Journal of Coastal Conservation 10: 93-100, 2004

Sustainability of sand dune restoration along the coast of the Tyrrhenian sea

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Abstract

This study reports the results of restoration management on sand dune environments along the coastal belt of the Castelporziano nature reserve (Rome, Italy) and the subsequent monitoring phases to test the sustainability of the 'soft techniques' applied. In the area concerned, over a length of ca. 3 km, 40 dunes were built up along with three belts located at < 40 m, 40-70 m, and > 70 m, respectively, from the shoreline. On each of 38 dunes 20 individuals of *Ammophila littoralis* were planted; this species is one of the local autochthonous species considered particularly suitable for stabilizing sand dunes. After one year, two years and five years, respectively, the changes in height and surface of each dune, the survival rates of *A. littoralis*, and its changes in cover, the appearance of new shoots and the establishment of new species were observed. A progressive increase in species number, which five years after the restoration amounted to about 60% of those characterizing the natural dunes, was reported indicating a progressive trend towards populations similar to natural ones. In the colonization of new species there is a prevalence of the *Sporobolus-Elymetum farcti* and the *Salsolo kali-Cakiletum maritimae* association, while the species established successively refer to the *Echinophoro spinosae-Ammophiletum arundinaceae* association and the *Crucianellion maritimae* alliance as occurring in natural successions.

This succession runs parallel to the natural dune colonization processes. In particular, the data regarding survival, cover and number of vegetative shoots indicate that the dune belt between 40 and 70 m from the sea is the one most suitable for restoration.

Some changes in dune morphology was observed: the height of the artificial dunes tended to decrease considerably in the five years of observation, whereas a progressive increase in their surface area was observed. During the study period, *A. littoralis* favoured the establishment of new species, but as yet exercises no action on increasing dune height.

Keywords: *Ammophila littoralis*; Coastal defence; Dune morphology; Dune system dynamics; Mediterranean sandy dune; Soft technique.

Nomenclature: Pignatti (1982).

Introduction

European sandy coastlines are everywhere under threat of extensive erosion (e.g. van der Maarel 1979; Anon. 1998; De Lillis 1998; Dean & Dalrymple 2002), in particular along the Mediterranean coastlines. Here ca. 75% of the sandy coasts are presently degraded (Géhu 1985; Salman & Strating 1992). To counteract coastal erosion and to restore or maintain coastlines, dune systems are the most efficient and least expensive defence against shoreline erosion. The typical sand dune vegetation plays a fundamental role in dune stabilization (Adriani & Terwindt 1974; van der Maarel 1993), consequently the loss of plant species that trap and hold sand makes the beach more vulnerable to wind and erosion. Among the approaches for coastal defence soft engineering techniques, both beach nourishment and planting of marram grass (*Ammophila* spp.) has gained a general consensus over the past two decades (Doody 2001).

Indeed beach nourishment and littoral restoration have been widely practised in northern Europe (Healy & Doody 1995), and on Mediterranean coastlines (Gomez-Pina 1999; van der Salm & Unal 2001). Marram grass planting has been successfully practised on North European dune systems and the consolidation capacities of the grass *Ammophila arenaria* (Wallén 1980; van der Putten **1989**; Vestergaard & Hansen 1992) have been investigated.

In contrast, few studies have been published on *A. littoralis* and on the sustainability of the management of Mediterranean coastlines, which have ecological conditions which are different from those of the Atlantic shores.

Some environmental restoration experiments on the dune system based on 'soft techniques' have been carried out in the coastal zone of Spain (Sanjaume & Pardo 1992; Gomez-Pina et al. 2002) and the success of the restoration management was emphasized, however the sustainability of this approach within natural dune systems was not tested.

The present study was carried out on the Tyrrhenian coastline of Lazio, along the Roman littoral where, thanks to the protected areas of Castelfusano, Capocotta and Castelporziano, it has been possible to safeguard, at least in part, the inland dune environments. However, the series of mobile dunes facing the high tide mark is virtually absent. Along this coastline the elements of the various plant associations are forced back to the next belt, where they are thus overlapping and compressed along a narrow and not very high dune system.

Restoration activities, mainly concerning dune nourishment by sand addition and marram grass plantations, have been carried out on the dune environments, from 40 to 80 m from the seashore, and their effectiveness and sustainability have been verified by five years of monitoring.

Our aim was to investigate the morphological dynamics of the built up dune systems and the ecology of the species present (germination characteristics and survival of the stabilizing species, rate of expansion of the plant cover, and change in species richness). The main objectives of the study were:
(1) to build up dune belts along the coast, located between the high water mark and the macchia vegetation behind this (consolidated dunes);
(2) to verify the optimal distance from the sea for planting *Ammophila littoralis* on the dunes which had been built up;
(3) to verify the sustainability of the restoration management.

Material and Methods

The study was carried out in the Castelporziano Presidential Estate, an area of considerable naturalistic interest due to its great floristic and faunistic diversity. The integrated management (dune nourishment and transplanted vegetation) was performed for ca. 3 km along the sandy coast, where there are no embryonic or shifting dunes.

In June 1995, 40 dunes were built up, accumulating sand on a base of dry trunks and branches of *Quercus* species occurring in the estate; these dunes were shaped according to the more or less elliptical morphology of the already existing ones. The sand used, of equal grain size, was taken from the sandy area immediately inland in order to avoid the presence of seeds from other vegetation types. The 40 built-up dunes formed three belts located at different distances from the high water mark: 14 at a distance of < 40 m (33 - 40 m) from the sea, 15 at a distance of 40 - 70 m, and 11 at a distance of > 70 m (70 - 86 m).

In January 1996 20 individuals of *Ammophila littoralis,* taken from the neighbouring dunes, were transplanted on each of 38 built-up dunes, and distributed evenly over their surface. In order to compare both the evolution of the morphology and the natural colonization of the plant species in the absence of the stabilizing species, *A. littoralis* was not transplanted on to the last two dunes, at a distance of < 40 m from the sea.

The phenology of the main species of the natural dune system was followed by means of monthly observations, from June 1995 until October 1996, in order to identify their growth and reproductive phases. At the same time the fruits were collected and the seeds at various stages of maturation were isolated. In October 1996 and in February, April and June 1997, germination trials were carried out on the main species present: *Ammophila littoralis, Anthemis maritima, Cyperus capitatus, Cakile maritima, Elymus farctus* and *Pancratium maritimum* – to verify the reproductive capacity of the seeds of each species.

The experiments were carried out in the laboratory under controlled conditions (ISP standard conditions; Hendry & Grime 1993). Seeds were exposed to fluctuating light (PAR = 125 μmol.m^2.s^{-1} over 14 hr) and temperature (15 °C by night; 22 °C by day); relative humidity was maintained at 95%. Seed was considered to have germinated the moment the first rootlet appeared. The minimum duration of the trial was 30 days, while the maximum duration depended on the species examined. The trial ended only when no further germination occurred for a five-day period.

The change in height and area of each dune, the survival of *A. littoralis*, the change in cover, the appearance of new shoots and, lastly, the establishment of new species were monitored after 1 yr, 2 yr and 5 yr since the starting phase. The cover of *A. littoralis* was measured as percentage of the surface covered in a grid-plot with eight subplots of 0.25 m^2 each.

Statistical analysis was also performed, i.e. linear regression analysis and non-linear regression analysis was used to investigate relationships between floristic variables such as number of species, total plant cover, survival, cover, and production of new shoots of *A. littoralis* and the morphological and topographic characteristics of the dunes, such as distance from the sea, dune height and surface.

We performed the *t*-test-PAST software (Ryan et al. 1995) on the data sets.

Table 1. Germination rates and times of appearance of the first rootlet in the various species.

Species	Germination (%)	Time of germination (days)
Ammophila littoralis	20	15
Elymus farctus	80	14
Cyperus capitatus	20	28
Anthemis maritima	50	21
Cakile maritima	30	35
Pancratium maritimum	60	47

Results

Germination rate and time (Table 1) is largely different among the species examined (Table 1). In some species, such as *C. capitatus*, *C. maritima* and *A. littoralis,* germination ranges between 20 and 30%, and takes from two up to five weeks. It reaches 60% in *P. maritimum*, the species that takes longest, almost seven weeks, to germinate. *E. farctus* exhibits the highest germination rate, 80%, but its seeds have the shortest germination time, just two weeks.

The survival rate of individuals of *A. littoralis* (Fig. 1), between January 1996 and February 2001, changes from 96 to 66%, on the dunes closest to the sea; at a distance between 40 and 70 m it decreases fairly slowly during the first year (99%) up to 74%, that is the highest survival rate registered in 2001 and, lastly, on the dunes furthest inland, more than 70 m from the sea, it remains at 100% until June 1997, after which it decreases to 60% in 2001.

The average cover of *A. littoralis* (Figs. 2a, b) also changes in time according to distance from the high water mark: in the first six months, from December 1996 to June 1997, the cover increases, especially on the dunes more than 70 m from the sea where it reaches an increment of 50% (Fig. 2a). However in the next four years the trend changes and in February 2001 the cover tends to be highest, although not significantly, at the intermediate distance (Fig. 2b). Over the latter period the cover tends to decrease slightly (Fig. 2b) on the dunes at a distance of less than 40 m and more markedly on the dunes at more than 70 m ; the cover is quite constant, between 25 and 30%, on the dunes at intermediate distance from the sea (40 m < *d* < 70 m).

Between October 1996 and February 2001 the average number of vegetative shoots for each dune increases progressively (Fig. 3): from 11 to 53 in those nearest to the sea, from 9 to 38 in those located at a greater distance, while the number increases from 10 to 56 in those located at the intermediate distance. The number of new shoots is lowest on the dunes at more than 70m), though not significantly.

During the five years of observation the number of species that colonizes the new dunes (Fig. 4) increases progressively from 7 (June 1996) to 16 (July 2000).

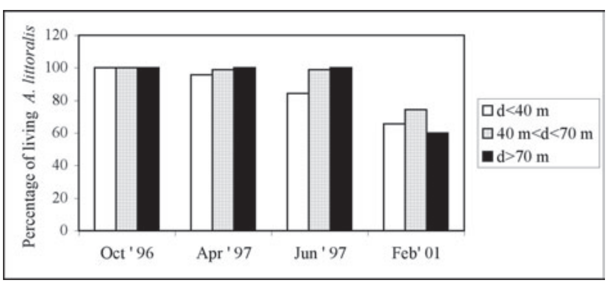
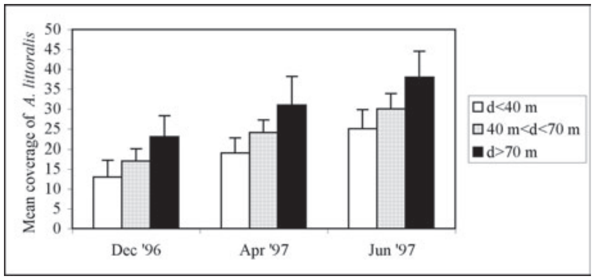


Fig. 1. Survival rate of individuals of *Ammophila littoralis* transplanted in February 1996 at different distances from the sea.



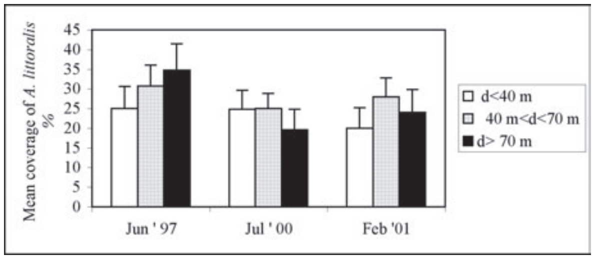


Fig. 2a. Changes in average cover (%) of *Ammophila littoralis* in the first six months after dune building-up, from December 1996 to June 1997. Cover increases. **b.** Changes in average cover (%) of *A. littoralis* in the years following dune building-up until February 2001.

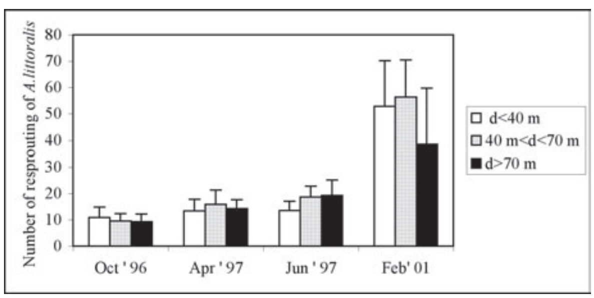


Fig. 3. Average number of shoots of *Ammophila littoralis* on each dune, according to distance from the sea, from October 1996 to February 2001. The number increases progressively.

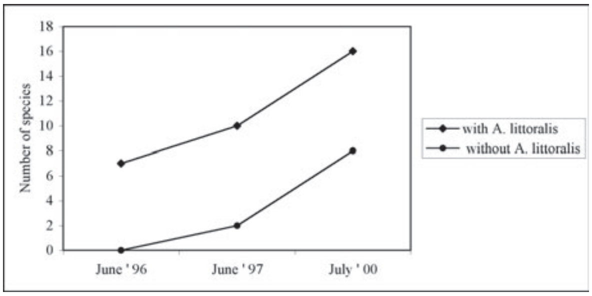


Fig. 4. Changes in species richness in the four years following dune building-up, from June 1996 to July 2000. The number and the progressive increase of the species is greatest on dunes stabilized by *A. littoralis*.

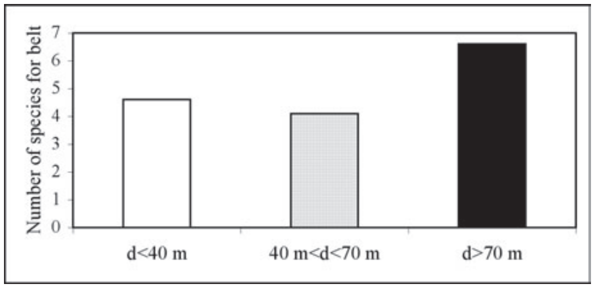


Fig. 5. Average number of species on each dune belt observed in June 2001. The largest number occurs more than 70 m from the sea.

These are autochthonous species, germinated from the seeds occurring in the sand used for building up the dunes (Table 2). The two dunes where *A. littoralis* does not occur show a smaller number of species than the others: two germinated in June 1997: *Cakile maritima* and *Raphanus raphanister* ssp. *landra*, and six in July 2000: *Elymus farctus*, *Anthemis maritima*, *Eryngium maritimum*, *Cyperus capitatus, Sporobolus pungens* and *Crucianella maritima*. In June 2001 the average number of species on each dune belt (Fig. 5) is highest (6.6) at the greatest distance from the sea ($d > 70$ m) and lower in the other dune belts (4.6, $d < 40$ m; 4.2, 40 m $< d <$ 70 m).

At the same time the total plant cover varies between 15 and 60% with an average of 28.6% (data not shown) and is composed mainly of *A. littoralis*.

The average cover and the frequency of the species present in June 2001 are set out in Table 3.

A. littoralis is the dominant species with 25% of the cover; among the species that germinate after planting *Ammophila*, only *Anthemis maritima, Elymus farctus* and *Echynophora spinosa* reach fairly high cover values. The range of the frequency of the species, from 3 to 90%, is very great: there are species present only on a few dunes (*C. maritima, S. kali, S. pungens*), whereas other species are widely represented (*A. maritima, E. farctus, E. maritimum*) .

The morphological characteristics of the dunes, the height and the surface particularly, show a progressive change during time. The height decreases progressively in all the three belts (Fig. 6). In July 2000 the height of the dunes located more than 70 m from the sea is about 60% of the initial one, that of the dunes closest to the sea was 50%, and that of the dunes located between 40 and 70 m from the sea was 49%.

In the two control dunes, i.e. without *A. littoralis*, the height progressively decreases until July 2000 when it reaches 47% of its initial value; the height of the control dunes is very similar to that of the dunes located in the belt < 40 m from the sea.

In the course of time the surface area of the dunes (Fig. 7) tends to increase due to the accumulation of sand at the sides of each dune. The surface area of the dunes at more than 70 m from the sea changes from 25 m^2 to 34 m^2 and, similarly, in the dunes located in the

Table 2. Floristic list of species present in June 1997 and in July 2000 on the 40 dunes studied. The number of species increases from 7 to 16 in four years (see also Fig. 4).

Species	June 1997	July 2000
Anthemis maritima	+	+
Elymus farctus	+	+
Ononis variegata	+	+
Eryngium maritimum	+	+
Cyperus capitatus	+	+
Echinophora spinosa	+	+
Cakile maritima	+	+
Raphanus raphanister ssp. *landra*	+	+
Euphorbia peplis	+	+
Sporobolus pungens	+	+
Calistegia soldanella		+
Xanthium italicum		+
Crucianella maritima		+
Cutandia maritima		+
Salsola kali		+
Teucrium polium		+

Table 3. Mean cover and frequency of species present on the 40 dunes under study in June 2001.

Species	Cov. (%)	Freq. (%)
Ammophila littoralis	24.5	90.2
Anthemis maritima	6.46	68.6
Elymus farctus	3.11	57.1
Eryngium maritimum	0.49	37.1
Ononis variegata	0.34	34.3
Euphorbia peplis	1.74	31.4
Echinophora spinosa	2.26	34.3
Cakile maritima	0.86	28.6
Cyperus capitatus	0.14	14.3
Raphanus raphanister ssp. *landra*	0.31	5.7
Crucianella maritima	0.03	5.7
Calystegia soldanella	0.03	5.7
Xanthium italicum	0.17	5.7
Sporobolus pungens	0.03	2.9
Salsola kali	0.03	2.9
Cutandia maritima	0.03	2.9

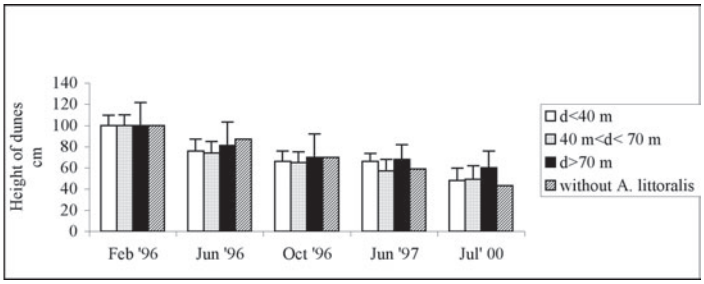


Fig. 6. Changes in average height of the 40 dunes at the different distances from the sea.

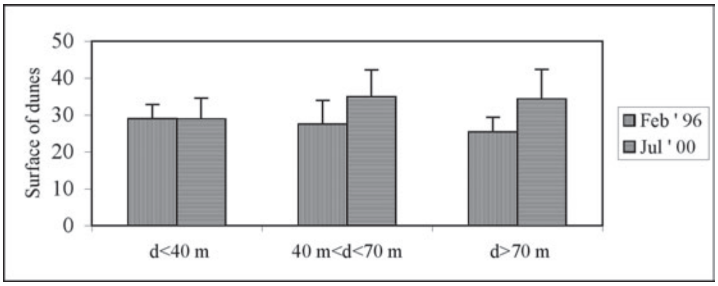


Fig. 7. Changes in dune surface area. The area increases on the innermost dune belt by around 30%.

belt between 40 and 70 m from the sea the area increase from 27 m^2 to 35 m^2, that is, by ca. 30%. However, at a distance of less than 40 m the surface does not change because at this distance the accumulation of sand at the sides is offset by their partial destruction by the tides; consequently the average area remains 29 m^2 the whole time.

The regression between morphological and topographic parameters of the dunes and the structural features of the vegetation (Table 4) is significant ($R^2 = 0.59$; $n = 40$; $p < 0.001$) between the number of species and the height of the dune; the regression between total plant cover and height, and between the number of species and the distance of the dune from the sea has lower R^2 values (0.38) though significant ($n = 40$; $p < 0.001$).

The polynomial regression between the cover of *A. littoralis* and the distance from the sea (Fig. 8) shows that maximum cover occurs between 50 and 70 m from the sea; the relationship explains 73% of the variation in cover ($n = 38$; $p < 0.001$).

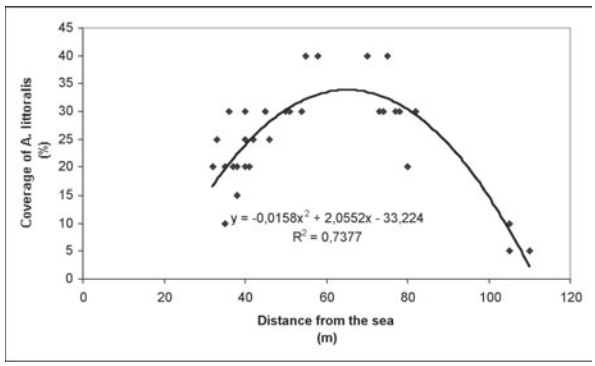


Fig. 8. Polynomial regression between cover of *Ammophila littoralis* and distance from the sea measured in June 2001, 5 years after dune building-up ($p < 0.001$). The resulting hyperbole indicates that the cover is greatest between 50 and 70 m from the sea.

Table 4. Values of the regression coefficient calculated by Linear Regression Analysis between structural parameters of the vegetation and morphological characteristics of the dunes. The regression is highly significant between the total number of species and the height of the dunes ($R^2 = 0.59$; $p < 0.001$).

	Date of sampling	Surface area		Distance from the sea		Height	
		R^2	p	R^2	p	R^2	p
Cover of *Ammophila littoralis* %	June 2001	– 0,09	n.s [1)]	– 0,18	< 0,001 [1)]	0,23	n.s. [1)]
Number of species	July 2000	0,21	< 0,05 [2)]	0,38	< 0,001 [2)]	0,59	< 0,001 [2)]
Total cover	June 2001	0,10	n.s. [2)]	0,22	< 0,001 [2)]	0,39	< 0,001 [2)]
New resproutings of *A. littoralis*	Feb 2001	– 0,02	n.s. [1)]	0,11	< 0,05 [1)]	0,22	< 0,001 [1)]
Mortality of *A. littoralis*	Feb 2001	0,18	< 0,05 [1)]	– 0,34	< 0,001 [1)]	0,24	< 0,001 [1)]

[1)] $n = 38$; [2)] $n = 40$

Discussion

The fast rate of growth through new shoots of transplanted *Ammophila littoralis*, and the increase of cover confirms the role of stabilizing species particularly suitable for restoration management on these environments (Figs. 2a, b, 3). The low reproduction rate using seeds of *A. littoralis* indicates, however, the difficulties of obtaining and finding an adequate number of seedlings due to the low germination rate, although rapid, of the seeds (Table 1), in accordance with the ecology of late successional species (Huiskes 1977; Huiskes & Harper 1979).

It is interesting that the germination rate measured in this study, not more than 20%, is similar to that reported for *A. breviligulata*, a species that plays an important role in stabilizing the dunes located along the shores of Lake Huron in North America (Maun 1985). The species with the highest percentage germination (70%), and also the quickest one (14 days), was *E. farctus*, which confirms the characteristics of pioneer species (Table 1).

In contrast, the trials on the planting and the vegetative reproduction of *A. littoralis* highlight the potential of this methodology for the restoration of sandy coast environments.

It is well known that this species forms a barrier that blocks the transport of wind-blown sand so that, at the base of the aerial shoots and therefore also on the surface of the dune, new sand grains are deposited. By this mechanism, a close link is established between the dune systems and *A. littoralis*: the dune grows by constant deposition of sand grains and at the same time it stimulates the development of new roots and of the soil fauna (van der Putten et al. 1989), which are essential for maintaining the survival and the vigour of this species (Hope-Simpson & Jefferies 1966; Eldred & Maun 1982).

Successful trials have already been carried out with the species *A. arenaria*, for consolidating dune systems in Denmark (van der Meulen et al. 1989; Vestergaard & Hansen 1992) and in The Netherlands (van der Putten **1989**). Sanjaume & Pardo (1992) successfully experimented with *A. littoralis* in dunes restoration on sandy coasts of Spain.

The present study also shows the strong consolidation potential of *A. littoralis* for dune build-up: survival (Fig. 1) of the tufts of *A. littoralis* transplanted can exceed 70% and cover (Fig. 8) reached after 5 yr in the belt between 50 and 70 m from the sea is high (40%), though still lower than on natural dunes (Pignatti et al. 2001).

The belt closest to the sea, in spite of the progressive increase in the number of shoots, showed a decrease of the survival rate of *A. littoralis* (Fig. 1), due above all to the violent coastal storms which have partly destroyed some of these dunes, so that the cover (Fig. 2b) showed small fluctuations only.

If survival, cover and the number of growth shoots are taken into account (Figs. 1, 2a, b, 3, 8), the belt between 40 and 70 m appears the most suitable one to guarantee the effectiveness of restoration techniques such as those performed in this study, since those closest to the sea are damaged by coastal-storms, and those furthest from the sea did not guarantee a favourable habitat as the survival rate and the number of new shoots of *A. littoralis* highlights.

The morphological characteristics of the dunes, shaped by simultaneous erosion and accumulation of grains of sand, become gradually modified: in all three of the belts considered, a reduction is noted in the height as well as an increase in the surface area (Figs. 6, 7). In some cases, the dunes examined actually tend to lose their initial elliptical shape due to the direction of the dominant winds, and they become crescent shaped. On the dunes furthest inland, where the grains of sand carried by the wind are most often deposited, the reduction in height is less marked (Fig. 6).

Colonization by new species is relatively rapid and takes place with species such as *Anthemis maritima*, *Cakile maritima, Elymus farctus* (= *Agropyron junceum), Cyperus capitatus* (= *C. kalii), Ononis variegata* and *Eryngium maritimum,* which play a role – albeit a secondary one – in the deposition of sand (Pignatti 1993). This indicates a progressive development towards populations similar to natural ones. Prevalent among these species are those of the associations *Sporobolo-Elymetum* and *Cakiletum,* whereas the species established subsequently pertain mainly to *Ammophiletum* and *Crucianelletum*. This gradual and directional process is in accordance with the natural dune colonization : the rapid establishment of pioneer species on the embryonic dunes is followed by a slower colonization by the species of the mobile dunes.

In fact, along the shoreline of the Italian peninsula, under natural conditions, there is a succession of various plant associations from the outermost belts, directly subject to the action of the sea, to the more sheltered inner ones (Lucchese & Pignatti 1990; Vagge & Biondi 1999). Starting from the sea, the first community is represented by the *Salsolo kali-Cakiletum maritimae* (Rivas-Martínez et al. 1992), barely inside the high tide mark, followed on the embryonic dunes by the *Sporobolo-Elymetum farcti* (Géhu et al. 1984), on the shifting dunes by the *Echinophoro spinosae-Ammophiletum arundinaceae* (see Géhu et al. 1984), and in the interdunal spaces with accumulation of organic matter by the *Crucianellion maritimae* (Braun-Blanquet 1933). This pioneer vegetation is followed on the consolidated dunes by pioneer macchia with junipers: *Asparago acutifolii-Juniperetum macrocarpae* (Bolós 1962; *typus* Géhu et al. 1990).

The colonization process presently in progress at the study site is shown by the establishment of a progressively larger number of species, up to the present number (16) on the dunes where individuals of *A. littoralis* have been transplanted (Figs. 4, 5). It is also of importance that the number of species increases with increasing height of the dunes (Table 4) from 20 to 150 cm; possibly this increase causes the development of a microclimatic gradient and the existence of more niches. The dunes where the number of species is highest are those furthest from the sea, more than 70 m (Fig. 5), probably due to seeds incoming from the dune belt behind.

However, the cover of *E. farctus*, greater than that of other species, and on average greater than in the natural dunes further back (Pignatti et al. 2001), indicates an as yet relatively early phase of the succession. In comparison with the natural dunes of Castelporziano, where ca. 26 species have been observed (Anzalone et al. 1990; Pignatti et al. 2001), the colonization that has so far occurred amounts to some 60% of the species that characterize these environments. Still lacking, compared with the natural dunes behind them, are the following species: *Pancratium maritimum, Pseudorlaya pumila*, *Daucus carota* ssp. *maritimus, Medicago marina, Lotus cytisoides* and, on the dunes furthest from the sea, *Silene colorata, Vulpia membranacea, Juniperus oxycedrus, Senecio leucanthemifolius* and *Sagina maritima*. These are species linked with a certain degree of soil evolution and typical of stabilized dunes and of inter-dune spaces with accumulations of organic matter. In the two dunes without any *A. littoralis*, instead, the colonizing process (Fig. 4) by new species is much slower; at present it is equal to 30%, demonstrating that the presence of *A. littoralis* favours the settlement of new species.

It is noteworthy that no increase in dune height can yet be observed, five years after the transplantation, probably because the cover reached by *A. littoralis* is still inadequate, even though relatively extensive.

Cakile maritima and *Elymus farctus* often occur in the built-up dunes closest to the sea, while in those situated furthest inland *Anthemis maritima*, *Eryngium maritimum* and *Ononis variegata* become established. In particular plant species referred to the *Sporobolus-Elymetum farcti*, which precedes the *Ammophiletum* in the series of mobile dunes, have mainly become established in the tongues of dune decay or in the spaces left free by the death of individuals of *A. littoralis* planted, and even between the dunes. This leads to a gradual modification in the structure of the built-up dunes which, at times, tends to merge with the natural dunes or to assume an aspect similar to them.

In conclusion, although at the present stage the building-up dune system is still too young to show evident effects on shoreline erosion, the data seem to indicate the effectiveness of the 'soft techniques' applied for the environmental restoration of this stretch of the Tyrrhenian sea coast, and offer a measure of the sustainability of these experimental activities within natural dune systems. The results also emphasize both the vitality of the rhizomes and the enormous potential of vegetative reproduction of *A. littoralis*. In general, for measures of this type, it seems in any case necessary to create a seed bank of the local autochthonous species and to set up a nursery *in situ* in order to guarantee the availability of seedlings and to minimize the negative effects of the method of collecting rhizomes in the field.

Acknowledgements. This work received financial support of the National Academy of Sciences within the 'Environmental Survey' carried out in the Presidential Estate of Castelporziano (Roma, Italy). We also thank Prof. S. Pignatti for valuable comments.

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Received 15 December 2003;
Revision received 5 April 2004;
Accepted 8 April 2004.
Coordinating Editor: W. Ritchie.