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Soil bioengineering techniques for Mediterranean coastal dune restoration using autochthonous vegetation species

G. Romano[1] · G. F. Ricci[1] · V. Leronni[1] · P. Venerito[2] · F. Gentile[1]

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Abstract
Coastal dunes are extremely fragile and threatened ecotones, which play a key environmental role in terms of functional connection between terrestrial and marine ecosystems. To counteract the hydrogeological vulnerability in coastal risk areas, reliance can be made on soil bioengineering techniques, consisting of planting native species in combination with natural inert materials. These interventions involve the use of typical Mediterranean plant species, which are fundamental for increasing soil surface protection as well as for their ecologic function in coastal dune consolidation. Monitoring studies on plant growth parameters are useful to assess the suitability of the different species to be used in soil bioengineering works. Hence, this study aimed to (i) identify some Mediterranean herbaceous and shrubby plant species to be used in coastal interventions, (ii) evaluate different plant propagation methods and short-term growth parameters, and (iii) provide useful insights into field management strategies before and after transplanting.*Juniperus phoenicea* L., *Juniperus macrocarpa* Sm., *Pistacia lentiscus* L., *Tamarix africana* Poir. and *Tamarix gallica* L. were the selected shrubs species while *Ammophila arenaria* (L.) Link, *Sporobolus pungens* (Schreb.) Kunth., *Agropyron junceum* (L.) P. Beauv., *Eryngium maritimum* L., *Calystegia soldanella* (L.) R. Br., and *Pancratium maritimum* L. were the selected herbaceous species. As to shrubs, seeds and cuttings proved the best propagation methods with an efficiency of up to 90%. Agamic propagation methods, on the other hand, were the most efficient (80–90%) for the herbaceous species. After transplantation, all the species showed an adaptation period to the new climatic and edaphic conditions. In particular, *Pistacia lentiscus* L. was found withered with the presence of some radical shoots.

Keywords Coastal erosion · Mediterranean vegetation · Plant propagation · Soil bioengineering · Dune re-naturalization

Introduction

Coastal dunes are small sandy hills, arranged parallel to the coastline, resulting from wind-driven processes that cause the sand carried by the sea currents along the coast to build up. Under the action of the prevailing sea winds, dunes move slowly following the upwards movement of the sand, which, after passing the ridge, falls on the opposite side by gravity (Psuty 1992; Pye and Tsoar 2009). They are an important transitional ecotone between extremely different environments, the sub-continental and the sandy seashores, and play a role in functional connectivity, both from a physical and biotic perspective, between terrestrial and marine ecosystems (Bovina and Sinapi 2009; Carboni et al. 2009). Also, the dune ecosystems represent unique habitats for the fauna because of their crucial role as ecological corridors in coastal environments (D'Alessandro et al. 2020).

Coastal erosion, defined as a long-term sediment loss that causes a coastline retreat or a dune erosion, is the result of several drivers: anthropic pressure, wind, and dynamic action of the waves (Yincan 2017; Ajedegba et al. 2019).

The impact on coastal areas of human anthropogenic pressures has increased significantly over the 20th century. The colonization of coastal areas, the construction of ports, the massive extraction of material from riverbeds and watercourse control interventions, and the spread of industrial and urban centers or tourist activities — together with climate change, sea-level rise and increase in storminess — contributed to increasing erosive processes in coastal environments (Brecciaroli and Onori 2009; Romano and Zullo 2014; Pinna et al. 2015; Prisco et al. 2016, Bombino et al.

✉ G. F. Ricci
giovanni.ricci@uniba.it

[1] Department of Agricultural and Environmental Sciences, University of Bari "Aldo Moro", Bari, Italy

[2] CRSFA - Centro di Ricerca e Sperimentazione e Formazione in Agricoltura "Basile Caramia", Locorotondo, Italy

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2022). Moreover, the lack of adequate planning has often led to the degradation of coastal regions due to inappropriate land management. Consequently, coasts and coastal dunes are among the most threatened ecosystems (Evans 2012; EEA 2015) so the problem of coastal erosion has over time become an emergency issue, mostly in those environments where ecosystem values and services ensured by coastal dune systems are definitely compromised (Castelle et al. 2019). Numerous studies have dealt, in recent years, with coastal erosion processes and coastal dune dynamics (Fenu et al. 2012; Eamer and Walker 2013; Keijsers et al. 2014; Ruocco et al. 2014; Louati et al. 2015; Prisco et al. 2016). In Puglia, especially in the areas surrounding the Gulf of Taranto, the natural fluctuation in dune morphology was ruinously altered by several factors, including the remediation of swampy areas, the construction of the railway line, and the intense urbanization and tourism development. Particularly, some of those factors prevented the natural supply of sediments to the coast, decreasing the growth capacity of the beaches and increasing the vulnerability of a system which, due to its intrinsic nature, is characterized by a dynamic equilibrium (Donnaloia et al. 2003; Petrillo 2007; Mossa 2014; Spilotro et al. 2006) showed that the coastal erosion on the Taranto sea coast, from 1955 to 1987, was neglectable while, in the following period until 2003, reached a maximum of 7 ha y^{-1}, corresponding to 110 hectares of the beach.

To counteract the hydrogeological vulnerability in coastal risk areas, a number of actions could be implemented, among which the vegetation restoration and the application of soil bioengineering techniques for coastal dune consolidation and ecological restoration (Bio et al. 2022; Rauch et al. 2022).

Plant communities of coastal dunes vegetation form complex and dynamic ecosystems which change from the shoreline to the inland areas (Frederiksen et al. 2006).

Vegetation, seeds and vegetable remains are important biotic components in coastal dune habitat as they play a direct and indirect role on the stabilization of the sandy material and resilience of dune structure (Wang et al. 2019).

Dune vegetation influences slope stability through hydrological and mechanical factors; mechanical factors originate from the action of root systems within the sandy soil and result in the stabilization of dune particles due to the anchorage of superficial layers to deep stable ones or to the bedrock (Miri et al. 2017; Chen et al. 2019). The stabilizing effect of vegetation is essential in remediation works based on soil bioengineering techniques, which make use of vegetation as a building material (Mattia et al. 2005; Parhizkar et al. 2021).

The ecological characteristics of the dune cordons allow a small number of plants to emerge, such plants being extremely specialized in growing on incoherent substrates, poor in nutrients, highly draining, with strong solar radiation, exposition to strong winds and salt spray (Brecciaroli and Onori 2009). Grazing and occasional flooding of sea water are further disturbing factors in these fragile ecosystems. Furthermore, the distribution of the coastal dune vegetation, regulated by an ecological gradient and characterized by a typical sea-inland zonation, is strictly related to the sedimentological and geomorphological characteristics of the dune system (Fenu et al. 2012; Valentini et al. 2020).

Hence, coastal vegetation constitutes an exclusive community able to establish itself at a certain distance from the coastline where the substrate — incoherent and rich in salinity — begins to show the edaphic and structural characteristics to support the sustenance of psammophilous and halophyte vegetation (Ciccarelli 2015; Bertacchi et al. 2016).

Soil bioengineering, taking into account biological and ecological concepts, use engineering design principles to construct living structures, in combination with plant communities propagation, that will naturally control erosion, sediment, and flooding. Engineering design principles are applied to sustainable interventions for immediate protection of slopes against surface erosion, shallow mass wasting, cut and fill slope stabilization, earth embankment protection, and dune stabilization (Bischetti et al. 2014). The development of vegetation, combined with naturalistic structural interventions, is of fundamental importance for the formation and subsequent soil surface protection of coastal dunes.

In this context, studies concerning autochthonous plant species' suitability to be used for dune consolidation, research assessing plant propagation and over time the growth of such plants after the realization of soil bioengineering works are to be promoted.

The individuation of the most suitable autochthonous plant species for propagation derives from the floristic and the vegetation analysis conducted to highlight the plant species frequencies and the vegetation classes of the intervention site and its surroundings.

This work sets out to (i) analyze and select Mediterranean shrubs and herbaceous species to be used in soil bioengineering dune restoration interventions, (ii) assess their most suitable propagation methods and their growth capacity, and (iii) provide useful insights into field management strategies before and after the realization of the soil bioengineering intervention.

The activities carried out to achieve these goals included:

- Choosing the suitable native species to be used in soil bioengineering coastal intervention in a specific case study located in the Ionic arch of Taranto;
- Assessing the best propagation methods (seeds, cuttings, vegetative parts, vegetal micro-propagation) for each of the selected plant species and performing a multi-temporal observation of the main growth parameters;

- Supplying some standard first insight on the realization and on the effect of the soil bioengineering intervention in order to transfer and increment the knowledge in the field of works for controlling dune degradation.

Materials and methods

Study area

Within Project 3 INTERREG WATCH OUT (Trilateral model of civil protection: WAys, Tools and CHallenges for OUr safeTy), a study area characterized by dune instability was selected to carry out the study. The site is located in a portion of the coast belonging to the Municipality of Massafra (Puglia region – Italy, province of Taranto) (Fig. 1a).

The area, specifically named Patemisco, is included in the Site of Community Importance (SCI) IT9130006 Pineta dell'Arco ionico and is near the Stornara State Natural Reserve, a naturalistic area.

The site falls within the Metaponto plain. This is crossed by several hydrographic networks and is characterized, especially in the coastal areas, by alluvial or wind fine sediment. The watercourses crossing the area, mainly fed by springs, are unable to provide solid material useful for the nourishment of the coast (Sabato et al. 2012). The beach is less deep than the next coastal areas, reaching a width of about 13 m (Fig. 1b). The emerged beach appears subject to coastal erosion (Fig. 1b) caused by the direct exposure of the shoreline to the prevailing wind and to the waves' motion. Indeed, the embryo and the mobile dune are absent and without vegetation, while the fixed and the inner mature dune are carved out with the presence of some shrubs (Fig. 1b). The retro dune instead is characterized by the presence of bushes.

As mentioned in the Coastal Regional Plan (PRC 2012), which is the instrument that governs the use of the public coastal areas, Patemisco is classified as a "sandy beach with medium criticality and sensitivity". The climate is the typical Mediterranean with warm, dry summers and mild, moist winters. The most frequent and strong wind event directions are W-NW and N-NW, with a percentage of appearance of 22.26% and 12.76%, respectively. Speed can reach 22 knots for winds directed from the W-NW sector. The wind regime directly influences wave motion. For 78.81% of the observation period, the wave regime is classified as "calm", with a maximum concentration in summer (80.49%) and a minimum concentration in spring (75.51%). The main direction of the waves is SSE and S with a frequency of 7.29% and 6.08%, respectively (PRC 2012).

Botanical characterization and choice of plant species

Vegetation analysis is an important phase as it makes it possible to identify the autochthonous species that could be potentially used in soil bioengineering works (Petrone and Preti 2010). The identification of the most suitable vegetal species, for the pilot interventions, was performed by the Department of Agricultural and Environmental Sciences (DiSAAT, University of Bari) and by the Center for Research and Experimentation and Training in Agriculture (CRSFA, Basile Caramia Institute of Locorotondo).

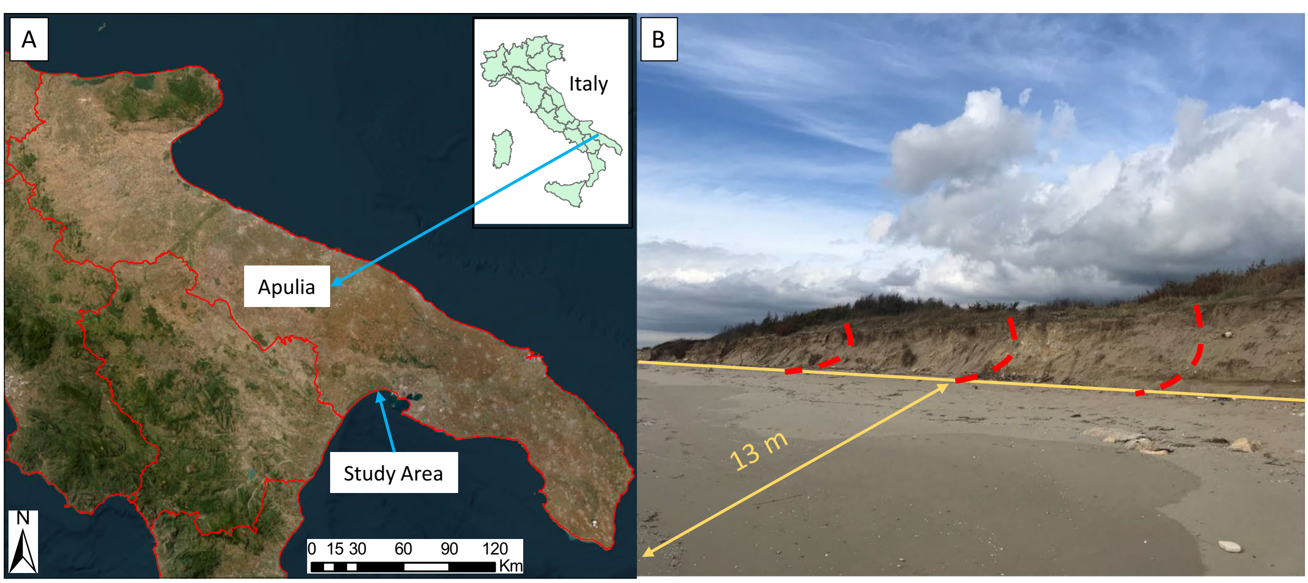

Fig. 1 **a** Study area: Patemisco (Puglia, Italy); **b** Coastal sand dunes located at Patemisco before soil bioengineering works

Botanical characterization was carried out in two phases: identifying the habitats, based on a literature analysis and, identifying the main species of the study areas, both based on a literature analysis and on an in-field survey.

The identification of the Habitats was carried out according to the Habitats Directive – 92/43 / EC, (European Commission 2013; EEA 2015). Specifically, the habitat distribution within the study area was defined by using the areal indicated in the "Manual for the monitoring of species and habitat of community interest" (Angelini et al. 2016) and in the "Distribution of habitats and animal and plant species present in the territory of the Puglia Region" (Puglia Region 2018). Specifically, five habitats were recognized for the study site (Table 1).

At this point, the Italian Interpretation Manual of the Habitats Directive – 92/43 / EC (Biondi et al. 2009), was used to typify the Psammophilous coastal vegetation categories. Moreover, a specific field survey was carried out (by Authors: Pasquale Venerito and Vincenzo Leronni) to list the floristic species effectively found in the Patemisco study site.

Starting from the shoreline, the strip of marine deposits is suitable for the development of the halo-nitrophilous vegetation of the class known as *Cakiletea maritimae* Tx et Preising in Tx. 1950. Annual pioneering species are widespread, such as *Cakile maritima* Scop. and *Salsola kali* L. (EU Habitat 1210). When the distance from the shoreline increases, these communities tend to be enriched with species typical of the *Ammophiletea* class Br.-Bl. et R. Tx. 1946, which contributed to the formation of the embryonic dunes (EU Habitat 2110). In this association of pioneer perennial bushy grasses, the *Agropyron junceum* (L.) P. Beauv., syn. *Elymus farctus* (Viv.) Runemark, the *Eryngium maritimum* L. and the *Calystegia soldanella* (L.) R. Br. are dominant (Pierfederici 2006) The base of the mobile dunes, which is enriched with organic matter, progressively facilitates the settlement of more demanding species. The pioneer species of this portion of the dune (EU Habitat 2120) is the *Ammophila arenaria* (L.) Link. Following its dynamic stabilization, the dune reaches a stage of maturity and the psammophilous vegetation increases its biodiversity by enriching itself with *Medicago marina* L., *Echinophora spinosa* L., and *Pancratium maritimum* L. (EU Habitat 2230). Other species found in the surrounding not eroded dune, and therefore considered for the project, were the *Crucianella maritima* L. and the *Sporolobus pungens* (Schreb.) Kunth. The fixed dune allows the characteristic sclerophyll shrubs consociation dominated by coastal junipers (EU Habitat 2250) to be developed. More specifically, the coastal scrub of junipers is dominated (in order of density) by *Juniperus macrocarpa* Sm., *Phillyrea angustifolia* L., *Tamarix gallica* L., *Tamarix africana* Poir., *Myrtus communis* L., *Pistacia lentiscus* L., *Juniperus phoenicea* L., and *Smilax aspera* L. These formations, particularly sensitive to the variation of natural and anthropic dynamics, show signs of deterioration almost everywhere, with frequent regression to discontinuous mosaic shrubs with herbaceous communities of the Ammophiletea. Finally, in the mature dune, which corresponds with the area

Table 1 EU Habitats identified within the study area and the species selected as suitable to be used in soil bioengineering works

Habitat name	Description	Characteristic species
1210 - Annual vegetation of drift lines (upper beach)	Formations of annuals or representatives of annuals and perennials, occupying accumulations of drift material and gravel, rich in nitrogenous organic matter	*Cakile maritima* Scop. subsp. *maritima*, *Salsola kali* L.
2110 - Embryonic shifting dunes (embryo dune)	Formations of the coast representing the first stages of dune construction, consisting of ripples or raised sand surfaces of the upper beach or by a seaward fringe at the foot of the tall dunes	*Agropyron junceum (L.) P. Beauv.*, *Calystegia soldanella* (L.) R.Br., *Eryngium maritimum* L.
2120 - Shifting dunes along the shoreline with *Ammophila arenaria* (L.) Link (white dune)	Mobile dunes forming the seaward cordon or cordons of dune systems of the coasts	*Ammophila arenaria* (L). Link *Echinophora spinosa* L.
2230 - *Malcolmietalia* dune grasslands	Associations with many small annuals and often abundant ephemeral spring bloom	*Echinophora spinosa* L., *Medicago marina* L., *Pancratium maritimum* L. *Crucianella maritima* L. *Sporolobus pungens* Schreb.
2250 - Coastal dunes with *Juniperus* (juniper scrub)	Juniper formations of Mediterranean coastal dune, slacks, and slopes	*Juniperus macrocarpa* Sm. *Phillyrea angustifolia* L., *Tamarix gallica* L. *Tamarix africana* Poir. *Myrtus communis* L. *Pistacia lentiscus* L *Juniperus phoenicea* L. *Smilax aspera* L.

in proximity of the Stornara State Natural Reserve boundaries, the coastal shrubs' vegetation is denser and associated with *Pinus halepensis* Mill., *Pinus pinea* L., *Cupressus sempervirens* L., *Eucalyptus camaldulensis* Dehnh. and extensive populations of *Acacia saligna* Labill. H.L. Wendl.

A preliminary selection of the native shrub and herbaceous species to be used in the pilot interventions took place considering the conservation of biodiversity, the ecological, and the phytoclimatic characteristics issues of the sites.

The choice of the psammophilous native species was performed taking into account the following characteristics:

- Resistance to the stresses due to erosive phenomena;
- Ability to consolidate the soil with the root system;
- Tolerance of particular edaphic conditions (e.g. resistance to sandy soils and/or to salinity);
- Soil drainage capacity;
- Membership of local dune vegetation successions.

The following six shrub species and six herbaceous species were selected: *Juniperus macrocarpa Sm.*L., *Juniperus phoenicea* L., *Pistacia lentiscus* L., *Phillyrea angustifolia* L., *Tamarix gallica* L., *Tamarix africana* Poir., *Ammophila arenaria* (L.) Link, *Sporobolus pungens* (Schreb.) Kunth., *Agropyron junceum* (L.) P. Beauv., *Eryngium maritimum* L., *Calystegia soldanella* (L.) R. Br., *Pancratium maritimum* L.

To complete the vegetation studies, the selected plant species were tested in the CRSFA research facility in terms of the best propagation method, growth capacity, and technical characteristics.

The floristic lists of the vegetal species characteristics of the embryonic, mobile fixed, and mature dunes and on found in the study area of the Patemisco (Table A1 and A2) are provided in the Appendix.

Propagation techniques

The experienced staff of the CRSFA collected plants and materials suitable for propagation directly into the studied site. The study of different propagation methods was conducted at the CRSFA of Locorotondo (affiliated institute; Author Pasquale Venerito). The CRSFA is a public body recognized by our government. In particular, The CRSFA obtained from the Ministry of Agriculture delegation (Convention 02.12.2002) the construction and operation of the National Citrus Incremental Section, the Region of Apulia, in the activities of premultiply citrus prunoidee, olive trees, and vines (resolution of Regional Council no. 871 of 23.06.1994), support activities for the Regional Plant Protection Service (correct annual conventions since 08.29.1995) and to establish (Regional council Resolution no.2254, 23/12/2003) at CRSFA the Concertation Committee for the enhancement of regional viticulture nursery.

The activity is stationed on the territory of the region in different sections Operative (S.O.) in the different vocations to meet the requirements of the different species in climatic pre-multiplication. Each S.O. has fields and facilities, provided by the technical protocols for the various species, suitable for farming, and the conduct of the other plants' cat. "Base" and nursery activity for the production of drill collars cat. "Base" (grafted and frank foot), as well as the production of potted rootstocks cat. "Base" bred in vitro. All the plant species collected in this study were reproduced, and bred at the CRSFA, where they are publicly available.

Gamic (seed) and different agamic propagation techniques were tested (Fig. 2). All methods were carried out in accordance with relevant guidelines that are useful to ensure success (CAES 2022; https://portal.ct.gov/CAES/Fact-Sheets/Plant-Pathology/Basic-Techniques-for-Propagating-Plants):

- Use only healthy, vigorous source plants;
- Use the most appropriate method, growth stage, and timing for the plant;
- Protect propagation material from heat and from drying; use the material as quickly as possible after it is prepared;
- Give newly propagated plants extra attention and care during their establishment phase.

The agamic propagation techniques tested included:

- Cuttings: pieces of a plant (stem or root) used for vegetative propagation. The cuttings, treated with auxins composts, are placed in moist soil. If the conditions are suitable, the plant piece will begin to grow as a new plant producing new roots or new stems, depending on its vegetative capacity.
- Roots with buds: a root stem cutting containing a terminal bud. The plant grows from the meristem of the root.
- Bulbs: short stems with fleshy leaves that function as food storage organs during dormancy.
- Stolons: stems that grow just below ground or at the soil surface that form adventitious roots at the nodes, and new plants from the buds.
- In vitro culture or plant tissue culture: a plant propagation technique that allows a clone of the plant to be produced with the same genetic heritage.

For each shrub and herbaceous species, the selection of a specific propagation method depended on the literature research carried out in technical reports (Piotto and Di Noi 2003; Bacchetta et al. 2015) considering the genus and species of the plant. The general rule adopted was that if the first method gave a survival rate (live individuals obtained from the mother plant or from seeds) below 50% another method would be tried. The propagating material was collected starting in autumn 2018.

Fig. 2 Example of propagation methods used

***Juniperus macrocarpa* Sm.L. and *Juniperus phoenicea* L.**

Juniper seeds, collected in autumn 2018 on plants of the Ionian-Taranto coast, were subjected to vernalization and scarification, then were sown, in January 2019, in jiffy of 2×2×2 cm in size with a 50% sand-peat substrate, in a growth chamber. The young seedlings obtained were first transplanted into 3×3×5 cm alveolar containers on peat-soil-sand substrate mixed together in equal parts and reared in a growth chamber at controlled brightness, temperature, and humidity. Subsequently, in May 2019, they were transplanted into larger 5×5×5 cm pots, with the same mixture preparation, and reared in acclimatization tunnels where they were subjected to periodic irrigation and fertilization. One-year-old seedlings showed an average height of about 60 cm. The study of the propagation of junipers by cuttings took place with twigs of 12 cm in length taken contextually with the seeds and rooted in a mix of perlite and sand, with the aid of hormones based on auxins. The cutting was executed both on semi-woody and herbaceous parts of the plant, giving similar results. The bases of the prepared cuttings were immersed for a few seconds in a 5% solution of IAA (indole-3-butyric acid or auxin) dissolved in ethyl alcohol and water. Then the cuttings were arranged in a substrate prepared with a base layer of sand, in order to retain the humidity dosed with the nebulization technique, and a top layer of perlite, an inert material particularly suitable for rooting. The boxes were covered with a plastic film in order to retain the moisture of the cuttings, which are provided with leaves for the induction of rooting. The boxes were placed in the growth chamber, a closed-cell in which brightness is controlled — and provided using LED lamps to simulate natural light — with a timer set to deliver 12 h of light per day. The chamber temperature is also guaranteed and constant with values ranging between 18 and 20 ° C, while humidity is kept at values close to 80–90%, ideal for rooting. Twice a week, the boxes with the cuttings were uncovered to treat them with an anti-mold spray, to prevent the rotting of the basal parts. The formation of the cicatrization callus occurred after about 60 days for *Juniperus phoenicea* L., while the cuttings of *Juniperus macrocarpa* Sm. suffered damage from rotting of the base, so the formation of the callus did not occur, except for very few cuttings. Probably this plant species needs fewer humidity phases during rooting. The cuttings with callus rootlets of 2–6 cm in length were transplanted into small cellular containers (2×2×5 cm) with a peat-soil-sand substrate, remaining all-time in the growth chamber until June 2019. Then, the seedlings were transferred to larger (5×5×10 cm) pots under acclimatization tunnels, where they received the necessary cultural care to ensure optimal growth (periodic irrigation and fertilization). These operations made it possible to overcome the trauma related to the transfer from a very humid environment to a drier one. The in vitro culture of meristematic apexes of the two species of juniper started in autumn 2018, on soil-agar culture. In vitro culture is a micropropagation technique consisting of the vegetative propagation of selected genotypes under sterile conditions. In order to obtain a rapid multiplication, the proliferation of sprouts is induced in a suitable culture medium, composed of mineral salts, vitamins, sugars, and hormones. Once the sterile culture of vegetative apexes has been started, the axillary development of the shoots occurs by adding cytokinin to the culture, a hormone that interrupts apical dominance. Proliferation occurred in 15–20 days, raising a clump of small sprouts. After the first phase of rooting and multiplication, the apexes were transplanted into new culture substrates and set into a growth chamber on a peat-based substrate. Then, they were moved to the acclimation tunnel before being transferred to the shadow plot.

Pistacia lentiscus L. and *Phillyrea angustifolia* L.

The seeds, collected in October 2018 and subjected to vernalization for three months in a cold room with a temperature of 4 °C, were then scarified and sowed, in February 2019, in a jiffy substrate of peat discs. The jiffy was immersed, for about 10–15 min until the discs were swollen, in a solution with 3 L of water and 10 ml of auxin hormones or root stimulator. They were then drained from the excess solution and placed in the growth chamber at controlled brightness, temperature, and humidity. The *Pistacia lentiscus* L. seeds were inserted into the jiffy at least half a cm under the surface of the disk to foster its germination, which occurred about 40 days after sowing. In June 2019, the seedlings were transplanted into 10 × 10 × 10 cm pots and transferred to an external shade plot with an upper shading net, ensuring irrigation, fertilization, and phytosanitary treatments against the aphids that had occurred. Semi-woody cuttings of 10 cm long were taken in autumn and in spring, washed, and immersed in the basal part into a solution of water and hormonal substances based on auxin for about 30 min. The cuttings were implanted in boxes containing an inert substrate based on perlite and sand, in the growth chamber. At the same time, the cuttings were covered with a plastic sheet for nebulization, so as to facilitate the formation of the scarring callus. Following the formation of the callus, the cuttings were transplanted into substrates based on peat, sand, and soil for the subsequent phase of growth of the seedlings, first in the growth chamber and then under shade.

Tamarix gallica L. and *Tamarix africana* Poir.

Woody cuttings were collected to propagate these deciduous species. The cutting took place in February 2019 with a collection of 10 cm long cuttings. The propagation techniques followed the same procedures as those indicated for *Phillyrea angustifolia* L.

Ammophila arenaria (L.) Link, *Sporobolus pungens* (Schreb.) Kunth *and Agropyron junceum* (L.) P. Beauv

The propagation of these herbaceous species took place in two phases, spring-summer 2019 and spring 2020, by using vegetative parts of the plant. Considering their cespitose attitude, roots with buds were inserted into small elongated jars, containing a peat-soil-sand substrate, and placed in acclimatization tunnels to induce root growth. The plants were subsequently transplanted and transferred to an external shaded plot where irrigation, fertilization, and phytosanitary treatments were ensured.

Eryngium maritimum L.

The seeds, collected in summer 2019, were sown in autumn 2019 on a sand-soil substrate. Germination occurred after 40 days.

Calystegia soldanella L. R. Br. and *Pancratium maritimum* L.

Stolons and bulbs were, respectively, the vegetative parts of plants used for the propagation of these herbaceous plants. Stolons were collected in the late spring of 2019 and transplanted into small jars, in acclimatization tunnels, where they started to grow. Bulbs were collected during the dormancy period (summer 2019, in this case). They were placed between a layer of sand, below, and an upper layer of soil mixed with peat to facilitate growth and further reproduction.

Morphological investigation

The morphological tests, which mainly concerned the shrub species, were conducted once a month from May 2019 to June 2020. For each species, five representative plants were selected and an identification number (ID) was placed on a tag, allowing measurements to be replicated on them at all times. Leaf sizes, internode length, total height, and the Soil–Plant Analysis Development (SPAD) index were measured as epigean parameters. Leaf sizes (mm) were measured, only for the *Pistacia lentiscus* L. and for the *Phillyrea angustifolia* L., using a ruler and a digital caliper. This parameter refers to the two largest leaf dimensions (height and width) of three distinct sectors of the plant (basal, median, and apical). For compound leaves, as in the case of *Pistacia lentiscus* L., the size of the individual leaflets and the length and width of the compound leaf were measured. Internode length (cm) corresponds to the elongations between the internodes measured using a digital caliper. The total height (cm) is the height of the epigean parts of the plant, measured with a ruler, starting from the base of the stem up to its apical part excluding any leaves. Evaluating the vitality of a plant using only morphological parameters of growth is certainly useful but does not always make it possible to correctly interpret the health state and the appearance of symptoms due to adverse factors. Therefore, the need arises to rely on methods that can be quickly used to obtain unambiguous data on the behavior of plants and their vitality. The classic method often used for this purpose is the SPAD index, which provides accurate and immediate information on the physiology of the plant by means of a synthetic measure of the plant itself, a key indicator of the health of the plant. The measurement technique is not invasive, as it is sufficient to clamp the instrument on a leaf or a plant tissue to obtain an indexed reading (from 0 to 99.9). The SPAD measures the foliage content of chlorophyll, one of the main indexes reflecting plant health conditions (Monje and Bugbee 1992; Jiang et al. 2017). The SPAD meter (Chlorophyll Meter SPAD-502Plus – Konica Minolta), used in this study, determines the relative amount of chlorophyll by measuring the absorbance of the leaf in the red and near-infrared wavelength regions (Süß et al. 2015). The chlorophyll present in the plant leaves is closely related to the nutritional condition of the plant. A higher SPAD value indicates a higher amount of nitrogen in the leaf and a healthier plant condition. From September 2019 to June 2020, one plant per species was randomly selected and measurements of the root length (underground parameter) and of the wet and dry weight were carried out. Finally, to allow a visual comparison to be made between the different monitoring periods, a photo of both the epigean and the underground parts of the plant was taken for every plant. The health of the foliage is linked to the development of the root system. For this reason, it is essential to know not only the situation of the epigean apparatus but also that of the roots. For the purposes of the study of the hypogeal apparatus, it was necessary to remove from time to time a plant for each species investigated. This operation ensured the direct measurement of the length of the main root. While it is difficult to obtain an absolute evaluation of the length of the root systems with this measurement, it can be used to provide a comparison between several successive measurements. The dry and wet weight determinations were also carried out on the seedlings removed to measure the roots. A form, composed of 10 inputs, containing the information necessary to be collected, was prepared and compiled for each monitoring (Table 2).

Table 2 Monitoring form of the plant growth parameters

Plant ID
Species
Photo
Root length (cm)
Root system photo
Leaf sizes (L x W) (mm)
Internode length and total height (cm)
Wet weight
Dry weight
SPAD Index

Intervention scheme

The soil bioengineering construction works were performed during autumn 2020 to meet the vegetative needs of the herbaceous and shrubby species to be planted. The interventions of protection and stabilization of the sandy dune took place in the order described below and were based on the use of techniques that involve (1) the remodeling of the degraded dune profile, (2) the placement of structural elements (of natural origin and essentially biodegradable), (3) the planting of native herbaceous and shrubby vegetation. The structural defense of the dune fronts was obtained through the installation of a wattle (Fig. 3), extended for 90 m long and 16 m wide, and arranged parallel to the shoreline, for foot protection. The wattle was made up of heather rods (or similar) with a diameter of 30–50 mm and lengths of no less than 1.5 m, intertwined on uprights 70 cm apart and fixed with galvanized iron wire. The uprights, made of debarked poles of durable wood, were fixed to the ground to a depth of at least 70 cm by simple beating or drilling. Their diameter was 8–10 cm and their height above ground was about 40 cm. The pointed-shaped end of the uprights subject to burial was treated with anti-rot protection such as flaming. Then, a protective bio-mesh, made up of jute fiber mats with tensile strengths generally not exceeding $3 \div 4$ kN m^{-1}, was installed along all the dune front, with the aim to reduce surface erosion and limit small landslides phenomena. To encourage the development of the roots (Mashayekhan and Hojjati 2013) and, consistent with the basic principles of the circular economy, wood chips, made from *Pinus halepensis* Mill. wood residues collected close to the intervention site, were used as a soil conditioner, by spreading and mixing it with the sand and as mulch, by letting it only on the surface.

The experimental design consisted of dividing the area of intervention into three sections of 30 m, where, different technical solutions were tested. The bio-mesh was placed, in the first two Section (60 m), also in the fixed and in the retro dune. In the same sections, wood chips were used for 30 m both as a soil conditioner and as mulch (Section A) and for 30 m only as mulch (Section B). In the third section (Section C), which was characterized by the presence of some well-developed *Juniperus macrocarpa Sm.* shrubs the intervention was limited to the sole use of wood chips both as soil conditioner and as mulch. Moreover, to assess the effect of the different technical solutions on both the herbaceous and the shrub species, each section was firstly divided into three plots of 10 m x 16 m and then was further divided into two portions. The top portion (10 m x 6 m) hosted the shrub species and the remaining portion (10 m x 10 m) hosted the herbaceous species forming six quadrants (Fig. 3).

The distribution of the plant species over the sections was established considering their natural distribution on the dune (Table 1). In particular, in the three quadrants used for the

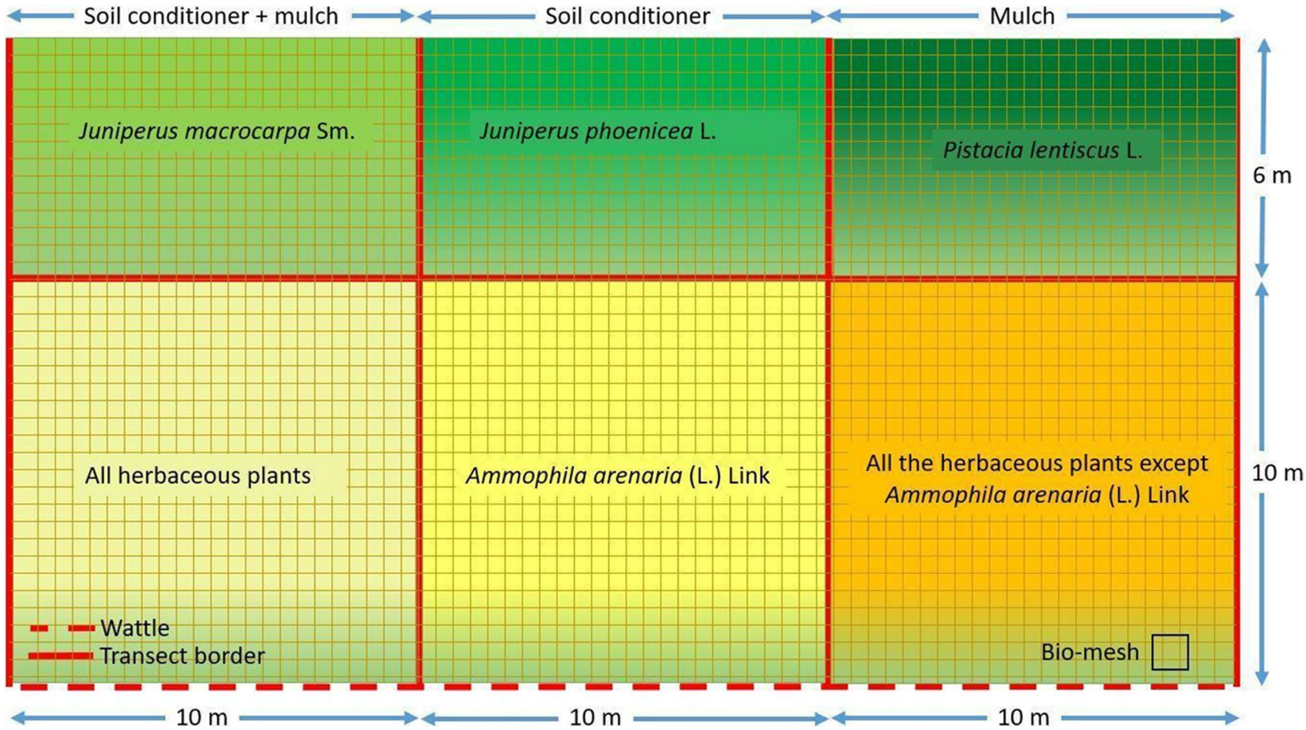

Fig. 3 Example of a section scheme

shrubs, only *Juniperus macrocarpa Sm.*, *Juniperus phoenicea L.*, and *Pistacia lentiscus* L. were effectively planted (Fig. 3). Indeed, *Phillyrea angustifolia* L., *Tamarix africana* Poir. and *Tamarix gallica* L. were excluded after the submission of the project to the opinion of the regional authorities. Although the study site was outside of the *Xylella fastidiosa* disease buffer zone, Phillyrea angustifolia L. was forbidden considering that this species is a possible host of the disease (Puglia Region 2020). *Tamarix africana* Poir. and *Tamarix gallica* L. were both forbidden because, despite being a species naturalized in dune habitats, is considered not-representative of the plant succession of the study site. In the three quadrants used for the herbaceous species instead, a mix of all herbaceous species, only the *Ammophila arenaria* (L.) Link and a mix of all herbaceous species without the *Ammophila arenaria* (L.) Link were planted. In each plot, the plants were planted with a planting sixth of 1 × 1 m.

Results

Propagation techniques

For each of the selected plant species, different propagation techniques were tested. The survival rates, defined as the live individuals obtained from the mother plant or from seeds are shown in Table 3. Both junipers showed good results for the seeds, with a survival rate of 35%. The two species of juniper also showed similar survival rates in the case of the in vitro culture (20%). Conversely, different results were obtained from the cuttings. In this case, no individuals survived for the *Juniperus macrocarpa* Sm., while for the *Juniperus phoenica* L. only 10% of the individuals started to develop. *Pistacia lentiscus* L. showed no survival rate when propagated by cuttings, while a 50% survival rate was observed when propagated by seeds. Similar results were obtained for the *Phyllirea angustifolia* L. when propagated by seeds (50%). With regard to cuttings, on the other hand, following a failure of those taken in autumn, a good success rate was achieved, with a survival rate of about 40% for those taken in spring. Both *Tamarix gallica* L. and *Tamarix africana* Poir. considered showed a very high-efficiency rate (80–90%) for cuttings.

Moving on to herbaceous species, almost all of them propagated with agamic methods (root with buds, stolon, and bulbs), except for the *Eryngium maritimum* L. Most notably, *Ammophila arenaria* (L.) Link, *Sporobolus pungens* (Schreb.) Kunth and *Agropyron junceum* (L.) P. Beauv. showed a survival rate close to 90% with the roots with bud propagation method. Similar results were also obtained for *Calystegia soldanella* (L.) R. Br. (90%), which was propagated by stolons. *Pancratium maritimum* L., characterized by the formation of bulbs, showed a survival rate higher than 90%. Finally, the *Eryngium maritimum* L., which was reproduced by seeds, scored a survival rate of about 80%.

Table 3 Experimentation of plant propagation techniques

Plant Species	Description	Survival rate(%)
Juniperus macrocarpa Sm.	Seeds; In vitro culture	35; 20
Juniperus phoenicea L.	Seeds; Cuttings; In vitro culture	35; 10; 20
Pistacia lentiscus L.	Seeds;	50
Phillyrea angustifolia L.	Seeds; Cuttings	50; 40
Tamarix gallica L.	Cuttings	80–90
Tamarix africana Poir.	Cuttings	80–90
Ammophila arenaria (L.) Link	Roots with buds	90
Sporobolus pungens (Schreb.) Kunth	Roots with buds	90
Agropyron junceum (L.) P. Beauv.	Roots with buds	90
Eryngium maritimum L.,	Seeds	80
Calystegia soldanella (L.) R. Br.	Stolons	90
Pancratium maritimum L.	Bulbs	> 90

3.2 Morphological investigation

Total height, internode length as well as the SPAD index of the selected shrubby species were monitored once a month from May 2019 to June 2020. Figure 4 describes the trend of the average heights, calculated on a total of five plants for each species, during the reporting period.

Tamarisks show the fastest growth in the spring-summer period and then settle on constant values during the remaining observation period. *Tamarix gallica* L. increased its initial height by almost 60 cm from May 31, 2019, to September 1, 2019, while the observed height increased for *Tamarix africana* Poir. was 45 cm during the same time interval. Both tamarisks showed almost asymptotic values after the fourth month of monitoring. *Phillyrea angustifolia* L. grew by about 20 cm in the first fourth months and then continued to develop also in the following period, reaching a final height before transplanting of about 70 cm. While *Pistacia lentiscus* L. showed a good increment in the first fourth months (30 cm), it only grew 3 cm in the rest of the monitoring period. In addition, during the last two months of observation, *Pistacia lentiscus* L. underwent a drying-up of the tops, which reduced the average height by about 12 cm. The juniper plants were the species that developed less in the first periods (5–7 cm). After September, and until the end of the monitoring period, the height of the *Juniperus macrocarpa* Sm. almost doubled. By converse, the *Juniperus phoenicea* L. underwent an asymptotic period that lasted until February 2020, and then showed an increment of about 5 cm. The observation of internode elongation, performed for *Phillyrea angustifolia* L. and *Pistacia lentiscus* L., shows a trend in line with seasonal trends: a growth phase from March to October followed by a vegetative dormancy in the rest of the year.

A progressive increase in leaf size was generally observed for *Pistacia lentiscus* L. and for the *Phillyrea angustifolia* L (Fig. 5). *Pistacia lentiscus* L. showed an increased trend considering all the positions (basal, median, and apical) of

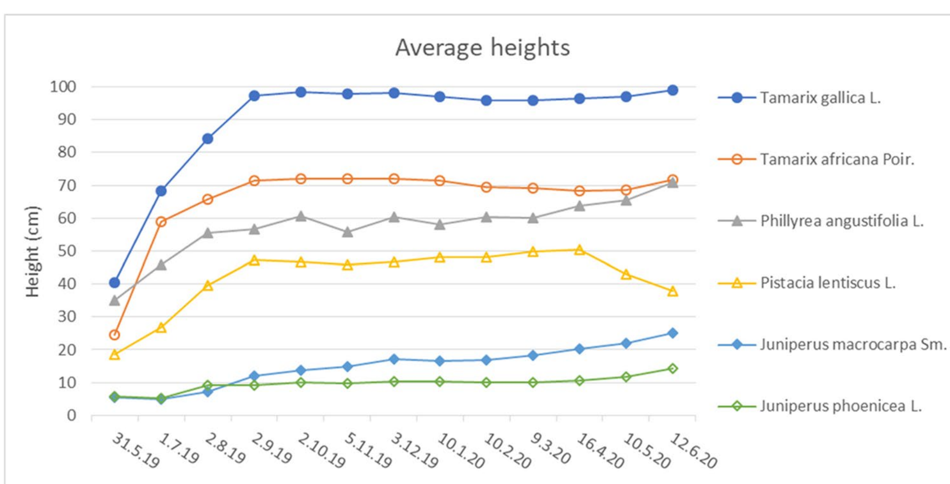

Fig. 4 Average heights of monitored shrubby species from May 2019 to June 2020

the leaves monitored. For basal and median leaves, the greatest increases were observed for length. Basal varied from 44.6 to 77.3 mm, while the median from 55.3 to 86.1 mm. The apical leaves increased their size mainly in width (35.9 to 56 mm). The foliar increases of the *Phillyrea angustifolia* L. plants turned out to be more contained. The greatest value was observed for the length of the basal leaves, which changed from 44.5 to 64.6 mm. In cases related to middle leaves, the size was almost constant. Conversely, for apical leaves, the greatest increase was observed for width (9.3 to 11.22 mm).

The leaf SPAD values at the midpoint of the topmost fully developed leaf revealed fundamental information regarding plant health. As outlined in Fig. 6, *Phillyrea angustifolia* L. showed a SPAD ranging from 52.1 to 95.7, such value being recorded at the end of the observation period. The SPAD values observed for *Pistacia lentiscus* L. were steadily lower, with a strong reduction during the spring season of 2020.

Table 4 pertains to the analysis carried out every month on the root length, the height above ground, and the wet and dry weight, using a destructive method. Generally, root length and height above ground showed variable values

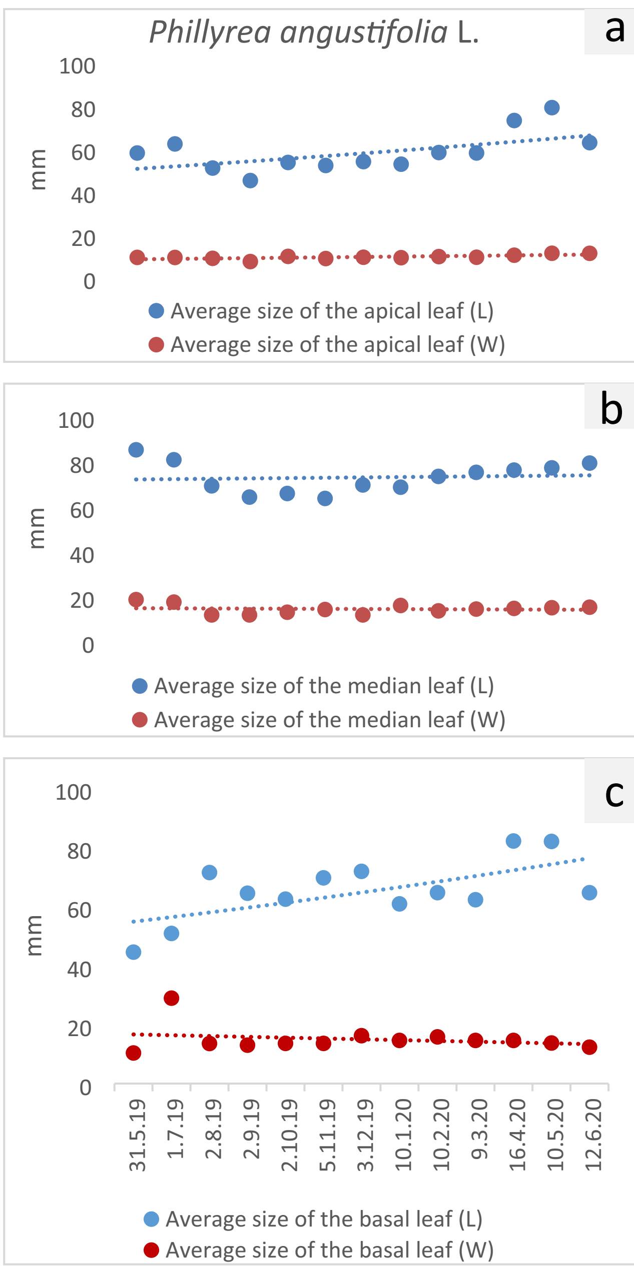

Fig. 5 Average sizes of apical (**a**), median (**b**) and basal (**c**) leaves of *Phillyrea angustifolia* L. and *Pistacia lentiscus* L. (L = Length, W = Width).

(Table 4) and provided unambiguous data about the vegetative growth of the plants being analyzed. As to *Phillyrea angustifolia* L., the root length ranged from 32.3 to 67.2 cm, while the height above ground varied from 54.0 to 77.2 cm. *Pistacia lentiscus* L. showed a root length varying from 10.3 to 55.2 cm and a height above ground ranging from 34.5 to 64.0 cm. The values for the root length shown by *Tamarix gallica* L. ranged between 31.3 and 70.0 cm, while the values for the height above ground ranged between 62.3 and 124.5 cm. *Tamarix Africana* Poir. showed similar values except for the highest height above ground, which stood at 138.3 cm. The two herbaceous species, *Ammophila arenaria* (L.) Link and *Agropyron junceum* (L.) P. Beauv., highlighted similar ranges for both the root length and the height above ground (from 10.5 to 16.5 cm to 100.7-102.4 cm). Dry weight was almost constant considering all the selected species (Table 4), while wet weight showed variable values. For *Phillyrea angustifolia* L., wet weights followed the seasonal phases since it was higher from spring to autumn. The other species showed values increasing in autumn and winter, until January 2020, and then a slight decrease.

Realization of the intervention with soil bioengineering techniques planting the shrubs and the herbaceous species

The construction site for the intervention in question has been operational for about two months. The workers of the Biodiversity Department of Carabinieri of Martina Franca carried out the work. The wattle, the length of which corresponded to that of the intervention area (i.e., 90 m) was built by first fixing the vertical poles using an auger and a sledgehammer (Fig. 7a). A trench was then made at the base of the wattle in which the rods and the bio-mesh were buried to increase the resistance of the works to waves and wind (Fig. 7c). The rods were superimposed on the vertical poles and fixed by means of nails. Overlapping was achieved by placing a (1.50 m) rod between two front and one rear vertical pole (Fig. 7b). After that, wood chips collected close to the site were apportioned across the intervention area (Fig. 7d). The bio-mesh was then rolled out to cover all the plot length and width (Fig. 7e). Finally, to complete the work, shrubs and herbaceous species were planted (Fig. 7f). Of all the selected shrub species, only three were actually planted in the intervention plots because of some regional constraints. Regarding the herbaceous plants, instead, since *Ammophila arenaria* (L.) Link is considered to be a highly pioneer and colonizer species (Moreno-Casasola 2008), it was decided to plant this species alone in one plot and to combine it with the others in another plot. Moreover, in the last plot, only the other herbaceous species were planted. The experimental nature of the works performed afforded the possibility of applying different technical solutions combined in both the sections and the plots with a view to testing their effectiveness over time.

In autumn 2020, when the works started (Fig. 8a), before being transplanted on the dune, all the seedlings were transferred to a specific nursery in close proximity to the intervention site to ensure plant adaptation to the weather conditions of the coastal area of intervention, which were different from those in the nursery, Once there, due to a dry period, the seedlings were subjected to different emergency irrigation until their planting, which took place between December 2020 and January 2021. *Pistacia lentiscus* L. underwent modest defoliation by a herd of wild boars, without compromising its vegetative vitality. For this reason, this

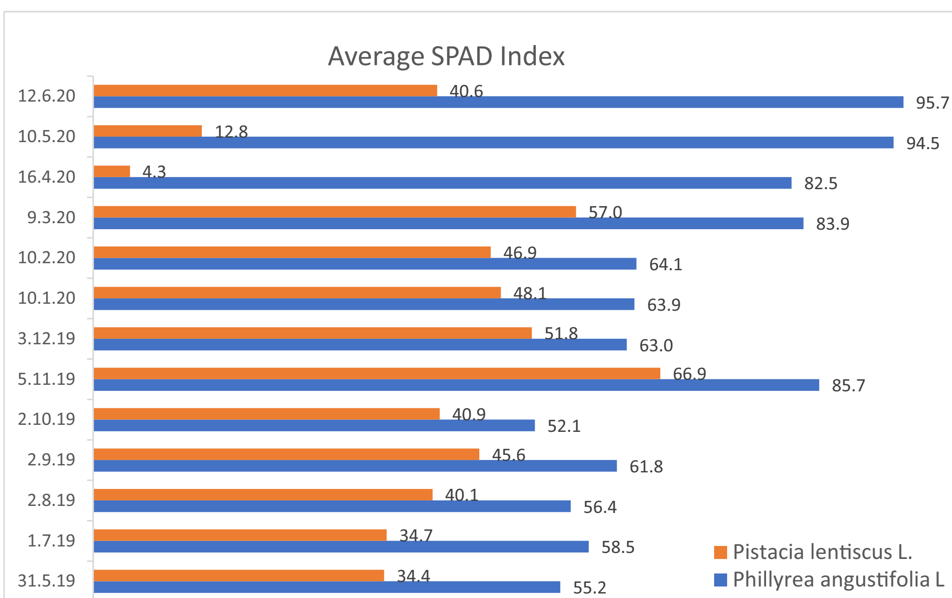

Fig. 6 Average SPAD values of *Phillyrea angustifolia* L. and *Pistacia lentiscus* L

Table 4 Plant parameters determined by destructive methods

	Roots Ienght (cm)	Height above ground (cm)	Weight (g)	Dry weight (g)	Roots Ienght (cm)	Height above ground (cm)	Weight (g)	Dry weight (g)
	Phillyrea angustifolia L.				*Pistacia lentiscus* L.			
02/09/2019	41.8	66.4	68.1	31.6	39.1	46.5	14.2	6.4
02/10/2019	51.2	71.4	64.1	34.8	38.1	39.5	22.6	12.4
05/11/2019	42.5	77.2	51.8	32.2	55.2	37.9	15.1	7.2
03/12/2019	43.0	54.0	53.4	24.9	50.0	60.4	30.2	14.0
10/01/2020	46.0	65.4	35.2	25.6	32.9	43.3	15.1	10.3
10/02/2020	29.5	62.9	31.5	24.3	15.7	34.5	11.1	8.27
09/03/2020	41.0	60.5			26.5	64.0		
16/04/2020	32.3	54.3	34.5	17.2	17.8	53.8	14.7	10.3
10/05/2020	67.2	51.2	65.3	42.3	10.3	49.2	11.4	7.85
12/06/2020	42.4	73.4	73.2	41.6	15.5	46.7	21.2	7.84
	Tamarix gallica L.				*Tamarix africana* Poir.			
02/09/2019	58.2	71.6	54.5	21.5	24.2	138.3	14.7	6.5
02/10/2019	66.0	124.5	20.6	15.7	34.6	70.0	17.2	10.9
05/11/2019	70.1	92.3	56.7	24.2	57.2	52.9	16.3	9.0
03/12/2019	43.0	103.0	39.4	21.3	37.0	78.6	35.8	18.6
10/01/2020	44.8	105.2	18.8	13.7	39.6	61.3	19.4	12.5
10/02/2020	66.5	102.3	29.9	23.1	55.5	60.0	10.7	9.0
09/03/2020	40.0	105.3			33.2	45.5		
16/04/2020	53.5	116.3	31.7	26.2	64.5	71.3	20.6	16.2
10/05/2020	57.2	84.2	25.2	18.3	21.4	83.4	13.2	8.4
12/06/2020	31.3	62.3	25.3	18.9	28.1	102.3	28.2	19.3
	Ammophila arenaria (L.) Link				*Agropyron junceum* (L.) P. Beauv.			
10/01/2020	88.0	80.0			71.0	100.7	9.2	7.3
10/02/2020	33.0	64.7	17.1	9.0			8.3	5.3
09/03/2020								
16/04/2020	43.4	102.4	28.1	19.2	32.5	81.2	7.0	4.6
10/05/2020	10.5	85.3	33.2	21.2	16.3	64.3	41.9	29.8
12/06/2020	24.4	92.3	42.4	28.3	18.6	88.4	23.9	14.2

species was moved to a fenced area. The other shrubs and herbaceous species were not hit by the wild boars. After the implant on the dune, herbaceous autochthonous species, such as *Ammophila arenaria* (L.) Link and *Pancratium maritimum* L., colonized the intermediate areas between the implant holes (Fig. 8b). This resulted in an almost complete cover of the intervention site by vegetation (Fig. 8b). *Pistacia lentiscus* L, *Juniperus phoenicea* L., and *Juniperus macrocarpa* Sm. were planted in the inner dune since these are species typical of this environment and of the Mediterranean maquis (Mulas et al. 1997; ISPRA 2015; Bonari et al. 2021). In the study site, the inner dune was directly exposed to the prevailing wind and to the waves' motion due to the lack of the mobile dune and part of the fixed one. Despite this, *Juniperus phoenicea* L. and *Juniperus macrocarpa* Sm (Fig. 8c) developed quickly without any problem showing high adaptability to changes in weather and edaphic conditions. *Pistacia lentiscus* L. instead, experienced widespread desiccation (Fig. 8d), suggesting the need of a longer on-site adaptation period. However, since *Pistacia lentiscus* L. is a phanerophytic bush (ISPRA 2015), it can emit basal shoots. This happened to start from March/April 2021 (Fig. 8e).

In the second year of plant life, approximately one year after planting (end of October 2021), *Ammophila arenaria* (L.) Link confirmed its potential as a pioneer herbaceous plant, during the first stages of the dunes consolidation. Indeed, the survival rate of individuals was extremely high and the plants were uniformly distributed along the entire dune front (Fig. 8f). Together with that, autochthonous spontaneous *Pancratium maritimum* L. established itself uniformly over the entire dune surface covering also some areas where the shrub species did not survive (Fig. 8b and f). Psammophytes indeed, due to their manifold adaptation

Fig. 7 Stages of intervention: **a** pole drilling; **b** wattle; **c** trench excavation; **d** wood chips spreading; **e** bio-mesh; **f** intervention accomplished

strategies are able to spread in the different environments of the coastal dunes (Angiolini et al. 2018; Ciccarelli 2015). This trend was also confirmed in the monitoring carried out in August 2022 (Fig. 8h).

In the inner dune, *Pistacia lentiscus* L. plants showed good vitality and basal shoots where the bio-mesh is present, while in the sector without the bio-mesh, it was dry and devoid of vegetative shoots. *Juniperus phoenicea* L. showed the highest mortality with respect to the *Juniperus macrocarpa Sm.* which seems, at present, to have better overcome the critical environmental conditions of the first year.

An analysis of the effect of the technical solutions, implemented in the two different sections, was carried out in August 2022 assessing the survival rate of the planted species. *Pistacia lentiscus* L. and *Juniperus macrocarpa Sm.* showed a higher survival rate in the section A with 53% and 80%, respectively. The rates were lower in section B where the survival rate was 4% for *Pistacia lentiscus* L. and 9% for *Juniperus macrocarpa Sm.* Finally, in the section C, *Pistacia lentiscus* L. and *Juniperus macrocarpa Sm.* showed a survival rate of 42% and 33%, respectively. It therefore appears that wood-chips used as soil conditioner and soil mulch (Section A and C) positively influenced the growth of these two shrub species. *Juniperus phoenicea* L. instead, showed low survival rate in both Sect. (8% in section A, 13% in section B and 6% in section C). Conversely, all the herbaceous species seem not to be very influenced by the presence of wood-chips because in each section the survival rates was higher than the 90–95%.

Taking into account the structural intervention, the positive effects of the wattle have to be highlighted. It was strongly anchored to the superficial sandy layers and allowed, in the first year after the intervention (October 2021), the elevation of the dune profile, following the accumulation of incoherent sandy material, both upward and downward the work (Fig. 8g). Moreover, in the second year after the intervention (August 2022), the accumulation of sand continued until almost all the wattle was covered (Fig. 8h).

Fig. 8 **a** Plants of Junipers, *Pancratium maritimum* L., *Ammophila arenaria* (L.) and *Pistacia lendiscus* L. on the temporary nursery nearby the intervention site; **b** *Ammophila arenaria* (L.) and *Pancratium maritimum* L. planted on coastal dune, **c** *Juniperus oxycedrus* (L.); **d** *Pistacia lentiscus* L.; **e** *Pistacia lentiscus* L. basal shoots; **f** *Ammophila arenaria* (L.) and spontaneous *Pancratium maritimum* (L.).; **g** accumulation of sand in correspondence of the wattle (October 2021), **h** accumulation of sand in correspondence of the wattle and dune herbaceous vegetation (August 2022)

4 Discussion

4.1 Plant propagation and growth

Considering the fundamental role played by vegetation in soil bioengineering techniques (Bischetti et al. 2014; Rauch et al. 2022), analyses focused on plant propagation and on plant growth are crucial and need to be carried out before any intervention, especially for Mediterranean species, in respect of which limited data is available (Mattia et al. 2005; Mira et al. 2021).

Shrubs species were propagated by seeds, cuttings, and in vitro culture. The two junipers were the species scoring the lowest in terms of survival rate. The best results were obtained for both junipers with seed propagation (35%). However, juniper germination varies greatly in terms of time. Once sown, junipers begin to germinate starting from the third month to the fifth year with a peak reached at the half of the second year. Hence, survival rates are greatly influenced by the duration of the trial. In this study, results were collected at the end of the first year. On the other hand, cuttings showed a survival rate of 10% for *Juniperus phoenicea* L., while a complete failure was observed for *Juniperus macrocarpa* Sm. One of the reasons for this result can be related to the time of the cutting (i.e., autumn), which may not be ideal. Van der Merwe et al. (2000) pointed out that with regard to the species investigated by them, the cuttings carried out in February resulted in a higher survival rate (67%) as compared to other periods. In the case of *Juniperus macrocarpa* Sm., however, the failure was due to the mold that had formed on the vegetative material despite continuous treatments with anti-mold substances. Specific further research is needed to gain further insights into this aspect, since this propagation method has the advantage of being more rapid as compared to other methods (Broome 2003). Regarding the in vitro culture, this methodology resulted in a survival rate of 20% for both juniper species. This type of propagation allows control of every single plant growth parameter. As a result, it is often used for *ex-situ* conservation. Despite these advantages, reliance on in vitro culture is limited because of its high costs of implementation (Espinosa-Leal et al. 2018). Some studies specifically conducted on juniper species highlighted a problem with the root development (Hazubska-Przybył 2019), which causes lower survival rates. With regard to plant development after germination, both juniper species considered in this study showed a low growth rate (Baravardi et al. 2014), especially during the first months of monitoring, while from spring 2020 the growth rate started to increase. Due to the small size of the juniper, it was decided not to include these species in the destructive tests. *Pistacia lentiscus* L. showed failure when the cuttings propagation method was used mainly because, as in other species, the high content of tannic substances in the wood can prevent the formation of the scarring callus and, consequently of the roots (Eckstein 1950; Osterc et al. 2003; Fascella et al. 2004). Conversely, a good survival rate was reached using the seed propagation methods (50%). However, in this case, the plant needs to spend at least one year in nurseries to reach a development status sufficient for plantation (Sauli and Cornelini 2007). *Pistacia lentiscus* L. growth, in terms of average height, was fast especially during the first month after germination, while it was constant until April 2020. Thereafter, there was a decrease in height due to some apical galls caused probably by an aphids' attack (Inbar 2008). Regarding the dimensions of the leaves, this species showed an increment trend throughout the monitored period. *Phillyrea angustifolia* L., on the other hand, showed the possibility of being reproduced with both seeds and cuttings (Piotto and Di Noi 2003) with survival rates of 50% and 40%, respectively. As was the case with *Pistacia lentiscus* L., *Phillyrea angustifolia* L. exhibited a higher growth in height during the first month followed by a more constant rate. The leaves showed an increase especially lengthwise, while they were almost constant in terms of width. Despite this species' aptitude for propagation and growth, *Phillyrea angustifolia* L. was not used in the intervention site because of the restriction related to the *Xylella fastidiosa* disease (Apulia Region 2020). Tamarisk was the shrub species that showed the higher survival rate when reproduced by cuttings with a value of 80–90% for both the considered species. The ability of these plants to produce adventitious roots is an important characteristic underpinning agamic reproduction (USDA Fire Effects Information System 2003; Steffens and Rasmussen 2016). In terms of growth in height, tamarisk behaved similarly to *Pistacia lentiscus* L. and *Phillyrea angustifolia* L., showing a high growth rate in the initial phases after the cutting and then a constant value. As was the case with *Phillyrea angustifolia* L., *Tamarix gallica* L. and *Tamarix africana* Poir. were not used either in the intervention site because of a legal requirement issued by the Puglia Regional Authority with respect to the specific project. Although this species is normally present in the intervention area, it is not autochthonous and is often considered invasive (Hamada et al. 2007). With regard to both *Pistacia lentiscus* L. and *Phillyrea angustifolia* L., the SPAD index was measured and used as an instrument to assess the vegetative state (Süß et al. 2015). Generally, *Phillyrea angustifolia* L. showed an incremental trend of SPAD throughout the monitoring period. By converse, *Pistacia lentiscus* L. showed lower and more variable SPAD values. This was due to the presence of tannin substances in the leaves. Moreover, a decrease in the SPAD values was detected between April and May 2020. In this period, *Pistacia lentiscus* L. was under stress conditions due to the presence of the aphid infestation. The analysis of plant height, leaves dimensions, and SPAD index can provide significant insights into both the development in the nursery and the need for care of plants when planted in the field. Aboveground vegetation, such as leaves and stems, positively contributes to decreasing the raindrop effect (Shinohara et al. 2016), and consequently, surface erosion (Gyssels et al. 2005). For this reason, plant species with a good rate of increase in height and in leaf areas, especially in the first months, such as *Phillyrea angustifolia* L. and *Pistacia lentiscus* L., can afford immediate protection of the dune surface during the first month following transplanting. However, since there are other factors influencing the ability of the plant to intersect the raindrops, such as canopy morphology (Fernández-Raga et al. 2017 Apollonio et al. 2021), *Pistacia lentiscus* L., which is characterized by lower growth, can contribute in time to increasing dune surface protection. Moreover, the rate of increase in height can be a useful indicator to establish when the plant is ready to be moved from the pot in the nursery to the open field. This will help plan cultivation times to the best extent possible. The SPAD was used mainly in the nursery to ensure that the plants were always kept in the best conditions from a nutritional point of view in order to foster their growth. Indeed, this index can be related to nitrogen, which is one of the most important growth limiting factors (Fernandez et al. 1996). Thus, the SPAD could be also measured on the intervention site in order to assess the health conditions of the plants and schedule extraordinary fertigation interventions.

Regarding the herbaceous species, all of those considered showed survival rates higher than 80%. In particular, *Ammophila arenaria* (L.) Link, *Sporobolus pungens (*Schreb.) Kunth, *Agropyron junceum* (L.) P. Beauv., *Calystegia soldanella* (L.) R. Br. and *Pancratium maritimum* L. are endowed with particular agamic reproductive structures such as roots with buds, stolon, and bulbs (de Meeûs et al. 2007). *Eryngium maritimum* L., instead, was the only herbaceous plant reproduced by seeds. Due to the high rate of survival and to the fast growth, it was decided to collect the propagation material of the herbaceous plant directly in fields at the time works got underway. For this reason, the number of plants reared in the nursery was low and did not make it possible to conduct the same analysis carried out for the shrub species. Starting from January 2020, some data was collected only for *Ammophila arenaria* (L.) Link and for *Agropyron junceum* (L.) P. Beauv., the two species with the higher number of individuals. However, data obtained proved extremely variable and dependent on the plant randomly analyzed.

One of the main purposes of this work was the transfer and the increment of knowledge in the field of works for controlling dune degradation. Although similar interventions were found in the literature (Gallego-Fernández et al. 2011; Sigren et al. 2014; Pennetta et al. 2018; D'Alessandro et al. 2020), the designs and the methodologies applied in soil bioengineering need to be derived from specific experiences in the field (Recking et al. 2019; Rauch et al. 2022).

With this in mind and taking into account the lack of information relative to the selected species found in the literature, especially regarding the period following their transfer to the intervention site, some insights were defined.

The transfer of all the seedlings to a nursery, occurred in autumn 2020, ensured the plant adaptation to the weather condition of the intervention site. Moreover, both the emergency irrigation and the transfer in a fenced area, occurred between December 2020 and January 2021, ensured both the shrubs and the herbaceous species vegetative vitality. One year after the realization of the intervention (end of October 2021), besides a rapid development of herbaceous autochthonous species, such as *Ammophila arenaria* (L.) Link and *Pancratium maritimum* L., *Pistacia lentiscus* L. experienced widespread desiccation (Fig. 8d), probably due to the direct exposition of the inner dune at wind. However, this species showed a high resilience by emitting basal shoots (ISPRA 2015).

In August 2022, *Ammophila arenaria* (L.) Link and *Pancratium maritimum* L., due to their adaptation strategy, showed the highest survival rates (Angiolini et al. 2018; Ciccarelli 2015) without an apparent correlation with the technical solution adopted. On the other hand, *Pistacia lentiscus* L. and *Juniperus macrocarpa Sm.*, showed higher survival rates where the wood-chips was used as soil conditioner and soil mulch (Section A and C).

Taking into account the structural intervention, the positive effects of the wattle have to be highlighted. In October 2021, the work was anchored to the superficial sandy layers and triggered a process of accumulation of incoherent sandy material, both upward and downward the work (Fig. 8g). The progression of this process was also observed in August 2022, when the sand accumulated until cover almost all the wattle (Fig. 8h). This last effect is of particular interest because it started to establish processes of beach progradation and habitat regeneration (e.g. embryo dune, mobile dune) (Pennetta et al. 2018).

Conclusion

Mediterranean shrubs and herbaceous species that can be used in dune soil bioengineering works are often poorly studied. As a result, there is a lack of knowledge about their propagation methods, their growth capacity, and their adaptability following transplanting. Against such a backdrop, this study was conducted with the aim to test the aforementioned plant characteristics as part of an experimental dune intervention site located in the area of Massafra, in the province of Taranto. After an extensive local area analysis, the shrubs and the herbaceous species selected were propagated in a nursery and their growth was monitored for a one-year period. The plant propagation techniques showed a greater survival rate for the herbaceous species, *Tamarix gallica* L. and *Tamarix africana* Poir., while a lesser survival rate was found for the remaining shrub plants. Within the shrub species, *Phillyrea angustifolia* L. and *Pistacia lentiscus* L. were characterized by a faster growth rate in the first few months, while *Juniperus macrocarpa* Sm. and *Juniperus phoenicea* L. highlighted more constant values. Some important insights were gained directly from in-field experience, such as the need for emergency irrigations, the higher adaptability of juniper, which grew fast after transplanting, and the desiccation of the *Pistacia lentiscus* L. followed by the formation of basal shoot from the same plants following adaptation to the new edaphic and weather conditions. Finally, the experimental design of the intervention will afford the opportunity to monitor the development of both the shrubs and the herbaceous species as part of the different technical solutions implemented. Moreover, the efficiency of the different combinations will also be monitored in order to develop some standard guidelines on how to replicate the best solution that may be useful for both land managers and land planners.

As regards the structural intervention, it should be reported the protection ensured by the wattle from a major storm occurred immediately after the construction of the work. In a short time, the wattle has allowed the accumulation of incoherent sandy material close to the work, the elevation of dune profile, and the return of autochthonous spontaneous vegetation, such as *Ammophila arenaria* (L.) Link and *Pancratium maritimum* L. This study will widen the information relative to the growth parameter of the Mediterranean species suitable for use in soil bioengineering techniques, their adaptation in the field, and possible soil bioengineering technical solutions to be used in the dune restoration.

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Data availability All data generated or analyzed during this study are included in this published article [and its supplementary information files].

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