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EVALUATION OF A TECHNICAL REVEGETATION ACTION PERFORMED ON FOREDUNES AT DEVESA DE LA ALBUFERA, VALENCIA, SPAIN

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ABSTRACT

We have evaluated the level of restoration achieved by a technical revegetation action carried out on reconstructed foredunes at the Devesa de la Albufera and compared this level with that achieved by spontaneous succession. Foredunes 1, 3, 6 and 20 y old since revegetated (1, 3, 6 and 20 y, respectively) were considered as spatially separated stages representing a successional trend in the development of the restored plant community. Lower and similar levels of diversity (richness and $\acute{H}$ and Pieloús indexes) and coverage, respectively, were found on dunes corresponding to the oldest stage of technical revegetation compared with that of the reference site. Diversity and coverage parameters increased during the first 6 y of the technical succession and decreased after 20 y of revegetation. Moreover, that increase was quite obvious as early as 3 y after the onset of revegetation. Results also showed that the Devesa de la Albufera has its own capacity for revegetation. According to the Jaccard and Sørensen indexes, these dunes were more similar to the reference than those from the 20 y old site. Beyond the current functionality of the revegetated sites, it is concluded that the natural and aesthetic values may be restored at the Valencian Devesa de la Albufera. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: Spontaneous succession; technical revegetation; foredune; diversity; coverage; Devesa de la Albufera; *Ammophila arenaria*; *Lotus creticus*; *Cyperus capitatus*; *Elymus farctus*; *Malcolmia littorea*; Spain

INTRODUCTION

Massive urban and tourist development during 1960–1970, totally altered and destroyed extensive dune areas in Spain (Gómez-Pina *et al*., 2002). The Valencian Devesa de la Albufera, held important dunes until 1970, when they were damaged by infrastructure and urban projects. These human activities destroyed the ecological equilibrium of the entire system (Sanjaume and Pardo, 1992).

Coastal dunes fulfil a primordial role in the protection and preservation of this ecosystem, by means of breaking severe Mediterranean winds. A restoration programme financed by the City Council of Valencia and the European Union allowed the geomorphological reconstruction of the area. Revegetation actions were carried out on reconstructed dunes as the last step of the restoration programme. The goals of these actions were to regenerate a stable plant community with a species composition comparable to those existing at undisturbed dunes, and to recover the natural landscape of the area.

Three approaches to revegetate a disturbed site have been recognized (Prach and Hobbs, 2008): (1) spontaneous succession; (2) technical measures and (3) spontaneous succession manipulation (a combination of the previous two alternatives). If any of the last two approaches is chosen, one way to recover species composition and structure in an ecosystem is the species introduction to the degraded site (e.g. Holl, 2002; Martínez-Garza and Howe, 2003).

Coastal sand dunes are often under environmental stress due to deficient water, nutrient supplies and to the effect of abrasive winds. On the other hand, vascular plants are decisive for dune stabilization as long as they are adapted to the local site condition (Kovář, 2004). Therefore, their selection becomes of vital significance for the revegetation of existing dunes. If the target of the restoration project is natural vegetation, then indigenous species should be used (Ford and Langkamp, 1987; Cobby, 1988; Avis, 1989).

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When the present work was undertaken, the Devesa counted with dunes 1, 3, 6 and 20 y of revegetation, which may be considered as spatially separated stages representing a successional trend in the development of the restored plant community (van Aarde *et al*., 1996; Zhang *et al*., 2005).

This study was aimed at: (1) assessing the level of restoration achieved by the revegetation action carried out on reconstructed dunes at the Devesa de la Albufera, evaluating at the same time, the occurrence of an aging-associated succession in the revegetated dunes and (2) comparing dunes revegetated by the technical method with those subjected to a spontaneous (or natural) succession.

The criterion to measure restoration achievement was the degree of approximation of plant structure in revegetated dunes to that of the undisturbed dunes in terms of diversity and vegetation structure (Ruiz-Jaen and Aide, 2005).

MATERIALS AND METHODS

Site and Restoration Programme Description

The Devesa de El Saler, located 20 km south from Valencia (Latitude 39° 20'41''N; Longitude 00° 19'12''W) is part of a narrow strip (30 × 1–1·5 km) beach barrier running from the Túria River in the north to the cliff of Cape Cullera in the south and separates the Valencia lagoon from the sea (Figure 1). The region is elevated 2·7 m above sea-level, presents a mediterranean subarid climate with a 17·1°C annual mean air temperature, 440–450 mm annual precipitation and calcareous arenosoil type (Sanchis *et al*., 1986; Requena and Rovira Forcada, 1991).

Before human disturbance, there were two dunar ridges separated by a longitudinal depression (Figure 2a), a 4–5 m dune running close to the sea, bearing wind and water tolerant herbaceous species that protected a shorter inner **dunar** ridge proximal to the Albufera. Between the two ridges there was a longitudinal depression (called **mallada**), close to the phreatic ground water, a salt marsh presenting different juncaceous and salt-tolerant plant species.

The human alteration of this Devesa, occurred during 1960, consisted of the subtraction of the sand from the dune and its substitution by concrete-made parking for cars, streets and urban buildings (Figures 2b, 4a). In turn, the removed sand was used to cover the **mallada** in order to avoid mosquito proliferation. Two decades later, the morphology of the Devesa dune was reconstructed by mechanical sand accumulation and stabilization of the material using palisade construction. As a first step, every urban construction was demolished, material debris cleaned and the original sand (which had been used to cover the salt marsh) was returned to its original place in order to regenerate the dune ridge. These newly formed dunes presented in general a 20 m width base, and run parallel to the coast with average 5 m height. Special care was taken by the truck drivers in order to avoid damaging the **mallada** soil. Once the dune was regenerated, the technical revegetation proceeded.

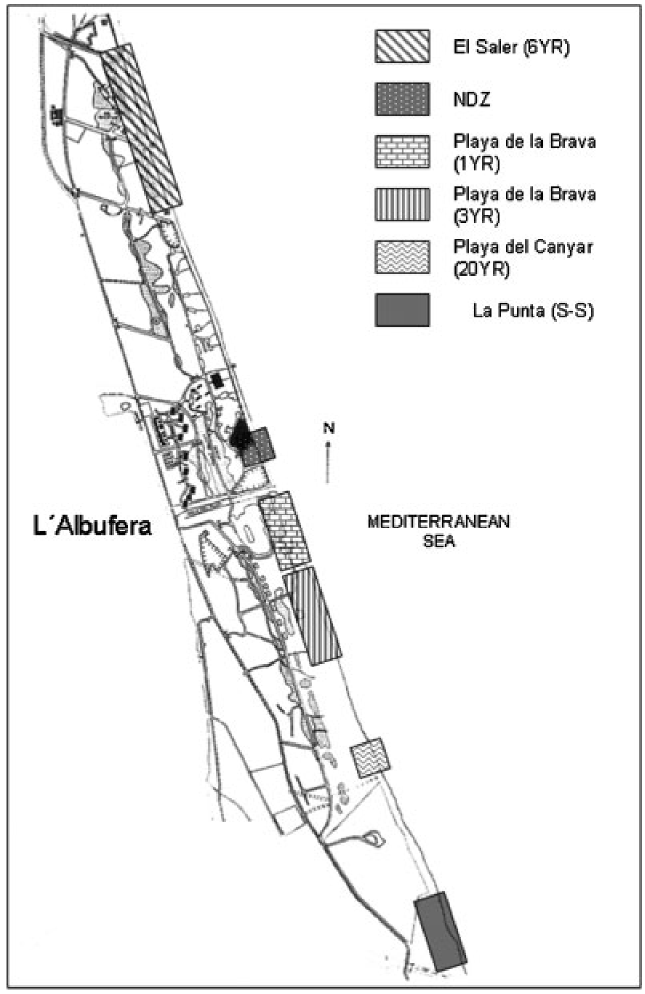

Figure 1. Map of the la Albufera de la Devesa indicating the locations of undisturbed (NDZ), spontaneous succession (S-S) and 1, 3, 6 and 20 y of technical revegetation sites.

Technical Revegetation

Plant material was provided by the technical office of the Devesa de la Albufera, where a plant-breeding programme is supported by the Valencia County government. Only autochthonous psammophytic species were used, based on a previous analysis of the existing vegetation in the best preserved dunes of the Devesa (Costa and Mansanet, 1981). Modules of plant repopulation were designed and established for a 25 m^2 surface, which reproduced as faithfully as possible the composition and structure of the undisturbed plant community (see Table II). Seeds, rhyzomes, bulbs or roots (according with the species) were distributed randomly in each plot.

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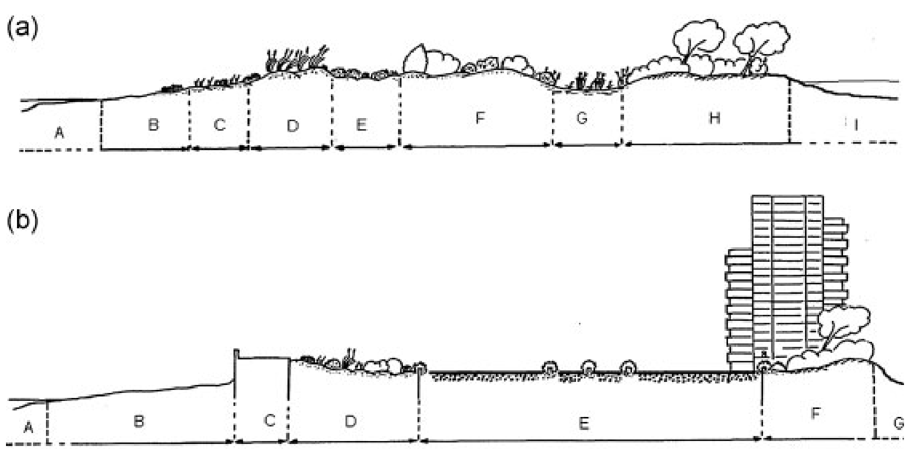

Figure 2. Transversal section of the different ecosystems present at the Devesa de El Saler. Modified from Costa and Mansanet (1981). (a) Before human disturbance: (A) mediterranean sea; (B–F) costal foredune (pioneer, mobile, semi fixed and stabilized dunes); (G) longitudinal depression; (H) old stabilized dunes; (I) Albufera edge. (b) After urbanization: (A) Mediterranean sea; (B) beach; (C) promenade; (D) rest of dunes; (E) roads and parking; (F) old dunes with constructions; (G) Albufera edge.

Sampling Sites

Sites representing four different chronosequence stages of the dune revegetation were available (Figure 1): (1) 1 y revegetated dunes (1 y) located in the Playa de la Brava and northern Malladeta, (2) 3 y revegetated dunes (3 y) in the same area as the former ones, (3) 6 y revegetated dunes (6 y) located at the Playa de El Saler and (4) 20 y revegetated dunes (20 y) located at the Playa del Canyar. These sites are assumed to develop along similar pathways over time (Twigg *et al*., 1989). In all cases, revegetated areas were temporary closed to avoid the interference of human trampling. In addition, we studied a reference site with undisturbed dunes (NDZ) at the Playa de Els Ferros-Garrofera, an area neighbouring the Gola del Pujol dunes (Figures 1 and 2) and dunes exposed to a natural successional revegetation process since 2000 (S-S), located at La Punta (southern limit of the Devesa de El Saler, Figure 1). Mechanical and chemical soil characteristics are shown in Table I.

Data Gathering and Analysis

Six plots were studied at each site from September to November 2008. A 10 m length transect was established randomly at each plot (Canfield, 1941). Taxonomical identification was performed for plants present at each of the 100 points distributed at 10 cm intervals along the transect. With the data, we calculated the coverage percentage (ratio between the number of points where a particular species is found to the total number of points). Moreover, we recorded the number of individuals per species along the transect and calculated dominance for each species as the ratio between the number of individual plants of a particular species to the total number of individuals. In addition, we calculated:

Shannon–Wiener diversity index (Krebs, 1985):

$$H' = -\sum_{i=1}^{s} p_i \log10 p_i$$

Table I. Mechanical and chemical analysis of first dune soils at Devesa de El Saler (extracted from Sanchis *et al*., 1986)

	Soil depth	
	0–15 cm	15–40 cm
Mechanical Analysis		
Sand (2–0·2 mm) %	67·5	64·5
Fine sand (0·2–0·02 mm) %	33·5	35·7
Silt (0·02–0·002 mm) %	0	0
Clay (<0·002 mm) %	0	0
Soil texture	Sandy	Sandy
Real density a 20°C (g cc^{-1})	2·35	2·38
Apparent density a 20°C (g cc^{-1})	1·45	1·58
Porosity %	38·2	33·6
Moisture retention %	7	5·5
Chemical Analysis		
pH, saturated paste extract with water	8·6	8·49
pH, saturated paste extract with CIK	8·53	8·34
Organic matter %	0·125	0·1
Total nitrogen %	0·007	0·005
C/N Ratio	10·4	11·6
Total carbonates %	25·53	27·18
Extractable nitrogen (NO_3^-), ppm	9·7	6·4
Extractable phosphorous (P_2O_5), ppm	7·5	6·2
Cation exchange capacity, meq 100-1	4·37	5·31
Soluble exchange calcium, meq 100-1	3·28	4·24
Soluble exchange magnesium, meq 100-1	0·63	0·52
Soluble exchange potassium, meq 100-1	0·2	0·31
Soluble exchange sodium, meq 100-1	0·31	0·38
Conductivity, saturated, mmohs cm^{-1} to 25°C	0·38	0·41

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Table II. Percentage of plant species dominance at dunes exposed to technical (1–20 y) and spontaneous revegetation (S-S), and at undisturbed dunes. Technically introduced plant species are presented separately from those grown spontaneously

	Dominance (%)					
	1 y	3 y	6 y	20 y	NDZ	S-S
Planted species						
Ammophila arenaria	5·0	0·7	10·6	—	0·9	2·0
Calystegia soldanella	1·0	5·5	2·5	5·9	—	—
Crucianella maritima	—	1·3	—	—	—	—
Cyperus capitatus	9·0	9·6	27·5	17·2	10·5	36·0
Echinospora spinosa	—	—	—	—	3·9	2·0
Elymus farctus	4·0	30·9	14·8	10·1	33·0	24·0
Eryngium maritimum	—	—	1·4	—	1·0	2·0
Euphorbia paralias	—	0·7	0·4	—	—	—
Lotus creticus	24·0	32·0	24·6	44·1	19·5	16·0
Malcolmia littorea	11·0	11·0	5·6	1·8	17·6	6·0
Medicago marina	—	—	2·4	0·8	0·5	—
Otanthus maritimus	—	0·9	0·8	19·8	4·6	—
Pancreatium maritimum	—	—	1·2	0·3	0·5	—
Sporobolus pungens	8·0	3·1	6·7	—	2·7	—
Subtotal	*62·0*	*95·7*	*98·5*	*100·0*	*94·7*	*88·0*
Non-planted species						
Cakile maritima	3·0		—	—	0·9	8·0
Carpobrutus acinaciformis	—	—	0·9	—	—	4·0
Cynodon dactylon	6·5	—	—	—	—	—
Erodium malacoides	—	—	—	—	2·0	—
Helichrysum stoechas	2·0	—	—	—	—	—
Salsola kali	15·0	4·1	0·5	—	2·2	1·0
Xanthium italicum	3·5	—	—	—	0·5	—
Teucrium belion	4·0	—	—	—	—	—
Lanuaea resedifolia	3·0	—	—	—	—	—
Unidentified species	1·5	—	—	—	—	—
subtotal	37·0	4·1	1·4	0·0	5·6	13·0
Species richness	15·0	11·0	14·0	8·0	15·0	10·0

where S is the number of species and p_i is the proportion of individuals belonging to the ith species, the Pieloús evenness index (Pielou, 1969):

$$E = \frac{H'}{H'_{\max}}$$

$$H_{\max} = \ln S$$

The following quantitative and qualitative similarity indexes were calculated in order to compare the outcome of technical and spontaneous succession processes with respect to the reference situation:

Czekanowski (Bray and Curtis, 1957)

$$\text{Czekanowski index} = \sum_{i=1}^{S} \mathrm{mi}'n\,(p_{i1}, p_{i2})$$

Jaccard similarity index (Krebs, 1989)

$$CC_j = \frac{c}{s_1 + s_2 - c}$$

where s_1 and s_2 are the number of species in sites 1 and 2 and c is the number of plant species shared by the two communities and the Sørensen's similarity index (Sørensen, 1948)

$$\beta = \frac{2c}{S_1 + S_2}$$

where S_1 is the total number of species recorded in the first community, S_2 is the total number of species recorded in the second community and c is the number of species common to both communities. The Sørensen index measures β diversity and ranges from 0, where there is no species overlap between the communities, to 1 when exactly the same species are found in both communities.

The following turnover indexes (percentage of similarity between successive time periods, a common approach to

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measure the number of species eliminated and replaced per unit of time) were also estimated:

Whittaker's β richness (Whittaker, 1960)

$$\beta_{\mathrm{W}} = \frac{S}{\alpha} - 1$$

where S is the total number of species recorded in both communities and α is the average number of species found within the communities.

Cody (1975)

$$B_{\mathrm{c}} = \frac{g(H) + l(H)}{2}$$

where $g(H)$ is the number of species gained and $l(H)$ is the number of species lost in the transect.

Statistical Analyses

Data obtained from the different sites was subjected to analysis of variance and means compared by Duncan's test (Duncan, 1955).

RESULTS

Technically introduced species represented the greater part of plant records at the different successional stages (Tables II and III). At the 20 y site, 8 out of the originally 14 planted species were recorded. This plant species amount was in turn lower than those recorded at the NDZ and S-S sites (Table II). At 20 y and S-S dunes, the average species richness was lower than that found at the reference site ($p < 0{\cdot}05$; Figure 3). On the other hand, the averaged species richness per site varied along the chronosequence, being highest at the intermediate stages and lowest at the initial and final successional stages. Eight non-planted species were found at the 1 y site, which were in most cases absent at the remaining technically revegetated sites.

Shannon–Wiener ($\acute{H}$) diversity and Pielou's evenness indexes were minimal at the first year of technical revegetation and then they increased showing similar levels thereafter. At the 20 y site, these indexes were lower than those from the reference site (Figures 3a and 3b), which in turn were higher than those from the S-S one.

Table III. Percentage of plant species coverage at dunes exposed to technical (1–20 y) and spontaneous revegetation (S-S), and at undisturbed dunes. Technically introduced plant species are presented separately from those grown spontaneously

	Coverage (%)					
	1 y	3 y	6 y	20 y	NDZ	S-S
Planted species						
Ammophila arenaria	1·3	1·3	25·0	—	0·8	1
Calystegia soldanella	0·1	1·5	1·7	2·8	—	—
Crucianella maritima	—	2·0	—	—	—	—
Cyperus capitatus	1·6	6·2	12·2	10·3	4·5	19
Echinospora spinosa	—	—	—	—	2·5	5
Elymus farctus	0·7	18·8	11·2	7·3	18·0	19
Eryngium maritimum	—	—	1·5	—	1·0	1
Euphorbia paralias		3·3	—	—	—	—
Lotus creticus	5·9	23·5	16·8	29·3	12·0	11
Malcolmia littorea	5·2	14·8	2·3	1·0	13·3	5
Medicago marina	—	—	2·0	0·5	1·0	—
Otanthus maritimus	—	0·8	2·0	24·0	3·7	—
Pancreatium maritimum	—	—	—	0·2	0·2	—
Sporobolus pungens	1·5	2·0	3·3	—	—	—
subtotal	*16·3*	*74·3*	*78·0*	*75·5*	*57·0*	*59·9*
Non-planted species						
Cakile maritima	2·4		—	—	0·3	3
Carpobrutus acinaciformis	—	—	5·3	—	—	8
Cynodon dactylon	1·3	—	—	—	—	—
Erodium malacoides	—	—	—	—	1·2	—
Helichrysum stoechas	0·6	—	—	—	—	—
Salsola kali	9·8	7·5	0·8	—	3·0	1
Xanthium italicum	2·4	—	—	—	0·2	—
Teucrium belion	0·4	—	—	—	—	—
Lanuaea resedifolia	2·3	—	—	—	—	—
Unidentified species	0·1	—	—	—	—	—
subtotal	*16·9*	*7·5*	*6·1*	*0·0*	*4·6*	*11·8*

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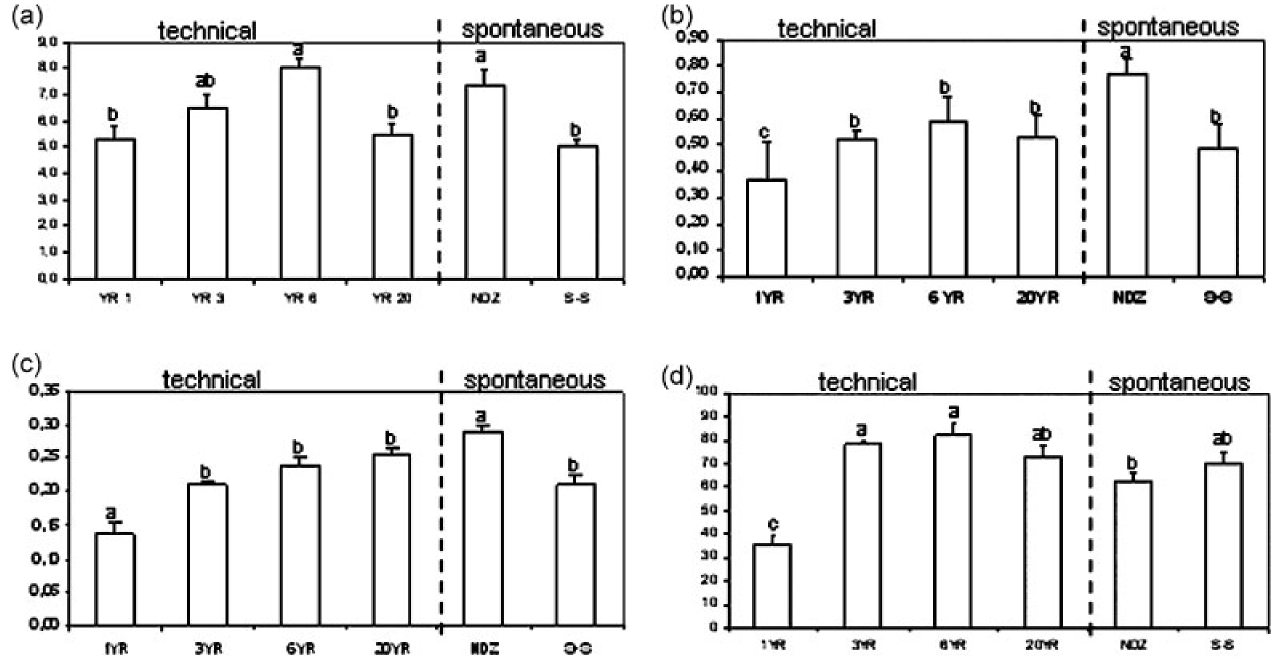

Figure 3. (a) Averaged plant species richness, (b) averaged Shannon–Wiener ($\acute{H}$), (c) Pieloús indexes and (d) averaged total coverage at 1, 3, 6 and 20 y of technical revegetation sites (y) and at undisturbed (NDZ) and spontaneous succession (S-S) foredunes of the Devesa de la Albufera. Bars ($\pm$ SE) with the same letter are not statistically different at $p < 0{\cdot}05$.

Planted species showed temporal cover and dominance variation along the chronosequence (Tables II and III). *Ammophila arenaria* displayed increasing values of vegetation recovery along the chronosequence up to the 6 y, where it showed a 25 per cent of coverage and was absent at the 20 y site. *Crucianella maritima*, *Eryngium maritimum, Euphorbia paralias* and *Sporobolus pungen*s also accounted among plant species that were absent at the end of the technical succession and *Echinospora spinosa* could not be found even at the 1 y dunes.

The dominance and coverage of *Malcolmia littorea* decreased from the 1 y to the 20 y dunes, where it was barely found, whereas it was among the most dominant species at the reference site. In contrast, the dominances and coverage of *Calystegia soldanella*, *Lotus creticus, Otanthus maritimus*, *Elymus farctus* and *Cyperus capitatus* showed significant increase after 20 y of revegetation. *L. creticus* presented the highest dominance at the initial and oldest stages of the revegetation chronosequence (24 and 44 per cent, respectively). At the 20 y revegetated site, this species covered almost 30 per cent of dunes, followed by *O. maritimus* with almost 25 per cent of coverage.

At the reference site, species showing the highest dominance and coverage percentage were *E. farctus*, followed by *L. creticus* and *M. littorea*. These species accounted for more than 50 per cent of plant coverage. At the S-S site, *C. capitatus* ranked first in dominance, followed by *E. farctus*. At these dunes, *L. creticus* reached its lowest dominance in the whole area of the Devesa. The remaining species presented dominances and coverages below 10 per cent.

According to the Czekanowski, Jaccard and Sorensen indexes, a higher similarity was found between the S-S and NDZ sites than between the last and the 20 y one (Table IV). Regarding species turnover, both Whittaker's and Cody indexes consistently indicated that the highest species turnover was observed between the first and the third year of dune revegetation and then the turnover diminished with age (Table IV).

The total plant coverage increased between 1 and 3 y sites showing similar levels thereafter (Figure 3d). In turn, coverage values at the oldest stage of the technical succession and at S-S were similar to that of the NDZ site.

DISCUSSION

Most studies on restoration assessment are based on the resemblance of the revegetated area to that of neighbouring undisturbed areas (Hobbs and Norton, 1996; van Aarde *et al*., 1996; Webb *et al*., 2001; Ruiz-Jaen and Aide, 2005). Such resemblance can be measured through parameters, which can be grouped in three major ecosystem attributes: (1) diversity; (2) vegetation structure and (3) ecological processes (Ruiz-Jaen and Aide, 2005). The first two attributes were considered in the present work. Diversity was measured by determining richness and the $\acute{H}$ and

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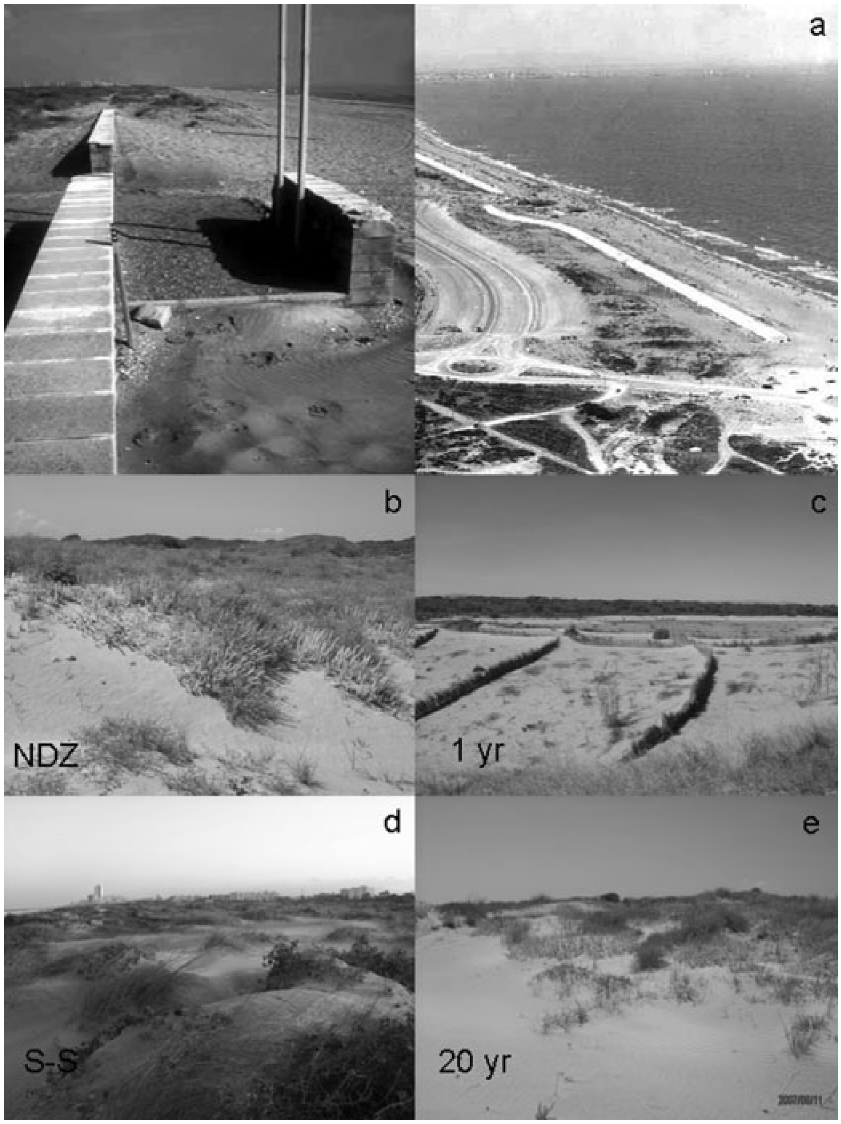

Figure 4. (a) Human alteration of the Devesa de la Albufera: sand from the foredune was removed and concrete-made parking for cars and urban buildings raised, (b) undisturbed dunes (NDZ) at the Playa de Els Ferros-Garrofera, (c) 1 y (1 y) revegetated dune located in the Playa de la Brava, (d) dunes exposed to a natural successional revegetation process since 1989 (S-S) at La Punta and (e) 20 y revegetated dunes (20 y) located at the Playa del Canyar.

Pieloús indexes, whereas species dominance and coverage were indicative of vegetation structure.

Our first objective was to evaluate the level of restoration achieved by a 20 y-old revegetation programme performed on reconstructed dunes at the Devesa de la Albufera. Obtained results revealed that plant community from the oldest site of the technical revegetation programme reached a partial resemblance with the reference site, since both sites differed in diversity but were similar in plant structure. Our results showed that diversity, coverage and the total and averaged species richness per site increased during the first 6 y of the technical succession. Moreover, that increase was quite obvious as early as 3 y after the onset of revegetation in most of these parameters. This fact is important as fast revegetation of a site is desirable either to decrease the threat of erosion or to increase its productivity or aesthetic value (Luken, 1990; Perrow and Davy, 2002), which is reinforced by the fact that *A. arenaria*, a species which is sensitive to the degree of dune fixation (Webb *et al*., 2001; Rozé and Lemauviel, 2004) is no longer found at the final stage.

The Whitakker and Cody turnover indexes decreased during succession to a minimum between the 6–20 y sites, probably due to the invasion during the first year of plants non-included in the revegetation modules, and their further local extinction at the 3 y site. On the one hand, this fact suggests that planted species could have somehow hampered

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Table IV. Similarity indexes with respect to the reference site and patterns of plant species diversity in technical and spontaneous succession sites

Site	Succession age (y) of technical method				Spontaneous succession
	1 y	3 y	6 y	20 y	
Similar index with respect to the undisturbed zone					
Czekanowski index				0·22	0·29
Jaccard index				0·44	0·56
Sorensen index				0·61	0·72
β-diversity between successive communities in the process of succession					
Technical succession interval		1–3 y	3–6 y	6–20 y	
Whittaker's index/elapsed years		1·19	0·77	0·14	
Cody index/elapsed years		1·67	1·00	0·14	

the attainment of higher species richness and reminds the relevance of counting beforehand with information related with the life story attributes of plant species to be introduced (Walker *et al*., 2007). On the other hand, this result, in addition to the similar coverage level observed among the 3–20 y and NDZ sites suggests that after 6 y the technical succession probably has reached a plateau. If this is the case, a higher resemblance with respect to the undisturbed site should not be expected in a further monitoring of this restoration action.

Dunes under a spontaneous revegetation process during similar time period also succeeded in establishing a natural plant community, demonstrating that the Devesa de la Albufera has its own capacity for revegetation. According to the Jaccard and Sørensen indexes, these dunes were more similar to the reference than those from the 20 y site. In addition, the total number of plant species in S-S dunes was slightly higher than that of the 20 y site, and there were no differences between both sites in terms of species richness per site, diversity and coverage. Our second aim was to compare technical and natural methods regarding their level of success for achieving dune revegetation. On the basis of the ecosystem attributes considered in this work (diversity and vegetation structure), both methods reached a similar degree of resemblance compared with the undisturbed condition. Another criterion to determine the convenience of using either of the two alternatives is the revegetation cost/surface/year. In this regard, it could be said that spontaneous succession was a better tool than technical revegetation for restoring dunes at the Devesa due to its inexpensiveness. An additional aspect to be considered is whether the established plant species favoured the development of a higher diversity. From the plant diversity view point, the natural revegetation process was more advantageous than the assisted one, since it allowed a slightly higher species richness. However, whereas *C. capitatus*, the dominant species at the S-S dunes is non-mycorrhizal (Allen and Allen, 1992) and considered an opportunistic species (Choi and Pavlovic, 1998), *L. creticus*, a N_2-fixing species, dominated at the 20 y site and it was intensively mycorrhized (own unpublished results). The fact that the most dominant species at the 20 y site was mycorrhizal and fixes N_2 suggest that this species could play an important role in the establishment of further species by improving soil structure and providing symbionts inoculum for later stages of vegetation. Thus, being pedogenesis a key factor in nutrient recycling and establishment of flora and fauna, a more valuable result with technical than with spontaneous revegetation in the long term is expected.

Finally, visual comparison of dune landscapes previous to the onset of the restoration and the revegetation projects (Figure 4a), with those resulting from the technical and natural succession (Figure 4c–e) allowed us to conclude that beyond the current functionality of the revegetated sites, the natural and aesthetic values may be restored at the Valencian Devesa de la Albufera.

Further studies are needed in order to assess ecological process attributes of the revegetation programme, measuring functional variables such as sustainability, productivity, nutrient retention and biotic interactions in these revegetated dunes would contribute with a more robust decision on the level of achieved restoration and should be addressed in future research (Ewel, 1990).

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