aggregated value would range between 0 and 1.

An alternative method would be to use the weighted average, in which the weight of each variable should be decided, justified and agreed upon for each habitat type by all the MSs that would apply the method. This method can be formulated with the following equation:

$$Local\ condition = \sum_{1}^{n} v_i * w_i / \mathrm{n}$$

Where n is the number of variables, v_i the rescaled value of the corresponding variable (between 0 and 1) and w_i the corresponding weight, with $\sum w_i = 1$. The aggregated value would range between 0 and 1.

This second method, however, presents some difficulties when assigning weights to the variables, which must be based on a proper evaluation of their importance and influence on the habitat condition, based on a robust scientific knowledge. It also requires reaching a consensus on the weights assigned to the variables measured for each type of habitat, among all the countries that must assess its condition. This is a crucial aspect to obtain comparable results in the assessments carried out by all the Member States.

Step 3 – Identify the threshold to determine good/not god condition at the local scale

Finally, a threshold must be applied to the aggregated value to distinguish between good and not good overall condition. This is a crucial step and, wherever possible, this threshold should be established based on empirical data from reference localities in good condition and from localities showing a degraded state. Where such reference localities are not fully available, modelling to obtain such thresholds could be applied.

3.4 Guidelines for aggregation at the biogeographical region scale

As a minimum requirement, MSs must adhere to the recommendations from the Article 17 reporting guidelines for the 2013-2018 period. These guidelines state that if 90% of a habitat area is in 'good' condition, the 'structure and functions' parameter is considered 'favourable'. Conversely, if more than 25% of the habitat area is reported as 'not in good condition', the 'structure and functions' parameter is deemed 'unfavourable-bad'. This rule highlights the importance of using a sample design that ensures a statistically sufficient representation of the total habitat area and diversity.

However, MSs may choose to adopt stricter thresholds, in particular for endangered habitats or habitats with a very limited restricted distribution, which may require that their entire entire area be in good condition.

3.5 Guidelines on general sampling methods and protocols

Effective monitoring of dune habitats requires a comprehensive approach that combines traditional field surveys with modern technological methods. Field surveys remain the cornerstone of most assessment methodologies, providing detailed, ground-level data essential for understanding the complex dynamics of dune ecosystems.

These surveys typically employ a multi-faceted approach (Jackson & Nordstrom, 2020). Transect-based sampling, utilizing lines perpendicular to the coastline, is widely adopted to capture the full spectrum of dune zonation (Bauer et al., 2025). This method allows researchers to observe and record changes in vegetation and physical characteristics across different dune zones, from the foredune to the backdune areas. Complementing this, plot-based vegetation sampling involves establishing fixed or random plots within each dune habitat type. These plots serve as focal points for detailed floristic and structural assessments, offering insights into species composition, vegetation cover, and structural diversity. Additionally, field surveys often include assessment and mapping of visible impacts and disturbances, which is crucial for identifying immediate threats and management needs (Labuz, 2016).

Monitoring the entire dune system can be carried out on plots arranged along transects perpendicular to the coastline, covering all dune habitat types and, if possible, also including habitat 1210 (Annual vegetation of drift lines) if present in the study area. This can be done by establishing a reference line, generally parallel to the coastline, with fixed points easily identifiable; where the system is too wide to determine these fixed points, a precision GPS reference line shall be established.

In the transect perpendicular to this reference line, plots with an appropriate size, e.g. 2x2 m (4 m2) can be arranged where the main compositional and structural variables (vegetation, animal species) are recorded. Field surveys provide information about vegetation composition, species diversity and richness, presence and proportion of key and indicator species such as pioneer, dune-builder, stabilizer, nitrophilous and exotic species.

The choice of plot size is also influenced by factors such as the type of vegetation, the scale of environmental variability, and the level of detail needed. Smaller plots (4 m2) are often used for detailed vegetation surveys, especially in areas with high habitat heterogeneity or where species abundance is being assessed, for instance to sample vascular plant species in different dune habitats. Larger plots (e.g., 10x10 meters) are useful for capturing the broader vegetation structure and community composition within a specific dune habitat type, for assessing morphological features and other variables at wider scale using aerial photography and remote sending (Agrillo et al., 2023). In some cases, buffer areas around vegetation with an appropriate radius (e.g., 2 to 8 m) can be used to analyse. Permanent plots that are revisited over time can be sued to track changes in dune vegetation and habitat structure. For example, one study used a supplemented panel design with a proportion of permanent plots.

The minimum number of transects should be proportional to the total area of the habitat and its geographical diversity, considering regional peculiarities. The number of plots per transect varies according to the width of the dune system. The sampling of dune vegetation should be carried out in the period of maximum flowering and vegetation cover: the ideal period is from April to June. Operators should have experience in vegetation and flora, photo interpretation, photodetection and SIG mapping. (Angelini et al., 2016).

To enhance the scope and efficiency of dune habitat monitoring, aerial photography, remote sensing and GIS analysis are increasingly being integrated into assessment protocols. These technologies complement field data by providing landscape-scale perspectives and facilitating the analysis of changes over time. Satellite imagery and aerial photography can reveal broad patterns of dune movement, vegetation cover changes, and human impacts that might be less apparent at ground level. Where available, existing habitat maps serve as valuable baseline data, allowing for comparative analyses and the tracking of long-term trends.

By combining these diverse monitoring approaches, a holistic understanding of dune habitat conditions, dynamics and threats can be achieved.

Detailed field protocols are essential for consistent data collection. Protocols should include clear instructions on plot establishment, data recording, and handling of equipment.

The monitoring process generally involves completing comprehensive forms that assess habitat composition, structure, functions, and impacts (Areia et al., 2023). These standardized forms ensure consistency in data collection across different sites and over time. Observations are typically conducted from May to October, with July and August considered optimal for monitoring due to peak vegetation growth and easier species identification during these months.

In any case, it is essential to adapt measurement methods to the scale and type of dune system under study, taking into account the natural variability of these ecosystems and the availability of data at each specific site. The selection of localities and sampling methodologies should be periodically reviewed and adjusted based on new findings and changing conditions.

Adaptive management practices allow for the incorporation of new knowledge and the refinement of monitoring strategies.

When establishing sampling methods and protocols, it is important to balance the need for standardized approaches with the recognition of local conditions and existing best practices. A more accommodating approach that allows for adaptation to national requirements and encourages the maintenance of best practices is more likely to be implemented effectively across the European Union.

3.6 Criteria to select a minimum number of localities

Effective habitat monitoring requires a thoughtful approach to selecting localities and implementing monitoring strategies. The selection of sampling localities - along with the sample size (number of plots) and power -is essential to ensure that the results of assessment and monitoring are representative for each habitat type at the biogeographical scale.

The selection process should prioritize ecological representativeness and accessibility, ensuring that the full spectrum of habitat diversity is captured. This includes both well-preserved and degraded habitats across various geographic regions, providing a comprehensive view of the ecosystem's health and variability.

To achieve a balanced representation, monitoring efforts should aim to reflect the geographical spread and variation within habitat types. This involves strategically distributing monitoring stations both inside and outside protected habitat areas. Such an approach allows for better understanding of habitat dynamics and the potential impacts of external factors on ecosystem health.

In determining suitable monitoring locations, multivariate techniques can be useful. These methods help identify homogeneous geo-environmental strata, facilitating a more targeted and efficient sampling process. To ensure thoroughness, steps should be taken to include all relevant sites in the monitoring process.

Coastal dune habitats present unique challenges for monitoring due to their dynamic nature. Natural processes continuously shape and reshape these environments, affecting their structure and composition. To effectively monitor these habitats, it is crucial to consider their interconnectedness. Methods such as aerial photography and vegetation transects can provide valuable insights into the complex dynamics of dune systems.

Identifying and selecting localities for sampling requires a systematic approach to ensure that the chosen sites provide comprehensive and representative data on dune habitat condition within the biogeographical region. Sampling localities should reflect the full range of habitat diversity, as well as environmental gradients, including variations in elevation, soil types, and climate. Moreover, sites should be selected both inside and outside protected areas. This requires a sound understanding of the distribution and variability of each habitat across its range, including the identification of ecotypes or sub-types, where relevant.

The main **criteria for selecting monitoring localities** are summarised below.

- **Ecological variability**: Localities must represent the full range of ecological diversity and variability within the habitat type. Selection should include different ecotypes or subtypes, successional stages, and reflect key environmental gradients such as altitude, soil type, moisture levels, geomorphological features, and topography.
- **Spatial Coverage**: Adequate spatial coverage is essential to capture habitat heterogeneity. Localities should be selected across the full geographical range of the

habitat type within the region, ensuring they are well distributed and represent a significant proportion of the habitat's total occupied area.

- **Degree of conservation and exposure to pressures and threats**: The selection of monitoring localities should include areas with varying degrees of conservation and degradation, in order to capture the full range of habitat condition across its distribution. This includes both well-conserved areas with minimal human impact, and areas affected by degradation and subject to different pressures. To reflect the diversity of pressures acting on the habitat, localities should span a range of intensity levels – from low to high – and account for different sources of disturbance, such as urbanisation, agriculture, and climate change.
- **Presence inside and outside Natura 2000 sites**: The assessment and monitoring of habitat conservation status must be carried out both inside and outside Natura 2000 sites. This requires selecting localities – and an appropriate number of plots – that reflect the proportion to the habitat's distribution within and outside the Natura 2000 network.
- **Habitat fragmentation at landscape scale**: Localities should be selected based on landscape metrics such as patch size and connectivity. Including both isolated and well-connected sites allows for the assessment of fragmentation effects on habitat condition. Understanding these patterns is essential for developing strategies to mitigate the negative impacts of habitat fragmentation.
- **Lack of Information**: Including areas where data are lacking contributes to building a more comprehensive dataset. Selecting localities in historically under-sampled regions ensures a more balanced and complete understanding of habitat condition across its range. This helps to address data gaps and supports more informed conservation planning.
- **Accessibility and practicality**: Monitoring localities should be accessible for regular field visits, taking into account logistical factors such as distance from roads and ease of access. Practical considerations also include the safety of field personnel and the feasibility of transporting equipment to and from the site.
- **Historical Data and existing monitoring sites**: Making use of existing monitoring sites with historical data can strengthen the understanding of long-term trends and changes in habitat condition. Such sites provide valuable baselines for comparison and support more robust trend analyses over time.

Once sampling localities have been identified for each habitat type, the minimum number of plots per locality – and across the biogeographical region – must be calculated to balance sampling effort with the need for representative data.

The **size of the sample** influences two statistical properties: 1) the precision of the estimates and 2) the power of the assessment to draw meaningful conclusions. The number of plots must be **statistically sufficient** to detect changes and trends with the desired level of confidence. Appropriate statistical methods should be applied to determine an adequate sample size.

Considering the heterogeneity of habitat types, it is highly recommended to consult a sampling statistician when determining sample size – that is, the minimum number of plots required to ensure representativity and statistical significance.

Some key elements for ensuring proper representation of habitat condition in the sample are summarised below.

Key elements for statistical representation

Sample size and distribution*:*

- The number of localities and plots should be sufficient to provide a statistically robust sample size. This ensures that the collected data can be generalised to the entire habitat type within the region.
- Statistical methods such as stratified random sampling are often applied to ensure that all habitat subtypes and environmental gradients are adequately represented.

Sampling design*:*

- Within each sampling area or locality, transects and plots are commonly used in dune habitats to collect detailed data on vegetation, soil, and other ecological indicators. The number and distribution of transects and plots depend on the size of the habitat patch and its internal variability.
- Sampling areas (e.g., plots, transects) should be laid out with consideration of the main ecological gradients, such as altitude, moisture, and exposure to sea influence.

Replication and randomisation*:*

- Replicating sampling units within each locality and randomising the location of sampling plots help reduce bias and increase the reliability of the data.
- Randomised plot locations also ensure that sampling captures the natural variability within the habitat.

3.7 Use of available data sources, open data bases, new technologies and modelling

New technologies provide useful tools to assess the status of dune habitats and should be further explored. Earth observation (EO) data, derived from remote sensing and unmanned aerial vehicle (UAV), have been recently demonstrated to be essential tools for dune ecosystem monitoring and habitat mapping.

Remote sensing, LiDAR, and satellite images can be useful to measure some key variables in dune systems, as the following (Oyedotun, 2014; Labuz, 2016; Cesnulevicius et al., 2018; Gonçalves et al., 2018; Talavera et al., 2018; Mitri et al., 2020; Grottoli et al., 2021; Agrillo et al., 2023; Evagorou et al., 2025):

- Habitat area and range: dune extent and distribution, changes in dune area over time and mapping of different dune habitat types.
- Habitat structure and function: vegetation cover and density, dune morphology (height, shape, slope), vegetation structure (vertical complexity), sand mobility and stabilization patterns and fragmentation patterns to assess habitat connectivity.
- Vegetation characteristics: species composition (dominant species), normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI) and phenological patterns.

- Topography and elevation: Digital Elevation Models (DEMs), dune height and volume, and slope and aspect.
- Hydrological features: presence and extent of dune slacks or wetlands and water fluctuations
- Disturbance indicators: human impacts (e.g., urbanization, recreational use), invasive species presence and spread and erosion patterns.
- Landscape context: connectivity to adjacent habitats, distance to sea and sediment supply dynamics.

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4. Guidelines to assess fragmentation at appropriate scales

As coastal areas face increasing pressure from human activities, particularly tourism and urban development, dune systems have become increasingly fragmented. This fragmentation poses several challenges for the conservation and proper functioning of these important habitats.

Dune fragmentation occurs when continuous dune systems are broken up into smaller, isolated patches. Natural processes linked to energetic wave events can produce dune ridge breaching and the generation of washover corridors and fans (Talavera et al., 2018). Their natural recovery can be achieved in a year cycle if sediment input in maintained, low-energy (good weather) wave climate prevails during the central months of the year and no human disturbance interrupts the normal return of sediment from the submerged nearshore to the beach and dunes. Human activities usually contribute to the fragmentation processes through activities that may be permanent, including the construction of buildings, roads, and other infrastructure in coastal areas, excessive foot traffic and recreational activities, removal of native vegetation or introduction of invasive plant species.

The consequences of dune fragmentation can be severe, including reduced habitat area for specialized dune flora and fauna, disrupted sand transport processes, affecting dune formation and maintenance, increased vulnerability to erosion and storm damage and finally loss of ecosystem services such as coastal protection and groundwater recharge.

Several relevant studies have explored dune fragmentation, highlighting its impacts on biodiversity, ecosystem functioning, and conservation efforts (Aguilera et al., 2022; Del Vecchio et al., 2022; Massarelli et al., 2023).

Habitat fragmentation can have profound effects on the population structure of dune-dwelling species. A 2017 study investigated how landscape fragmentation alters biotic and abiotic characteristics of dune landscapes, affecting the size and demographic structure of populations (Walkup et al., 2017). This research underscores the importance of considering population dynamics when assessing the impact of fragmentation on dune ecosystems.

The fragmentation of dune habitats not only affects biodiversity but also impacts ecosystem services. A comprehensive study on coastal dune vegetation found that disturbance, including habitat fragmentation, negatively affects carbon sequestration rates (Del Vecchio et al, 2022). In highly trampled areas, the carbon sequestration rate decreased by as much as 60% compared to less disturbed areas. This highlights the far-reaching consequences of fragmentation on ecosystem functioning.

Remote sensing technologies have emerged as powerful tools for assessing and monitoring dune fragmentation:

- **Satellite-based assessment**: Satellite imagery provides a broad-scale view of dune systems, allowing researchers to track changes in vegetation cover and land use over time. Multispectral sensors on satellites can detect different vegetation types and their health, which is crucial for identifying fragmentation patterns. For instance, the Normalized Difference Vegetation Index (NDVI) derived from satellite data can be used to quantify vegetation cover and its changes, indicating areas of habitat loss or fragmentation.
- **LiDAR and UAVs technology**: LiDAR has become an invaluable tool for assessing dune morphology and vegetation structure in three dimensions. This technology offers several advantages. It can create detailed digital elevation models (DEMs) of dune systems, revealing subtle changes in dune morphology that may indicate fragmentation. LiDAR can also penetrate vegetation canopies, providing information on understory structure and vertical complexity, which are important indicators of habitat quality and fragmentation. Finally, repeated LiDAR surveys allow for the

detection of changes in dune height, shape, and vegetation cover over time, helping to identify fragmentation trends.

- **Hyperspectral data:** to classify vegetation species and sand cover using linear spectral mixture analysis (LSMA) and identify invasive species and halophytic colonization in deflation zones.

While remote sensing offers powerful tools for assessing dune habitat fragmentation, the following challenges remain:

1. **Scale considerations**: Balancing the need for broad-scale assessment with fine-scale detail remains a challenge, often requiring multi-scale approaches.
2. **Temporal resolution**: Increasing the frequency of data collection, especially with LiDAR, can improve our understanding of short-term changes in dune habitats.
3. **Data integration***:* Developing methods to effectively combine data from multiple sensors and platforms is crucial for comprehensive fragmentation assessment.
4. **Automation***:* Machine learning and artificial intelligence techniques are being developed to automate the detection and mapping of dune habitats, potentially improving the efficiency and accuracy of fragmentation assessments.

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5. Next steps to address future needs

These guidelines offer a proposal for moving towards harmonized procedures in the assessment and monitoring of coastal dune habitats, based on existing methodologies and with a view to promote common approaches that can produce comparable results.

Possible next steps to continue progressing in this direction could include the following activities:

- Testing the proposed monitoring methods including the use of the selected variables and common protocols for sampling and measurement procedures, while considering the particularities of different habitats and the existing contextual factors at local and country level; this testing would be useful to identify gaps of knowledge, flaws of applicability and robustness and reliability of results. The evaluation should provide recommendations to be further integrated in the harmonized procedure, as needed.
- Explore further the combined used of field surveys and remote sensing tools;
- Agree on criteria and best methods for the definition of reference values and thresholds to determine good condition for all the proposed variables;
- Agree on the definition of aggregation methods at local level to integrate the results obtained from all the variables measured;
- implementation of an aggregation method at biogeographical level taking into account a sufficiently representative sample;
- Agree on the criteria and procedures for the selection of monitoring localities and sampling design to ensure a sufficiently representative sample that allows proper implementation of the aggregation of results at the biogeographical region level;
- Identification of further research and knowledge improvement needs.
- Design and develop a training programme and further guidance for experts from the different MSs on the measurement of the proposed condition variables, establishment of thresholds, application of aggregation rules for variables, selection and monitoring of localities and sampling design. This training should include a pilot testing of the evaluation method, including the use of different specific metrics for the proposed variables.

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Annex. Examples of variables used by MSs for assessing and monitoring dune habitats condition

Variable type	Variable	Metrics and measurement methods	MS	Habitats
1. Abiotic variables				
Physical	Length and width of the active dune system	Kilometres (km), metres (m) Topographic maps, aerial photography, satellite images	ES, FR	2110, 2120, 2130 2150, 2210, 2230, 2240, 2250, 2270
	Height of the dunes	Metres (m). Field measurements with dynamic GPS.	ES, GR, IT, LV	2110, 2120 2130, 2140, 2150, 2160, 2210, 2220, 2230, 2240, 2250, 2260
	Relief, microtopography and dune structure	Visual assessment of natural relief and diversity of dune structure corresponding to natural potential of habitat complex	DE, RO	2110, 2120, 2130, 2140, 2150, 2160, 2170
	Wind erosion	Percentage of eroded slopes (ES); Visual assessment of degree of erosion – low, high, very high (FR). Transects.	ES, FR, PL	2110, 2120, 2130
	Degree of marine erosion	Visual assessment of degree of erosion - low, high, very high. Transects.	ES, FR	2110
	Sand granulometry	Sand grain size (mm)	RO	2110, 2130, 2160
	Soil humidity	Visual assessment as dry, moderate, excessive	RO	2110, 2130, 2160
	Soil thickness	Soil layer thickness (cm)	DK	2140
	Bare sand cover	Percentage cover (%) of bare sand	DK, IE, LV, NL	2110, 2120, 2130, 2140, 2160, 2170
Chemical	Soil pH	Laboratory analysis from soil samples (taken to analyse also other chemical elements)	BE, DK, NL	2110, 2120 2130, 2140, 2160, 2170, 2180, 2190, 2250
	Chemical elements and soil nutrient level (C/N ratio)	Nitrogen (N), Phosphorus (P), potassium (K), Calcium (Ca); soil nutrient level (C/N ratio). Laboratory analysis from soil samples.	BE, DK, GR, NL,	2110, 2120, 2130, 2140, 2160, 2170, 2220, 2230, 2250, 2260, 2270
2. Biotic variables				
Composi-tional	Presence or abundance of characteristic/typical/ key/dominant/positive indicator plant species	Presence or abundance of species from a predefined list. Floristic survey Visual field identification.	BE, BG, DE, DK, ES, FR, IE, IT, LT, LV, NL, PL	2110, 2120, 2130 2140, 2150, 2160, 2170, 2210, 2220, 2230, 2240, 2250, 2260,

Variable type	Variable	Metrics and measurement methods	MS	Habitats
2. Biotic variables				
Composi-tional	Presence of animal species	Entomofauna: species from a list of psammo-halophilic Coleoptera belonging to 3 families: *Carabidae, Scarabaeoidea* and *Tenebrionidae*.	FR	2120
		Small mammals, ground beetles, Hymenoptera and other psammophytic invertebrates, reptiles, amphibians, birds.	BE	2110, 2120, 2130, 2150, 2160, 2170,
		Identification of relevant species indicated for each habitat type, including e.g. nesting birds, molluscs, reptiles, beetles, Orthoptera.	IT	2110, 2120, 2130, 2160, 2210, 2220, 2230, 2240, 2250, 2260
		Presence of invertebrates, reptiles and bird nests	ES	2110, 2120, 2130, 2150, 2210, 2230, 2240, 2250
	Invasive/ non-native/ negative indicator species, ruderal, nitrophilous species	Presence and abundance Vegetation survey	BG, DK, IE, LV, PL, DE	2110, 2120, 2130, 2140, 2150, 2160, 2170, 2210, 2220, 2250
Structural	Height of vegetation	cm	GR, IE, PL	2130, 2220, 2230, 2160, 2250, 2260
	Total cover of vegetation, cover of characteristic, dominant or typical species	Vegetation survey with estimate of total cover in plots of 1x1m along transects perpendicular to the coast line	DK, IT, RO	2110, 2120, 2130, 2160, 2210, 2220, 2230, 2240, 2250, 2260
	Herbaceous cover	Percentage cover (%) Visual estimation	FR, NL	2120, 2130, 2160
	Coverage of psammophilous species	Percentage cover (%) above a threshold value. Visual estimation	GR	2110, 2120, 2220, 2230, 2250, 2260,
	Proportion of area with pioneer vegetation	Percentage cover (%) Visual estimation	LV, NL	2110, 2120, 2130, 2140, 2150, 2170
	Cover of mosses, lichens and open sand	The projected coverage of mosses and lichens and the proportion of open sand in the transect are evaluated separately (%).	DK, LT, LV	2110, 2120, 2130, 2140
	Mosaics of mosses and lichens	Visual assessment in the field	BG	2110, 2130
	Cover of woody species, cover of shrubs	Percentage cover (%) Visual estimation	DK, FR, LT, NL, RO	2120, 2130, 2140, 2160, 2170
	Cover of trees and scrub other than *Juniperus*	Percentage cover (%) Visual estimation	IE, LT	2130, 2170

Variable type	Variable	Metrics and measurement methods	MS	Habitats
2. Biotic variables				
Structural	Cover of alien species, invasive species, species indicative of disturbance	Percentage cover (%) by invasive allochthonous species. Visual estimation on the same plots as for the surveys of the positive indicator species of the habitat.	DK, FR, IT, LT, LV	2110, 2120, 2130, 2160, 2170, 2210, 2220, 2230, 2240, 2250
	Nitrophilous species coverage	Percentage cover (%) of the herbaceous stratum occupied by nitrophilous species Visual estimation at the plot level, using a list of nitrophilous species	FR, PL	2110, 2120, 2130, 2140,
	Presence of seagrass	Direct visual observation: presence/ absence. This parameter indicates whether or not the beach is mechanically cleaned.	FR	2120
	Height of vegetation	cm	GR, IE, PL	2130, 2220, 2230, 2160, 2250, 2260
	Total cover of vegetation, cover of characteristic, dominant or typical species	Vegetation survey with estimate of total cover in plots of 1x1m along transects perpendicular to the coast line	DK, IT, RO	2110, 2120, 2130, 2160, 2210, 2220, 2230, 2240, 2250, 2260
Functional	Plants with exposed roots	Percentage (%) Visual inspection	ES	2110, 2120, 2130, 2150, 2210, 2230, 2240, 2250,
	Flowering and fruiting of positive indicator species	% frequency	IE, PL	2130, 2170, 2210, 2220
	Natural vegetation dynamics	Not available	BE	2110, 2120, 2130, 2150, 2160, 2170
	Shrub regeneration, Juniper regeneration	Expert visual assessment	PL, LT	2160, 2170
	Stages of wood decay	Assessment of the amount of wood at each stage of decomposition	LT	2170
	Presence of rabbits	None, sporadic, high/frequent, Field observation.	ES	2110, 2120, 2130, 2150, 2210, 2230, 2240, 2250, 2270
3. Landscape variables				
Landscape	Coastal trend over the last 10 years	Measured in m/year (progression: >0; regression: <0) by comparing aerial photographs that cover approximately a 10 years period. Annual frequency	ES	2110, 2120, 2130, 2150, 2210, 2230, 2240, 2250

Variable type	Variable	Metrics and measurement methods	MS	Habitats
3. Landscape variables				
	Patch size/ distance between patches	Not available	BE, NL	2110, 2120, 2130, 2150, 2160, 2170
	Surface of the dune system	Measured on topographic map, or using aerial photography or satellite image (biannual freq.)	ES	2110, 2120, 2130, 2150, 2210, 2230, 2240, 2250
	Habitat area / extent	Field measurements, GIS	RO	2110, 2130, 2160
	Area, shape and contacts between patches	Spatial analysis using GIS. Remote sensing and field inspection.	IT	2110, 2120, 2130, 2160, 2210, 2220, 2230, 2240, 2250, 2260
	Spatial conditions	GIS analysis and field observations every 6 years	NL	2120, 2130, 2140, 2150, 2160, 2170,
	Degree of fragmentation of the dune system	Metrics: Percentage (%) Aerial photography	ES	2110, 2120, 2130, 2150, 2210, 2230, 2240, 2250
	Habitat fragmentation	Presence of new anthropogenic created structures (buildings, roads, etc.)	BG	2120, 2130
	Coastal defences	Presence of coastal defences which affect the habitat due to changes to the sediment cycle	IE, DK	2110, 2120, 2130, 2170
4. Other				
Other (degradation signs)	Access and parking of vehicles	Visual inspection: permanent, seasonal, absent	ES	2110, 2120, 2130, 2150, 2210, 2230, 2240, 2250
	Percentage of the dune system affected by solid waste or garbage	Visual estimation on the ground of the percentage of solid waste that covers the dune area	ES	2110, 2120, 2130, 2150, 2210, 2230, 2240, 2250
	Anthropic activities	Presence and intensity of anthropic disturbance by paths, urbanization, grazing, sediment extraction, etc.	IE, IT, LT, PL, RO	2110, 2120, 2130, 2140, 2160, 2170, 2210, 2220, 2230, 2240, 2250, 2260
	Damage cover (%)	Visual, aerial photography or expert estimate of percentage area impacted by urbanisation, car parks, roads, leisure sports facilities, camping, embankments, artificial beaches, etc.	FR	2130
	Proportion of area (%) with negative anthropogenic impact	Visual inspection along a 50 m long and 10 m wide belt transect	LV	2110, 2120, 2130, 2140, 2170
	Disturbance affecting the habitat (% of habitat),	% of habitat affected by disturbance (e.g. trampling, vehicle transit, removal of substrate)	IE, LV	2110, 2120, 2130, 2170

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