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Chapter 3
Conditions for Growth of Plants

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Abstract This chapter sets out the approach and research methods used to assess the plant types and species that grow in different parts of the targeted Mediterranean landscape and that could potentially be used in restoration strategies and mitigation of desertified and degraded land. Species occurring in the various land units in the study catchment in southeast Spain are identified. These units are reforested land, rainfed croplands, semi-natural and abandoned land and stream channels, Factors restricting growth of trees and understorey vegetation in reforested land were assessed using experimental plots and the effects of pine litter on seed germination were tested. The potential for growth of cover crops between orchard trees was assessed from hydrological balances. Using multivariate statistical analysis various factors were found to influence the regrowth of vegetation in abandoned agricultural

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lands. In the ephemeral stream channels a wide range of variables was analyzed and presence of species found to be clearly related to substrate and hydrological zone. The results on differential conditions necessary for or favouring growth of various species are used in subsequent design of optimal spatial strategies of planting and restoration.

Keywords Reforestation conditions • Pine litter • Cover crops • Abandoned land • Ephemeral channels • Species zonation

3.1 Introduction

The basic approach has been to assess what plant species grow in the different parts of the target environment then to select those species in each land unit which, because of their life-traits, have characteristics that may be used as mitigation measures against erosion and desertification. In order to be able to use these plants it is necessary that measurements are taken in the field of the conditions under which those plants are growing successfully, the conditions where growth is marginal and the conditions where the plants are not growing. On the other hand, the Cárcavo catchment can be considered itself an experiment of massive reforestation in semiarid conditions intended to: (i) reduce erosion; (ii) improve soil quality; and (iii) accelerate vegetation recovery from a degraded state. The effects of this management strategy on the conditions for growth of plants may be tested. The effects of particular plant characteristics e.g. rooting properties, and of vegetation characteristics e.g. density, pattern, on processes have also been assessed and measured, some by experimentation. Measurements and experiments have also been made on the strength and resistance of the plants to water and flow erosion, including measurements of root strength as well as resistance of aerial parts. The conditions for the growth of plants and those most likely to grow in hotspots and positions that reduce connectivity are described in this chapter. The effectiveness of the plants is assessed in Chap. 4.

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3.2 Types of Plants in Mediterranean Environment and Land Units

Vegetation present in the two main study catchments in Southeast Spain (Torrealvilla and Cárcavo) and also two catchments in Tuscany, Italy (Landola and Scalonca) has been identified. Research focused on vegetation within the main study area of Southeast Spain (Cárcavo). Detailed reviews of the literature were undertaken to compile the existing information available on conditions, requirements and threshold tolerances for each of the plant species identified (Hooke 2007b). Research focused on the following five different plant functional groups: grasses, herbs, reeds, shrubs and trees. An overview of those plants that are present in each of the major land units used in this study is provided below.

The classification of the life form of the species following Raunkiaer's biotypes, [TER, GEO, HEM, CAM, NAN, FAN, LIA] which uses the vegetative form of a plant based on the position of growth point (buds) during adverse times of the year, has been applied in some cases. TER: Therophytes, annuals, survive in form of seeds; GEO: Geophytes, underground buds (usually bulbous, rhizomatous, etc.); HEM: Hemicryptophytes, buds at soil surface level; CAM: Chamaephytes, buds near ground level (buds < 25 cm high); NAN: Nanophanerophytes, buds near ground level (buds 25–75 cm high); FAN: Phanerophytes, trees and large shrubs; LIA: Lianes, plants growing leant against other plants.

3.2.1 Reforested Lands

Cárcavo catchment is a typical example of an eco-hydrological restoration project carried out in Mediterranean lands in the 1950s–1980s decades. The project goal was simultaneously controlling torrential flows by the construction of checkdams on main channels and their tributaries and afforesting/reforesting hillslopes. This is very similar to the projects carried out from the end of the nineteenth century with the major difference of using massive mechanization of reforestation works mainly by terracing in order to supposedly increase water yield to the planted trees (Querejeta et al. 2001). In Cárcavo catchment 25–30 years after the reforestation works the vegetation characteristics changed from a grassland dominated by the alfa grass (*Stipa tenacissima*) to a cover dominated by the planted Aleppo pine (*Pinus halepensis*) works, with alfa grass as subdominant (Table 3.1 vs. Table 3.2). Despite the increase of vegetation and therefore the soil organic carbon concentration, in the case of Cárcavo catchment, the reforestation strategies (especially those on terraces) have not preserved soil from organic carbon losses by active soil erosion processes, due to often high sedimentological connectivity between reforested terraces and channels (Boix-Fayos et al. in press).

Castillo et al. (2001) studied the development, success and effects of the afforestation programmes on the pre-existent and planted vegetation. The survivorship of

Table 3.1 Dominant species on reforested land directly affected by pine plantation

Species	Mean cover (%)	SE	Life type
Pinus halepensis	23.65	2.997	Tree
Stipa tenacissima	14.46	2.367	Perennial grass
Brachypodium retusum	7.31	2.514	Perennial grass
Rosmarinus officinalis	4.38	0.813	Shrub
Anthyllis cytisoides	0.81	0.546	Shrub
Fumana ericoides	0.77	0.424	Chamaephyte
Quercus coccifera	0.77	0.769	Nanophanerophyte
Thymus membranaceus	0.73	0.232	Chamaephyte
Salsola genistoides	0.58	0.319	Shrub
Fumana thymifolia	0.50	0.262	Chamaephyte

Table 3.2 Dominant species on reforested land on control slopes not affected by pine plantation

Species	Mean cover (%)	SE	Life type
Stipa tenacissima	20.16	2.675	Perennial grass
Rosmarinus officinalis	5.16	1.188	Shrub
Brachypodium retusum	4.74	1.845	Perennial grass
Pinus halepensis	1.68	0.865	Tree
Ononis tridentata	1.21	0.728	Shrub
Anthyllis cytisoides	0.79	0.430	Shrub
Fagonia cretica	0.74	0.737	Chamaephyte
Plantago albicans	0.47	0.300	Hemicyptophyte
Thymus zygis	0.42	0.268	Chamaephyte
Fumana thymifolia	0.37	0.232	Chamaephyte

the planted pine seedlings was only 37 % (CI 95 %, 29–47 %) for reforestations ranging from 5 to >20 years old. It could be expected that survivorship could be negatively related to the time since the restoration if mortality increases with time because interspecific competition is more intense as trees grow, but this was not the case. The only environmental predictor significantly related to survivorship was slope gradient, with higher survivorship on gentler slopes. This result indicates that the intended improvement of water availability by mechanical terracing was not achieved, and is consistent with the increase of hydrological connectivity noted on reforestations with terraces as acting as preferential flow paths (Sect. 2.4.2.1, connectivity on reforested lands). In terms of growth (height and stem diameter of pines) there was a strong variability among plots, in agreement with the very high environmental variation of them in Cárcavo basin, to the extent that the predictive power of statistical models relating growth to environmental variables is low. Specifically, there is a very low correlation between growth and age of the reforestation. This counterintuitive result suggests that harsh conditions severely limit tree growth in Cárcavo, and that the mechanized land preparation (terracing) more than favouring water availability is increasing environmental harshness through increased hydrological connectivity. Tree growth was severely limited by slope gradient, incoming direct solar radiation and the presence of marls and limestone-marls, reinforcing the idea of the negligible positive effect (if any and positive) of mechanical terracing on improving plant growth conditions.

As regards the pre-existing vegetation, the greatest problem is the very poor species richness and vegetation cover on terrace banks. The reasons for this were researched in the framework of the RECONDES project and are reviewed in Sect. 3.3.1.

3.2.2 Rainfed Croplands

In the northern Mediterranean, the most important crops grown under rainfed conditions are olive, grapevine, almond, barley and wheat. The olive (*Olea europaea* L.) is an evergreen tree with a biennial growth cycle that results in one main harvest every 2 years (Ferguson et al. 1994; Rallo and Cuevas 2004; Tubeileh et al. 2004b). The extent of this alternate bearing is greater when tree vigour is low, for example as a result of water and nutrient stress (Ferguson et al. 1994). In contrast to the olive, the almond tree *(Prunus dulcis* Miller*)* is deciduous and does not feature alternate bearing. The major commercial cultivars are self-unfruitful and need cross-pollination to produce almonds (Micke 1996). Therefore, in almond plantations it is common to alternate one row of a major cultivar with one row of a pollinizer cultivar (Micke 1996). Both winter barley (*Hordeum vulgare* L.) and winter wheat (*Triticum aestivum* L.) cereals are cultivated in the northern Mediterranean. They are sown in autumn and harvested before the start of the dry summer. Barley can be grown at drier locations than wheat because it matures 2–3 weeks earlier (Metochis and Orphanos 1997). In this way, barley is less affected by droughts at the end of the growing season and produces higher and more stable yields (Metochis and Orphanos 1997). In spite of the adaptation to drought of almond and barley (the main crops in Cárcavo catchment) their productivity is severely affected by droughts with productivity decrease of more than 50–80 %, respectively, in very dry years (Barberá et al. 1997).

Traditional mixed cropping systems that still occur in the Northern Mediterranean are the dehesa system in West Spain and the montado system in South Portugal (Ceballos and Schnabel 1998; Joffre et al. 1988; Pinto-Correia and Mascarenhas 1999). The montado features a widely spaced tree stand, some 20–80 trees ha^{-1} and a ground cover of arable crops like barley and wheat in rotation with fallow and pasture (Pinto-Correia and Mascarenhas 1999). Typical trees in such systems are cork oak (*Quercus suber* L.), holm oak (*Quercus rotundifolia* L.), some mountain oaks (*Quercus pyrenaica*), olive and sweet chestnut (*Castanea sativa* Miller) (Pinto-Correia and Mascarenhas 1999). Another example of a mixed cropping system is the so called “coltura mista” in Italy, where olive, grapevine and cereals are grown together. The difference with the montado is that this system involves no pasture and livestock, and that the climate is more humid. In modern agriculture, these systems are becoming rare. Instead, new agricultural fields are large and aimed at the production of a single crop. Examples of the intensification and the economy of scale are the modern olive and almond plantations in Spain and the practice of land levelling in Tuscany, Italy (Borselli et al. 2002; Clarke and Rendell 2000; Hooke 2006; Martínez-Casasnovas and Sánchez-Bosch 2000; Ramos and Martínez-Casasnovas 2006).

Cover crops are defined here as crops that are grown to provide soil cover during winter and fallow periods in annual cropping systems and crops that are grown next to the main crop to provide soil cover in perennial cropping systems. The application of cover crops was still rare in the early 2000s in the Mediterranean. Díaz-Ambrona and Mínguez (2001) report that grain legumes cover less than 3 % of the cultivated land in Central Spain. Research by Pastor (2004) demonstrated that it is possible to grow cover crops in rainfed olive plantations during winter. The cover crop consisted of weeds located in between the rows of trees, whereas the soil beneath the trees was kept bare by chemical weeding. When this cover crop is present only during the winter months and is removed in spring, its water use is relatively low (Pastor 2004).

In order to collect more information on the use of cover crops, a field survey was done in Southeast Spain in September 2004, covering parts of the provinces Valencia, Murcia and Jaén. No signs of cover crops were observed, both for non-irrigated and irrigated tree plantations and vineyards. On the other hand, cover crops were observed in Tuscany, Italy (May 2004) and southeast of Grenoble in France (July 2004). It should be noted that the climate at those locations is much more humid than in Southeast Spain, the former having an annual rainfall of 800 mm or more and the latter 300 mm.

3.2.3 Abandoned Lands

After agricultural land abandonment the secondary succession starts and can be described by functional groups, starting with annual or biennial plants and followed by perennial forbs, perennial grasses and shrubs. Annual plants and short-lived perennials have a higher cover and species richness during the first phase of abandonment, forbs during the second phase and woody species increase after 10 years of abandonment (Bonet 2004). Under the semi-arid conditions of Southeast Spain a forest may not be representative of later stages of succession, due to low water resources and intensive human actions in the landscape over millennia. A late successional community composed of shrublands is more plausible for these areas (Rivas-Martínez 1987). As a result of changes in vegetation and soil management the soil properties of abandoned fields will change with time of abandonment. In general, a progressive recovery of vegetation cover, litter production, organic matter, water retention capacity and stability of aggregates takes place on abandoned fields (Bonet 2004; Cammeraat et al. 2010; Cerdà 1997; Dunjo et al. 2003; Kosmas et al. 2000; Martínez-Fernández and Esteve 2005a; Martinez-Fernandez et al. 1995).

Table 3.3 Description of the field sites (From Lesschen et al. 2008a)

ID	Substrate	Stage	Gravel cover (%)	Crust type	Slope (%)	Slope form	Main vegetation species
M1	Marl	Fallow	5	Slaking	4	Straight	Annuals
M2	Marl	±6 years abandoned	5	Slaking	0	Concave	*Bromus* sp., *Eryngium* sp., *Artemisia herba-alba*, *Plantago albicans*
M3	Marl	±25 years abandoned	14	Slaking	0	Concave	*Plantago albicans*, *Artemisia herba-alba*, *Lygeum spartum*
M4	Marl	Semi-natural	13	Cryptogamic	3	Convex	*Quercus coccifera*, *Brachypodium retusum*
C1	Calcrete	Fallow	46	Slaking	5	Convex	Annuals
C2	Calcrete	±9 years abandoned	88	Sieving	1	Convex	*Helichrysum stoechas*, *Artemisia herba-alba*, *Teucrium capitatum*
C3	Calcrete	±40 years abandoned	35	Sieving and cryptogamic	2	Straight	*Stipa tenacissima*, *Thymus* sp., *Teucrium* sp., *Artemisia herba-alba*
C4	Calcrete	Semi-natural	75	Sieving and cryptogamic	15	Straight	*Rosmarinus officinalis*, *Stipa tenacissima*

We studied the development of spatial heterogeneity in vegetation and soil properties after land abandonment on two different lithological substrates in Southeast Spain. Based on the space-time substitution approach (Pain 1985), to overcome the problem of long term monitoring, two sequences of abandoned fields were selected (fallow, recently abandoned, long abandoned and semi-natural vegetation) in the south-eastern part of the Cárcavo basin. One sequence of fields is located on a Cretaceous marl substrate (M-sites) and the other sequence on Quaternary colluvial pediment with a calcrete, which was partly broken by ploughing (C-sites). The main difference between the two substrates is the amount of gravel on the soil, which influences crust formation and infiltration. On these fields a vegetation survey was conducted and soil samples collected. In each field a representative plot of 10×10 m was selected and all species and the estimated cover were recorded, using Sánchez Gómez and Guerra Montes (2003). Afterwards the vegetation species were classified according to the vegetation type, i.e. herbs, grasses, shrubs or trees. Furthermore, a description of each field in terms of topography, crust and vegetation was made (Table 3.3). The age of abandonment was estimated using aerial photographs of 1956, 1985, 1997, 1999 and 2002 and by asking the owner of the fields.

On each field site four topsoil samples (0–5 cm) were taken from bare patches and four from vegetated patches on each field. The following analyses were carried out on the soil samples: organic carbon, aggregate stability, pH and EC. Furthermore, one subsoil sample of each site was analysed for $CaCO_3$ content, soil texture, micro-aggregation, soluble salts and sodium absorption ratio (SAR_p).

For calcrete sites a clear decrease in number of species with time since abandonment was found, while this trend was less pronounced for marl. This decrease is mainly associated with the decrease in annuals and herbs, which for marl is only observed on the semi-natural site. Although the number of shrub species barely increased with time since abandonment, the shrub cover increased considerably. On the fallow sites mainly annual herbs like *Anagallis arvensis*, *Moricandia arvensis*, *Centaurea aspera* and *Filago pyramidata* grew, but also some chamaephytes such as *Artemisia herba-alba* and *Teucrium capitatum* were found, but none of the species was dominant. On the recently and long abandoned sites on marl patches of herbs (*Carrichtera annua*, *Eryngium sp.* and *Eruca vesicaria*), grasses (*Bromus sp.*, *Lygeum spartum* and *Dactylus glomerata*) and few chamaephytes and shrubs (*Artemisia herba-alba* and *Salsola genistoides*) occurred with *Plantago albicans* in between on bare patches. The recently abandoned site on calcrete was dominated by the chamaephytes *Artemisia herba-alba*, *Helichrysum stoechas* and *Teucrium capitatum*. The long abandoned site on calcrete had similar plant species as the semi-natural vegetation, like the perennial bunchgrass *Stipa tenacissima* and the shrub *Rosmarinus officinalis*, but the occurrence of the chamaephyte *Artemisia herba-alba* and some hemicryptophyte *Plantago albicans* indicated its former agricultural use. Finally, on the semi-natural sites mainly *Stipa tenacissima* and *Rosmarinus officinalis* were found with some *Quercus coccifera* shrubs and *Pinus halepensis* trees, and for the site on marl also some *Brachypodium retusum* grass. Vegetation recovery after land abandonment in a semi-arid environment appears, from the field evidence and dating of abandonment, to be slow and to take at least 40 years. This recovery rate is much slower compared to more humid environments in the Mediterranean.

3.2.4 All Land Units

Combining the different land units, the vegetation of 134 plots was described and all species were identified and their cover was estimated.

Table 3.4 shows the distribution of the species over the different land uses and indicates significant differences between abandoned land and semi-natural vegetation and between natural forest and reforestations. The abandoned land can be distinguished from the semi-natural vegetation by the lower occurrence of *Stipa t.*, *Rosmarinus o.*, *Pinus h.*, *Cistus c.* and *Helianthemum sp.* and the higher occurrence of *Atractylis h.*, *Plantago a.* and *Poa a.* The difference between natural forest and reforestation is made by the lower occurrence of *Pinus h.*, *Brachypodium r.*, *Quercus c.*, *Juniperus o.*, *Lapiedra m.*, *Pistacia l.* and *Cistus a.* on reforested land. The lower occurrence of *Pinus h.* on reforested land seems strange, since all reforestations in the study area consist of *Pinus h.*, however, this may be an indication of the failure

Table 3.4 Species per land use

Species	N	Abandoned	Semi-natural	Natural forest	Reforestation
		%	%	%	%
Stipa t.	119	62[a]	92	82	94
Rosmarinus o.	111	31[a]	84	94	89
Pinus h.	83	0[a]	37	100	79[a]
Thymus v.	77	54	61	53	58
Brachypodium r.	65	31	42	76	48[a]
Cistus c.	57	15[a]	55	53	38
Helianthemum sp.	53	8[a]	39	59	41
Anthyllis c.	51	38	42	29	38
Sedum a.	46	8	34	59	33
Atractylis h.	41	69[a]	34	12	26
Teucrium c.	38	23	11	18	42
Helichrysum d.	36	15	32	24	27
Asparagus h.	33	46	24	6	26
Rhamnus l.	29	15	32	29	15
Quercus c.	29	0	21	59	17[a]
Juniperus o.	27	0	18	65	14[a]
Salsola g.	25	31	16	18	18
Asphodelus f.	25	15	29	18	14
Lapiedra m.	25	0	18	53	14[a]
Pistacia l.	24	15	26	29	11[a]
Juniperus p.	21	8	18	29	12
Stipa c.	20	8	16	29	12
Herniaria f.	16	8	18	0	12
Cistus a.	15	0	8	41	8[a]
Lithodora f.	15	0	21	35	2
Teucrium p.	15	15	11	0	14
Plantago a.	14	46[a]	11	6	5
Diplotaxis l.	13	8	13	12	8
Thymus z.	13	8	13	12	8
Helianthemum a.	12	0	24	6	3
Ononis t.	11	0	3	0	15
Artemisia h.	11	23	13	0	5
Poa a.	10	46[a]	3	0	5
Number of species		52	65	38	63

[a]Significant difference ($P<0.05$) between abandoned land and semi-natural vegetation or forest and reforestation

of the reforestation program since part of the *Pinus h.* has died. When comparing the total number of species, the reforested areas have many species, which is probably related to the previous land use of semi-natural vegetation, which has the highest species richness. The natural forest has less species, but more late successional species such as *Quercus*, *Juniperus* and *Pistacia*.

3.2.5 Hillslopes and Gullies

The major focus of studies working at the scale of hillslope and gullies has been on the role of roots in increasing erosion resistance against concentrated flow. Information on root characteristics of Mediterranean plants is limited. Therefore, various characteristics were assessed for 26 typical Mediterranean plant species. Plant species of three different habitats were selected, i.e. phreatophytes or species growing in gullies or channels (Group 1), species growing on Quaternary loam deposits, frequently found on abandoned croplands (Group 2) and species growing in marls on steep badland slopes (Group 3). The species identified in each zone and some of their characteristics are listed in Table 3.5.

The root to shoot (R:S) ratio is generally smaller than 1 (Table 3.5), indicating that the above ground biomass is usually higher than the below ground biomass for the species measured in this study. In most cases, this can be attributed to an underestimation of the total below ground biomass due to the lack of measurements at depths > d_{max} (see Table 3.5). The soil depth at which 50 % of the total measured below-ground biomass is present varies between 10 and 20 cm for species growing in concentrated flow zones (group 1) and on steep badland slopes (Group 3). All species growing on relatively flat (slope of 1–2 %) abandoned croplands (Group 2) have 50 % of their below ground biomass present in the first 10 cm of the soil. The depth at which roots concentrate is most probably linked to the availability of soil water, but the influence of the vertical distribution of available nutrients which are strongly concentrated in surface soil layers, and the need for plant anchorage should not be neglected. For each particular environmental setting the balance between water and nutrient acquisition and the necessity for plant anchorage on unstable geomorphological configurations may mark differences in root development and its vertical distribution. Therefore, species growing in channels have more roots at greater depths compared to species growing on flat abandoned fields. Species from Group 3 (growing on steep badland slopes) have the highest root mass at greater depths. Deeper roots are needed in this habitat to ensure anchorage. Species belonging to group 2 are generally not so deeply rooted (max. 30 cm, except for *Dorycnium pentaphyllum* and *Rosmarinus officinalis*) compared to species from group 1 (ranging from 30 to 90 cm deep). The measured root depth for plant species from group 3 ranges between 20 and 80 cm.

3.2.6 Channels

The types and distribution of plants vary markedly along the channels, but it is possible to identify distinctive variations and patterning. This variation has been the basis for further detailed studies of the conditions under which the plants grow, monitoring of plants and interactions with channel processes. A list of the dominant plants identified within the Cárcavo and Torrealvilla channels is presented in Table 3.6.

Both Cárcavo and Torrealvilla channels share the same major plant species, as listed in Table 3.6. Annual and perennial grasses exist in the channels. Perennial

Table 3.5 Characteristics of 26 plant species in the Cárcavo basin

Name of the species	N	H (cm)	D_{sv} (cm)	d_{max} (cm)	% of total root mass				R:S
					D>2 mm	2<D<5 mm	5<D<10 mm	D>10 mm	
GROUP 1									
Atriplex halimus [Shrub]	5	62	51	60	3	12	7	78	0.70
Dittrichia viscosa [Shrub]	6	47	13	40	2	40	37	21	0.41
Juncus acutus [Reed]	5	40	19	40	55	0	45	0	0.49
Limonium supinum [Herb]	5	45	19	30	39	56	5	0	0.23
Lygeum spartum [Grass]	5	66	24	30	57	0	43	0	0.46
Nerium oleander [Shrub]	2	88	95	50	0	2	11	88	0.86
Phragmites australis [Reed]	5	40	3	40	3	12	81	4	1.02
Retama sphaerocarpa [Shrub]	4	140	51	40	1	5	8	86	0.68
Tamarix canariensis [Tree]	5	59	17	90	10	40	44	6	0.75
GROUP 2									
Artemisia barrelieri [Shrub]	4	34	34	30	43	35	15	7	0.14
Avenula bromoides [Grass]	5	58	11	20	100	0	0	0	0.44
Brachypodium retusum [Grass]	4	28	14	20	100	0	0	0	0.53
Bromus rubens [Grass]	28	8	1	10	100	0	0	0	0.07
Dorycnium pentaphyllum [Shrub]	5	49	29	50	4	18	31	47	0.19
Fumana thymifolia [Shrub]	5	6	9	20	33	67	0	0	0.18
Piptatherum miliaceum [Grass]	5	119	23	30	34	0	66	0	0.16
Plantago albicans [Herb]	18	5	2	30	100	0	0	0	1.50
Rosmarinus officinalis [Shrub]	4	50	34	60	10	39	22	29	0.29
Teucrium capitatum [Shrub]	5	27	20	20	47	29	24	0	0.15
Thymus zygis [Shrub]	5	33	29	30	18	60	14	8	0.22
Thymelaea hirsuta [Shrub]	5	62	38	40	7	27	38	28	0.18

(continued)

Table 3.5 (continued)

Name of the species	N	H (cm)	D_{sv} (cm)	d_{max} (cm)	% of total root mass				R:S
					D>2 mm	2<D<5 mm	5<D<10 mm	D>10 mm	
GROUP 3									
Anthyllis cytisoides [Shrub]	5	80	27	60	4	43	17	36	0.31
Helictotrichon filifolium [Grass]	5	57	16	20	73	0	27	0	0.88
Ononis tridentata [Shrub]	3	39	42	70	3	16	30	51	0.38
Salsola genistoides [Shrub]	5	65	39	80	10	41	17	31	0.23
Stipa tenacissima [Grass]	8	70	51	40	83	0	17	0	0.15

Group 1 are phreatophytes or species growing in channels. Group 2 are species growing on Quaternary loam deposits, frequently found on abandoned croplands. Group 3 are species growing in marls on steep badland slopes. N is number of selected plants, *H* (cm) is mean plant height, D_{SV} (cm) is mean diameter of the rooted soil volume, D_{max} (cm) is the maximum sampled root depth, *D* is root diameter and R:S is the mean root to shoot ratio (g g^{-1}) (After De Baets et al. 2007b)

Table 3.6 Plant functional group and species identified along Cárcavo and Torrealvilla channels in SE Spain

Plant functional group	Ephemeral channel species list	
	Torrealvilla	Cárcavo
Trees	*Eucalyptus (sp)* [FAN]	*Eucalyptus (sp)* [FAN]
	Populus nigra [FAN]	*Pinus halepensis* [FAN]
	Tamarix canariensis [NAN]	*Tamarix canariensis* [NAN]
Shrubs	*Anthyllis cytisoides* [NAN]	*Anthyllis cytisoides [NAN]*
	Artemisia barrelieri [CAM]	*Ballota hirsuta [CAM]*
	Ballota hirsuta [CAM]	*Dittrichia viscosa [CAM]*
	Dittrichia viscosa [CAM]	*Genista spartioides* [NAN]
	Dorycnium pentaphyllum [NAN]	*Nerium oleander* [NAN]
	Genista spartioides [NAN]	*Rosmarinus officinalis [NAN]*
	Nerium oleander [NAN]	*Salsola genistoides [NAN]*
	Retama sphaerocarpa [NAN]	*Suaeda vera [NAN]*
	Rosmarinus officinalis [NAN]	
	Salsola genistoides [NAN]	
	Senecio linifialaster [CAM]	
	Suaeda vera [NAN]	
	Thymelaea hirsuta [NAN]	
Herbs	*Foeniculum vulgare* [HEM]	*Limonium (sp)* [HEM]
	Limonium (sp) [HEM]	
	Polygonum equisetiforme [TER]	
Grasses	*Lygeum spartum [HEM]*	*Lygeum spartum [HEM]*
	Piptatherum miliaceum [HEM]	*Piptatherum miliaceum* [HEM]
Reeds	*Juncus maritimus [GEO]*	*Juncus acutus [GEO]*
	Phragmites australis [GEO]	*Juncus maritimus [GEO]*
	Saccharum ravennae [GEO]	*Phragmites australis* [GEO]
	Typha dominguensis [GEO]	*Saccharum ravennae [GEO]*
		Schoenus nigricans [GEO]
		Scirpus holoschoenus [GEO]
		Scirpus maritimus [GEO]

[TER, GEO, HEM, CAM, NAN, FAN, LIA] refer to the lifeform of the species following Raunkiaer's biotypes, which uses the vegetative form of a plant based on the position of growth point (buds) during adverse times of the year. *TER* Therophytes, annuals, survive in form of seeds; GEO: Geophytes, underground buds (usually bulbous, rhizomatous, etc.); *HEM* Hemicryptophytes, buds at soil surface level; *CAM* Chamaephytes, buds near ground level (buds < 25 cm high); *NAN* Nanophanerophytes, buds near ground level (buds 25–75 cm high); *FAN* Phanerophytes, trees and large shrubs; *LIA* Lianes, plants growing leant against other plants

species are of greater interest for erosional control as they provide a permanent ground cover throughout the year. The perennial *Lygeum spartum* is a tussocky grass with an extensive rooting system, that can form a dense cover over the bed of marly channels (Navarro-Cano 2004). These communities have been identified as playing a role in countering erosion and desertification; the root systems of these tussocks are particularly effective on steep slopes (Garcia-Fuentes et al. 2001;

Mattia et al. 2005). *Piptatherum miliaceum* and *Brachypodium retusum* are also present. Dominant herb and chamaephyte species present include *Foeniculum vulgare*, *Limonium sp*. and *Polygonum equisetiforme*. Their occurrence within the ramblas is highly opportunistic, often growing where conditions are too hostile for more demanding plants. They have a low resistance to erosion and are easily washed away by floods (Johnson and Simpson 1985), with Mant (2002) documenting their removal by minor to moderate floods.

A range of reed species are present along the channels, each adapted to varying levels of water hydroperiod (the average duration of water saturating conditions in the substrate) and soil salinity. *Juncus maritimus* and *Phragmites australis* have deep growing rhizomatous root structures, that spread laterally, permitting individual plants to quickly form extensive stands (Hara et al. 1993; Snogerup 1993). Other reed species documented include *Juncus acutus*, *Saccharum ravennae*, *Scirpus holoschoenus*, *Scirpus maritimus*, *Schoenus nigricans* and *Typha dominguensis*.

Dominant shrub species are *Anthyllis cytisoides*, *Artemisia barrelieri*, *Ballota hirsuta*, *Dittrichia viscosa*, *Dorycnium pentaphyllum*, *Genista spartioides*, *Nerium oleander*, *Retama sphaerocarpa*, *Rosmarinus officinalis*, *Salsola genistoides*, *Senecio linifoliaster*, *Suaeda vera* and *Thymelaea hirsuta*. Most of the literature pertaining to shrubs in the Mediterranean is based on hillslopes and not channel environments. Moisture and aspect are two factors considered particularly important in influencing the density of shrub seedlings (Smith et al. 1993). In comparison to grasses, herbs and reeds, shrubs contribute a greater roughness value to the channel. Resistance to erosion varies markedly between the different species, with *N. oleander*, noted for its high resistance to erosion (Herrera 1991).

Tamarix canariensis is the dominant tree species found in the channels. A moist substrate for a period of 4–6 weeks is required for seedlings to establish (Brock 1994). They are able to tolerate extended periods of drought, flooding and sedimentation and also have a high salt tolerance (Birkeland 1996). They may form dense stands in close proximity to dams, this being in part due to their higher stress tolerance and ability to reproduce under a range of conditions (Levine and Stromberg 2001). This species has a high resistance to erosion; an extensive search of the literature has not revealed any studies where flows are quoted as having been effective in removing individuals. Other tree species found occasionally near the channels include *Eucalyptus camaldulensis* and *Populus nigra*.

3.3 Assessment of Conditions for Plants

3.3.1 Reforested Lands

In Sect. 3.2.1 the environmental template created by pine reforestation in Cárcavo was briefly reviewed. The reforestation does not only intend to introduce and promote the growth of one or some planted species, as its main underlying premise

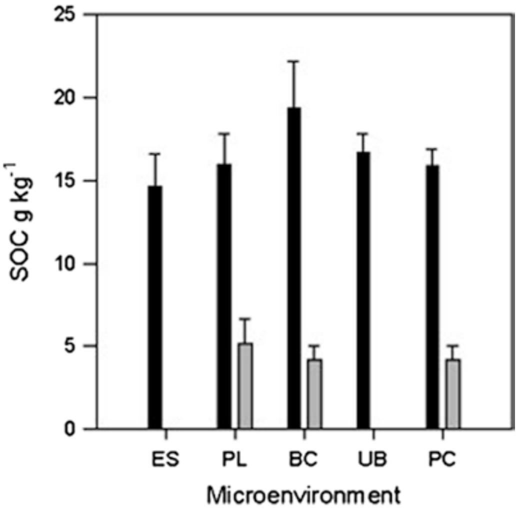


Fig. 3.1 Soil organic carbon on reforestation microenvironments, *ES* under the escarpment in the transition bank/terrace, *PL* adjacent to the stem of pines planted on the terrace, *BC* beneath tree crown cover, *UB* external border of the terrace and upper rim of bank, *PC* pseudocontrol, remaining hillslope vegetation unaltered by mechanical works. *Black bars*, former seminatural vegetation on hillslope; *grey bar*, former barley field. ES and UB microenvironment were absent on former barley fields as they were produced by mechanical terracing of the hillslope. (Source: Modified from Ruiz-Navarro et al. (2009))

hypothesis is that this planted vegetation will increase soil quality and, in general, other environmental conditions favoring faster secondary succession. Cárcavo reforested land was an excellent bench mark to test this hypothesis for traditional approaches to land reforestation in the framework of a harsh environment. In the RECONDES project it was studied whether soil quality improves with reforestation and how the planted vegetation (Aleppo pine) conditions other species. In order to test the effect of the reforestation on soil quality twenty plots were set on one of the oldest reforested areas (about 30 years), ten plots on a terraced hillslope formerly covered by seminatural vegetation and ten on a nearly flat area formerly cultivated with barley (Ruiz-Navarro et al. 2009). The working hypotheses were that tree development would generate changes in the soil (reflected in a radial gradient around planted trees), and that disturbance by mechanical site preparation would result in some microenvironments with unfavorable conditions for plant growth.

On abandoned barley fields, pine litter layer thickness was clearly distributed in a radial gradient around trees. However, despite the large differences in litter abundance, there were no differences in soil organic carbon (SOC) along this gradient, nor with the unaltered soil representing conditions prior to reforestation (Fig. 3.1). Thus, after 30 years of development of the planted vegetation the purpose of improving soil quality was not reached or even approached. The recalcitrant nature of pine litter combined with the unfavorable conditions for decomposition in semi-arid Mediterranean conditions (low average rainfall; moderately wet conditions in the

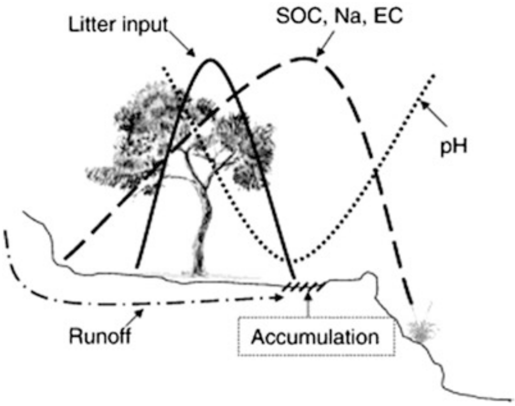


Fig. 3.2 Soil characteristics on terraced and reforested hillslopes. The sediment flows decouple SOC from litter input spatial distribution. Scale is exaggerated for visualization, true differences in SOC are shown in Fig. 3.1. (Source: Ruiz-Navarro et al. (2009))

cool winter and absolute dryness in the warm and hot season) synergistically act to delay the incorporation of litter carbon into the soil, thus preventing the improvement of soil quality. In the hillslope formerly covered by seminatural vegetation SOC was three times higher on average than in the former barley fields, which is an indicator of the very poor soil status induced by long barley cultivation (see Sect. 2.4.2.3 for a discussion about the degrading effect of cereal cultivation in the catchment), but not an indication of better effects of reforestation in the hillslope with seminatural vegetation. Differences of SOC between tree influenced microenvironments were minimal compared to pseudocontrols on unaltered hillslopes (Fig. 3.1). In terraced hillslopes the SOC distribution was clearly spatially uncoupled from that of litter layer depth. This was an effect of sediment redistribution by runoff within the terrace that preferentially moved fine sediments to terrace rims (Fig. 3.2).

Additional experiments were set up to elucidate if the establishment of a tree cover may improve the activity of biogeochemical cycles in soils (Bastida et al. 2008). Soil microbiota activity has been usually overlooked but as responsible for nutrient cycling and organic matter decomposition is key in the process of restoring degraded lands. Four experimental plots, two on north facing slopes (75 % vegetation cover) and two on south facing slopes (25 % vegetation cover) representing, respectively, moderately wet vs. dry conditions were established. In each topographical position one plot was covered by pine forest and the other by shrubland. Microbial activity was markedly higher on north facing slopes than on south facing slopes with average respiration rates of 15 mg CO2-C kg^{-1} $soil^{-1}$ day^{-1}, vs. less than 2 mg CO2-C kg^{-1} $soil^{-1}$ day^{-1}, respectively. This was in agreement with the enzymatic activity involved in biogeochemical cycles, like for example protease activity linked to N cycling. The effect of the type of vegetation cover was weak (if any) and undetectable at the most favourable site, the north facing slope. In summary, the study of the microbiological activity in soils shows that the topographic controls were much stronger than the supposed benefit of a new tree cover over the preexisting shrubland. This is also in agreement with the very weak improvement of soil quality by afforestation/reforestation in the medium term as observed in the previous experiment.

The pine development in reforestation leads to considerable litter accumulation in comparison to the pre-reforestation situation. As we saw in the previous paragraphs this accumulation does not translate in the medium term (about 30 years) into improved soil quality but it could interfere with seed germination and seedling emergence. Control on plant communities by plant litter has been pointed out on numerous occasions. It is exerted not only by the nutrient levels, moisture, temperature and the allelopathic effects of leaves or other organs (Carson and Peterson 1990; McAlpine and Drake 2002; Xiong and Nilsson 1999) but also by the physical properties of litter (Facelli and S. 1991). These factors may differentially act on germination and seedling establishment (Baskin and Baskin 1998; Facelli 1994; Rice 1979), that represent the most critical period for population dynamics in plants (Harper 1977; Kitajima and Fenner 2000).

Pinus litter layer is present both in natural and planted pinewoods, usually showing a thickness of several centimetres (McAlpine and Drake 2002). Several authors have estimated the mean time necessary for pine needle decomposition as more than 4 years (Moro and Domingo 2000; Prescott et al. 2004) but in Cárcavo conditions it is estimated to be much longer. Allelopathic control has not been detected in the plant dynamic regulation of *P. halepensis* semi-arid plantations (Maestre and Cortina 2004), although Izhaki et al. (2000) and Eshel et al. (2000) pointed out the quimiotoxic effect of the post-fire pine ash on the plant succession of the pine understorey in subhumid Mediterranean conditions. On the contrary, the physical effect of the pine litter could play an important role in seedling emergence of early successional species (Izhaki et al. 2000). During the project RECONDES both field and laboratory experiments were carried out to test several hypotheses about how pine litter could condition seedling emergence and growth.

In the field, direct sowing of *Stipa tenacissima* and *Anthyllis cytisoides*, two dominant species in the shrublands and grasslands and in the pine understorey, was carried out on the footslope site in order to test the hypothesis of a negative interaction between litter accumulation and seedling emergence (Navarro-Cano et al. 2009, for consistency with Ruiz-Navarro et al. 2009 we changed here terms to name microenvironments). Each plot was divided into three microenvironments below pine plantation line (PL) adjacent to the trunk, below pine canopy (BC) and bare soil between plantation lines unaffected by reforestation and acting as pseudo-controls of conditions prior to the reforestation (PC). *S. tenacissima* seedling emergence began 26 days after sowing. Two germination periods took place. In a first period, from 6 April to 25 April, significant differences between microsites were found (One-way ANOVA, $F_{2,14}=7.586$; $P=0.006$). There was a gradual increase in the seedling emergence mean rate from PL (1 ± 0.65 %) to PC (40 ± 11.9 %), following a gradient of needle thickness. However, seedling survival was nil in all the microsites 3 months after sowing. We detected new seedling emergence during the following autumn, but all the new plants grew between 28/9/05 and 19/10/05. The accumulated seedling emergence reached 3.5 ± 0.9 % in PL, 26 ± 7.2 % in BC and 45 ± 11.1 % in PC (Fig. 3.3a). Significant differences were only found between PL and PC microsites (Tukey test, $P=0.004$), as happened in the spring period. However, marginally significant differences were found now between BP and BC

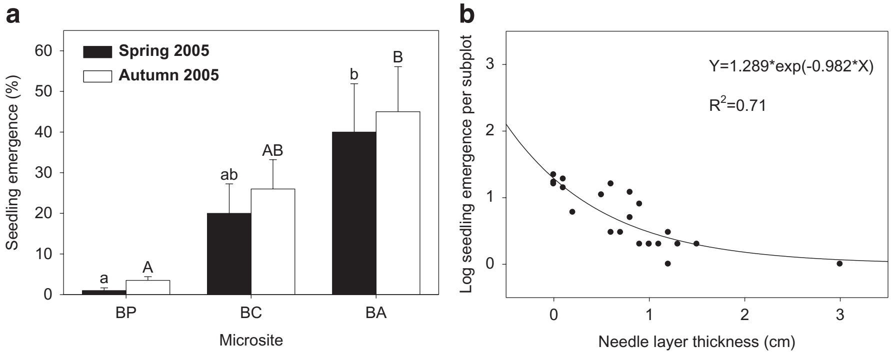


Fig. 3.3 (**a**) Variation of seedling emergence among microsites. Columns marked by different letters indicate significant differences (Tukey, $P < 0.05$); (**b**) The relationship between seedling emergence per plot and the needle layer thickness. Seedling emergence was previously log (x + 1) transformed to pass Normality and Constant Variance tests. Fitted line is for exponential decay equation

(Tukey test, $P = 0.053$). As a benchmark the germination of *S. tenacissima* under controlled conditions on a growth chamber reached 69.3 ± 3.4 %.

The hypothesis that *Pinus* litter layer can act to hinder seedling emergence is supported by the results, which show a decrease of seedling emergence when *Pinus* litter layer increases (Fig. 3.3b). Considering that germination of *S. tenacissima* is not affected by the light environment (Gasque 1999), our results support the hypothesis that the fine-scale distribution of the *P. halepensis* needle layer hinders seedling emergence by a physical effect. Needles form a very intricate and porous layer, which might hamper burial, seed-soil contact and seed imbibition. In this situation, once the seed has germinated, moisture and temperature stress conditions can negatively affect the radicule rooting in the soil and subsequent seedling emergence. Since the negative effect of litter disappeared when water balance was improved in the growth chamber, our results support this interpretation. In any case, we detected a significant decrease of *Stipa* seedling emergence with a mean needle layer thickness of 1.3 cm (PL microsite), but litter layer is usually larger than 2 cm in older pine plantations with a larger size than in our study site (personal observation) so a generalization of this effect may be expected in other semi-arid afforested areas.

In semi-arid ecosystems there are a plethora of species that are early-colonizers capable of occupying highly stressful niches. In the previous experiment we ascertain how pine reforestation can affect the seedling establishment of subdominant understorey species. A second experiment was conducted to investigate how pine litter may affect species that have this role of early-colonizers, and whose ecology may be very different to that of the subdominant species. On the other hand the effect of litter may imply alelopathic effects and the previous experiment was not designed to evaluate this possibility. The herb *Diplotaxis harra* and the chamephytes *Thymus zygis* and *Teucrium capitatum.* were selected for this second experiment. Three treatments were set up (Navarro-Cano et al. 2010) (i) soil without litter,

Fig. 3.4 Effects of the pine litter layer on the seedling emergence and early growth of *Diplotaxis harra* under controlled conditions

taken from the PC microenvironment (BARE); (ii) intact soil and litter forming two distinct layers as in the field taken from the BP microenvironment (PINE); and (iii) as (ii) but soil and pine litter were mixed in the laboratory (PINEMX). From the comparison of the results between treatments (ii) and (iii) it is possible to infer the different effects of a physical barrier with or without alelopathic effects (treatment ii) from purely alelopathic effects (treatment iii).

The three species do germinate significantly more on Petri dishes than in each of the treatments, something that is probably related to the presence of pathogens and allelopathic substances on natural substrates. When comparing between treatments, seedling emergence of *Diplotaxis harra* was significantly higher on BARE than on PINE or PINEMX. In respect of *Thymus zygis* there was a 50 % decrease in seedling emergence on PINE in respect of BARE and more than 70 % of decrease on PINMX in respect of BARE. Seedling biomass, length and number of leaves were also reduced by the presence of litter. On the contrary, *Teucrium capitatum* was weakly affected by the presence of litter, mixed or not with soil.

From this experiment it is confirmed the negative effects of pine litter on plant growth conditions of other species, at least in respect to the seedling establishment phase. As results for *Diplotaxis harra* (Fig. 3.4) and *Thymus zygis* show, this effect is not only caused by physical barrier effects, but is also an allelopathic effect. In this way, when the physical barrier effect of the litter was eliminated (PINEMX), seedling emergence was still as low as in PINE (*Diplotaxis harra*) or even lower (*Thymus zygis*).

3.3.2 Croplands

Water availability is a limiting factor for plant growth in semi-arid, rainfed conditions. The key issue of cover crop implementation is in how far the cover crop competes for water with the main crop and in how far this competition affects the economic feasibility of the cropping system. Therefore, our investigations were focused on water availability as a function of climate, soil properties, topography and cropping system.

At the European scale, climate is the most important factor that determines water availability and the potential for the application of cover crops. If the climate is drier and water availability lower, individual trees need a larger volume of soil to meet their water requirement. Hence, at sites with lower water availability, the trees need to be spaced further apart for optimal production. Climate was expected to be the most important parameter to explain the spatial variation in tree spacing at the European scale. This hypothesis was tested using a dataset of the projected canopy cover and tree density in the Mediterranean. The dataset was compiled from various sources, including field work in Southeast Spain, literature and the consultation of colleagues in Italy (contractor CNR), Spain, Portugal and Syria. The interpretation of the dataset and the implications in terms of physical thresholds for cover crops are reported in Chap. 4. The results show a significant correlation between tree density and climate (using a humidity index), this placing a limit on the extent to which cover crops can be applied for a given region.

The role of lithology on the water balance and occurrence of almond orchards was investigated at the province scale in Murcia, Southeast Spain. By courtesy of CSIC we were able to obtain a dataset on the occurrence of almonds of 1 ha resolution as well as a dataset on lithology at a resolution of 1 km^2. Lithology is directly related to the properties of marginal soils such as water retention capacity. The almond and lithology data were combined to test the hypothesis that there is a preference for almond orchards to be located on soils with a higher water availability. The results show a marked concentration of almond orchards on marls, shales and schists and an absence on limestone and dolomites.

The concentration of orchards on marls, shales and schists is probably related to the mouldability of the rock that facilitates the planting of new trees and clean-sweeping of the orchards as well as a higher water availability compared to limestones and dolomites. The second point illustrates that lithology plays an important role in terms of water availability and would therefore make a difference for the growth of cover crops. The effect of lithology on the soil water balance and the water availability for cover crops was studied in detail by quantitative modelling of the water balance on stony soils and soils on marls (see Chap. 4).

The spatial variability in water availability at the field scale was investigated by a combined field survey of almond tree vigour and patterns of overland flow. The aim was to study the importance of patterns of water availability related to topography and runoff on vegetation growth. In the literature, the trunk diameter of olive trees has been related successfully to soil properties and topography (Aragüés et al. 2004; Gálvez et al. 2004). In turn, soil properties and topographic parameters are correlated to soil moisture (Gómez-Plaza et al. 2001; Western et al. 1999). It was therefore assumed that the spatial variation in trunk diameter in young and homogeneously planted almond groves reflects the spatial variation in available water. Trunk diameter measurements were conducted in four rainfed orchards in Murcia, of which two were located on stony soils on slate and phyllites and two on marls.

On marl soil *ESV* (effective spatial variance) as measured by variograms was around 40 % and on stony soil around 24 %. Hence, the relative spatial variation in tree growth on marl soil is considerably larger. Probably this is related to a larger spatial variation in soil moisture. Nevertheless, there are also some other factors that can influence the shape of the variograms. For example, the effects on tree growth of pruning and fertilisation might not be homogeneous throughout the plantation.

A second step consisted of a study of the correlation between trunk diameter and topographic indices. A topographical survey was made for a total of five almond orchards in Murcia. The position of the almond trees, field and terrace borders were recorded with a total station and differential GPS. Subsequently, digital elevation models (DEMs) were constructed. The topographic variables considered were slope, aspect, profile curvature, tangential curvature, specific upslope area (ln$a$) and wetness index (*WI*). These parameters showed low correlations with trunk diameter, never exceeding 0.19. The low correlation between the terrain indices and trunk diameter implies that runoff patterns and storm events are of minor importance to the variation in tree growth within these orchards, probably because of the dry climate.

The hypothesis that runoff events are rare and that runoff quantities are limited is supported by rainfall measurements during the period from February 2005 to November 2006. During this period, the 10 min rainfall intensity exceeded the saturated hydraulic conductivity of the almond fields just six times. The last event was extreme with 92 mm of rainfall in 3 days, having a recurrence interval of approximately 9 years. The amount of runoff produced in the almond fields on marls remained rather limited. The results indicate that the upper limit of water availability, biological productivity and vegetation growth is determined by climate. Nevertheless, variability at finer scales (province, catchment, field) can be considerable as well, governed by lithology, soil properties and topography. This has direct consequences for the cultivation of rainfed crops and the potential for the application of cover crops: the lower the water availability, the more restricted the possibilities for the growth of cover crops.

3.3.3 Semi-Natural and Abandoned Lands

The physical characteristics and coordinates of each of 134 plots were described and all species were identified and their cover was estimated. In total 92 different species were identified of which 33 occurred in ten or more plots, which were used in the statistical analyses. The plots were chosen more or less evenly on different substrates (Quaternary colluvium, Tertiary marl, Cretaceous marl, Muschelkalk limestone, Jurassic dolomite and Keuper) and different land uses (abandoned land, semi-natural vegetation, natural forest and reforestation). With the GPS-coordinates the topographical variables (altitude, slope, position and solar radiation) were derived from a DEM for each plot (Fig. 3.5).

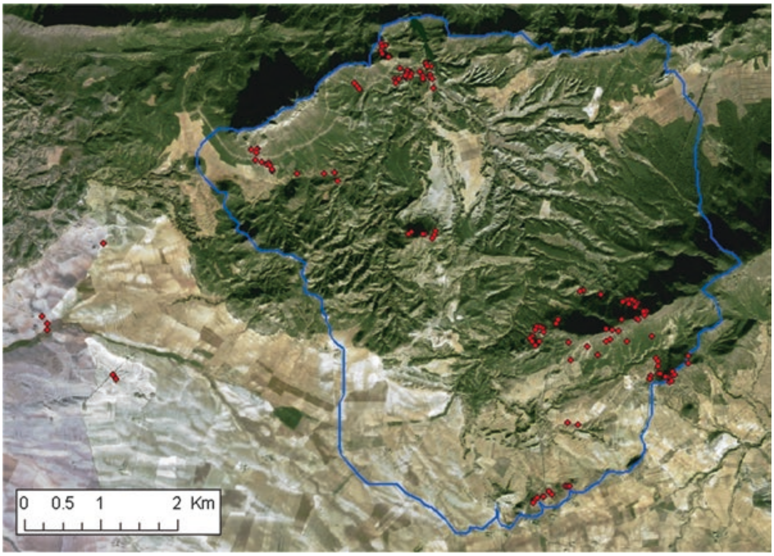


Fig. 3.5 Location of all vegetation plots in the Cárcavo basin

The species data was available in binary form (presence-absence), but also as estimated fraction of the vegetation cover. For the statistical analysis the following environmental variables were included: land use, substrate, topographical position, altitude, slope, radiation, soil depth, micro-topography and bare ground fraction. In SPSS we used the independent samples *t*-test (for continuous variables) and the Pearson's chi-square test (for binary variables) to test which environmental variable is significantly related to each vegetation species. Table 3.7 shows for each species the resulting significant positive or negative associations with environmental variables and in Table 3.8 the mean values of the continuous variables per species are presented.

A Principal Component Analysis of the main vegetation species and the environmental factors was conducted in which the binary variables were converted to percentages of occurrence. Four different components were extracted that explain 83 % of the variance (Table 3.9). The resulting scatter plot (Fig. 3.6) of the first two axes, which explain 67 % of the variance, shows that two groups of species can be identified. One group (*Atractylis h.*, *Diplotaxis l.*, *Artemisia h.*, *Plantago a.* and *Poa a.*) represents typical species on abandoned land, while the other group (*Quercus c.*, *Cistus c.*, *Cistus a.*, *Lithodora f.*, *Lapiedra m.* and *Juniperus o.*) corresponds to species in natural forest on steep and high positions, i.e. early against late successional species.

For the independent samples *t*-test the plots should be more or less randomly chosen, however due to the sampling scheme and the distribution of land uses and substrates this is not the case. Besides some of the environmental variables are highly correlated, e.g. abandoned land and Quaternary colluvium and Tertiary marl

Table 3.7 Species and significant associations with environmental variables

Species	Type	Positive association	Negative association
Stipa tenacissima	Grass	Bare ground*	Abandoned land**
			Quaternary colluvium*
			Soil depth*
Rosemarinus officinalis	Shrub	Reforestation*	Abandoned land***
		Limestone*	Quaternary colluvium***
		Top position*	Flat position***
		Micro-topography*	Radiation**
			Soil depth*
Pinus halepensis	Tree	Natural forest**	Abandoned land***
		Reforestation***	Semi-natural vegetation***
		Cretaceous marl***	Quaternary colluvium***
		Top position*	Keuper*
		Altitude**	Flat position***
		Slope**	Radiation*
		Micro-topography**	Bare ground*
Thymus vulgaris	Shrub	Cretaceous marl*	Keuper**
			Limestone*
Brachypodium retusum	Grass	Natural forest*	Keuper*
		Cretaceous marl***	Radiation***
			Bare ground*
Cistus clussii	Shrub	Jurassic dolomite**	Abandoned land*
		Muschelkalk limestone*	Tertiary marl***
		Altitude***	
		Micro-topography**	
Helianthemum sp.	Shrub	Tertiary marl*	Abandoned land*
		Jurassic dolomite**	Quaternary colluvium*
		Slope**	Keuper*
			Soil depth*
Anthyllis cytisoides	Shrub	Keuper**	
Sedum album	Herb	Natural forest*	Abandoned land*
		Jurassic dolomite**	Quaternary colluvium**
		Valley position**	Flat position*
		Slope**	
Atractylis humilis	Herb	Abandoned land**	Jurassic dolomite***
		Quaternary colluvium***	Altitude**
		Flat position*	Slope***
			Micro-topography***
Teucrium capitatum	Shrub	Reforestation***	Semi-natural vegetation**
			Muschelkalk limestone**
Helichrysum decumbens	Shrub	Keuper**	Slope*
		Bare ground*	

(continued)

Table 3.7 (continued)

Species	Type	Positive association	Negative association
Asparagus horridus	Herb	Tertiary marl***	Cretaceous marl**
		Slope position*	Top position*
		Radiation***	Altitude***
Rhamnus lycioides	Shrub	Jurassic dolomite**	Keuper*
		Slope***	Soil depth**
Quercus coccifera	Tree	Natural forest***	Abandoned land*
		Jurassic dolomite***	Tertiary marl**
		Muschelkalk limestone**	Keuper**
		Top position**	Slope position*
		Altitude***	Soil depth**
			Bare ground***
Juniperus oxycedrus	Tree	Natural forest***	Quaternary colluvium*
		Jurassic dolomite***	Tertiary marl**
		Top position***	Keuper**
		Altitude***	Slope position***
		Slope***	Radiation*
			Soil depth**
			Bare ground*
Salsola genistoides	Shrub	Tertiary marl**	Jurassic dolomite**
		Soil depth*	Altitude***
			Micro-topography*
Asphodelus fistulosus	Herb	Keuper***	Cretaceous marl**
		Top position*	Slope position*
Lapiedra martinezii	Herb	Natural forest***	Quaternary colluvium*
		Jurassic dolomite***	Soil depth**
		Altitude**	Bare ground**
		Slope**	
Pistacia lentiscus	Tree	Jurassic dolomite***	Reforestation*
		Valley position*	Tertiary marl**
		Altitude***	Soil depth*
		Slope*	Bare ground**
Juniperus phoenicea	Tree	Slope**	Radiation**
			Soil depth*
			Micro-topography*
Stipa capensis	Grass	Jurassic dolomite**	Keuper*
		Muschelkalk limestone**	Soil depth*
		Top position*	
		Altitude***	
		Micro-topography*	
Herniaria fruticosa	Shrub	Keuper***	Tertiary marl*
		Bare ground*	Jurassic dolomite*
			Slope*

(continued)

Table 3.7 (continued)

Species	Type	Positive association	Negative association
Cistus albidus	Shrub	Natural forest***	Tertiary marl*
		Cretaceous marl*	Slope position*
		Jurassic dolomite***	Radiation***
		Top position*	Bare ground***
		Altitude***	
		Slope***	
Lithodora fruticosa	Shrub	Semi-natural vegetation*	Reforestation***
		Natural forest**	Tertiary marl*
		Jurassic dolomite***	Cretaceous marl*
		Top position**	Slope position*
		Altitude***	Soil depth**
		Slope*	
Teucrium pseudochamaepitys	Shrub	Slope position*	
Plantago albicans	Herb	Abandoned land***	Reforestation*
		Quaternary colluvium**	Slope***
		Flat position**	Micro-topography***
		Soil depth*	
Diplotaxis lagascana	Herb	Keuper**	
Thymus zygis	Shrub	Quaternary colluvium*	Soil depth*
		Muschelkalk limestone***	
Helianthemum almeriense	Shrub	Semi-natural vegetation***	Reforestation*
		Keuper**	
		Muschelkalk limestone*	
Ononis tridentata	Shrub	Reforestation**	Altitude**
		Keuper***	
		Soil depth*	
		Micro-topography***	
Artemisia herba-alba	Shrub	Abandoned land*	Altitude*
			Slope*
			Micro-topography***
Poa annua	Grass	Abandoned land***	Top position*
		Quaternary colluvium**	Altitude***
		Tertiary marl*	Slope**
		Flat position***	Micro-topography**
		Soil depth***	

*$P<0.05$, **$P<0.01$, and ***$P<0.001$

Table 3.8 Mean values for the continuous environmental variables

Species	N	DEM	Slope	Radiation	Soil depth	Micro-topography	Bare ground
		m	Degrees	MJ cm^{-2} year^{-1}	1–4*	1–3*	%
Stipa t.	119	426	20.2	0.79	2.1	2.0	36.5
Rosemarinus o.	111	433	20.3	0.77	2.1	2.0	34.4
Pinus h.	83	451	22.1	0.75	2.1	2.1	31.9
Thymus v.	77	429	18.3	0.79	2.1	1.9	32.4
Brachypodium r.	65	446	20.7	0.72	2.2	2.0	30.7
Cistus c.	57	492	20.4	0.77	2.0	2.2	36.1
Helianthemum sp.	53	429	23.3	0.79	1.9	1.9	34.5
Anthyllis c.	51	437	21.2	0.82	2.0	2.0	37.0
Sedum a.	46	418	23.5	0.79	2.0	2.1	38.3
Atractylis h.	41	396	13.2	0.80	2.3	1.5	39.4
Teucrium c.	38	406	19.2	0.75	2.3	2.1	36.2
Helichrysum d.	36	434	16.3	0.74	2.2	1.9	41.5
Asparagus h.	33	358	18.0	0.87	2.1	1.8	39.1
Rhamnus l.	29	452	26.7	0.80	1.8	1.9	30.7
Quercus c.	29	552	23.2	0.73	1.8	2.1	19.3
Juniperus o.	27	532	27.5	0.69	1.7	2.0	27.6
Salsola g.	25	350	19.3	0.75	2.6	1.6	40.0
Asphodelus f.	25	407	18.1	0.74	2.1	2.0	41.6
Lapiedra m.	25	489	25.1	0.73	1.7	2.3	24.0
Pistacia l.	24	531	24.0	0.84	1.8	2.3	25.2
Juniperus p.	21	408	27.2	0.67	1.8	1.6	33.1
Stipa c.	20	539	23.5	0.79	1.8	2.4	28.0
Herniaria f.	16	410	14.0	0.77	2.4	2.2	46.6
Cistus a.	15	529	29.7	0.56	2.2	1.8	14.7
Lithodora f.	15	538	25.5	0.78	1.4	1.8	37.3
Teucrium p.	15	399	20.7	0.87	2.1	1.7	26.3
Plantago a.	14	398	9.2	0.78	2.8	1.2	37.5
Diplotaxis l.	13	396	14.6	0.76	2.3	2.1	42.3
Thymus z.	13	450	20.0	0.79	1.7	1.8	25.0
Helianthemum a.	12	425	15.3	0.78	2.1	1.6	43.3
Ononis t.	11	335	19.8	0.68	2.7	2.6	41.8
Artemisia h.	11	388	14.4	0.76	2.5	1.1	38.2
Poa a.	10	334	9.3	0.82	3.5	1.3	41.0

*Soil depth (1=<10 cm, 2=10–25 cm, 3=25–50 cm and 4=>50 cm) and micro-topography (1=low, 2=medium, 3=high)

and reforestation. Therefore, a careful interpretation of the analysis is required, e.g. a very significant negative relation between a certain species and a certain environmental variable indicates a low probability of occurrence on such a location, however, it does not mean that such a species cannot grow in that environment. For example, *Pinus halepensis* had a very significant ($P<0.001$) negative relation with

Table 3.9 Component factors from PCA

Environmental variable	Axis 1	Axis 2	Axis 3	Axis 4
Altitude	−0.497	0.733	−0.236	0.054
Slope	−0.103	0.797	−0.457	−0.070
Radiation	0.029	−0.340	0.141	0.888
Soil depth	0.285	−0.679	0.405	−0.317
Micro-topography	0.161	0.658	−0.021	−0.009
Bare ground	0.257	−0.608	0.465	−0.003
Abandoned land	0.423	0.571	0.632	−0.086
Semi-natural vegetation	0.946	0.060	0.009	−0.048
Natural forest	0.793	−0.270	−0.440	−0.077
Reforestation	0.958	0.066	−0.080	0.134
Quaternary colluvium	0.674	0.430	0.525	−0.089
Tertiary marl	0.839	0.217	0.060	0.026
Keuper	0.697	0.207	0.000	0.351
Cretaceous marl	0.908	0.013	−0.058	0.049
Jurassic dolomite	0.784	−0.358	−0.362	−0.225
Muschelkalk limestone	0.823	−0.040	−0.262	0.118
Flat position	0.574	0.537	0.445	−0.039
Valley position	0.852	−0.128	−0.191	−0.213
Slope position	0.961	0.155	0.058	0.086
Top position	0.941	−0.115	−0.267	0.054

abandoned land, but this can be explained by the slow secondary succession and the absence of reforestation on abandoned land. Especially on abandoned land and in reforested areas, the human influence has highly disturbed the natural occurrence of vegetation species.

3.3.4 Channels

Recognising that the variation in mapped vegetation reflects a range of conditions, further site investigations were undertaken to determine the conditions for growth and survival of plants within each assemblage. Site selection was based on the maps of vegetation assemblages, such that there was sufficient number of sites within each of the assemblage categories identified. A site is an area of vegetation within a reach and cross-section. There may be more than one zone of vegetation within a cross-section and each is a site. In total, 39 sites were selected for detailed study along Cárcavo (c.7 km in length) and 36 along Torrealvilla (c.6 km in length). At each site a number of variables were measured. The choice of variables measured was based on those variables identified in the literature as possibly exerting a controlling influence on the composition and distribution of riparian vegetation (Baker 1989; Birkeland 1996; Craig and Malanson 1993; Harris 1987; Hupp and Osterkamp

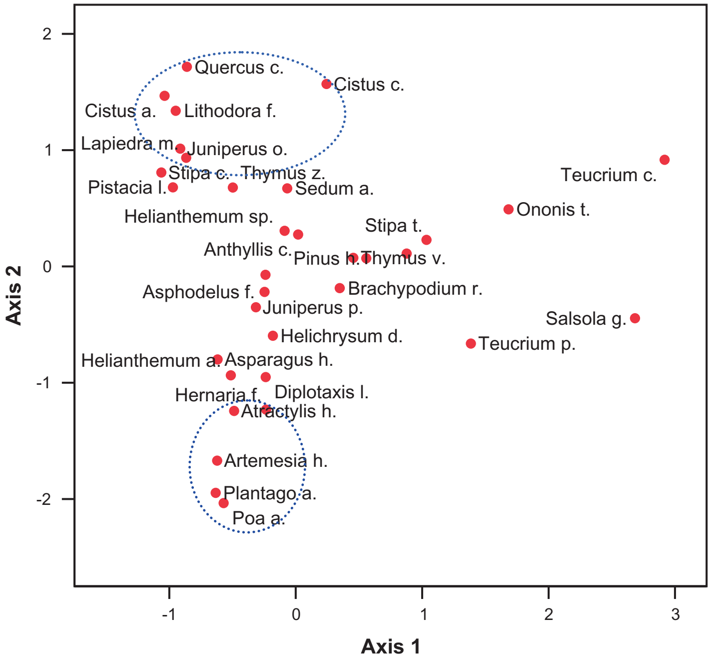


Fig. 3.6 Scatter plot of the principal component axes

1985; Malard et al. 2002; McBride and Strahan 1984; Osterkamp and Hupp 1984; Tabacchi et al. 1996; Zimmerman 1969; Zimmerman and Thom 1982). Variables measured can be grouped into four main categories: water availability, substrate, geomorphology and hydraulics.

Availability of water has been identified as a key factor controlling the distribution of vegetation in semi-arid channels (Tabacchi et al. 1996; Zimmerman 1969). Studies of vegetation patterns along ephemeral channels in SE Spain by Tabacchi et al. (1996) indicated that longitudinal change in water supply was probably the most important factor in structuring riparian communities. Zimmerman and Thom (1982) showed how vegetation patterns reflected changes in surficial geology and the influence that this has on surface water/groundwater flows, with marked increases in vegetation diversity associated with sections of the channel where there was a perched aquifer with baseflow on a bedrock aquiclude. Hence, the thickness of sediments and/or depth to bedrock is also considered to be important in influencing water availability along the channel.

A means of measuring both the depth to bedrock and depth to water was therefore considered important. Where it was possible, a hand auger was used to core through the bed to bedrock. The thickness of the unconsolidated sediments, depth to bedrock and water table was then determined with a measured tape. However, it was not always possible to core to bedrock, such as in circumstances where there were coarse gravels, or the substrate was loose and could not be brought to the surface.

For sites positioned on gravel bars and where bedrock was exposed in the thalweg, the vertical distance of the site above bedrock was measured and used as a value of depth to bedrock and water. Where bedrock was not exposed, the vertical distance of the site above the thalweg or depth of sediments augered was used as a minimum estimate of water table depth. Where the site was situated in close proximity to a check dam, it was possible to estimate the depth to bedrock by measuring the height of unconsolidated sediments behind the check dam.

Variation in *sediment characteristics* is considered to be one of the most important factors influencing plant establishment and survival (McBride and Strahan 1984; Osterkamp and Hupp 1984). The texture of channel sediments at the surface were described in the field and classified into 16 simple and mixed classes Where gravels and boulders were present, the mean size and range of clasts were measured. Where finer channel sediments were present, sediment samples were collected and analysed in the laboratory for particle size, carbon content and aggregate stability. In the process of augering to determine the depth to bedrock and water table, the stratigraphy of the channel bed was also described, documenting the variability in thickness and calibre of sediment layers.

Different *landforms* within the channel are characterised by a particular flow and sediment regime that has led to their development, and the regime associated with each landform may support a particular assemblage of plants (Bendix and Hupp 2000). Therefore, the overall morphology and positioning of the vegetation assemblage within the channel is of importance in influencing conditions. The overall morphology of the site was classified as: 1. flat bed, 2. flat bed with vegetation wakes, 3. thalweg, 4. mid-channel bar, 5. side bar, 6, point bar, 7. floodplain and 8. bedrock. The lithology of the valley walls varies markedly along the course of the channels and may influence the characteristics of the sediment supplied to the channel. The lithology of the base of the valley walls was distinguished. The dimensions of the channel (width, depth) and valley (width) were measured in the field and channel width/valley width and channel width/depth ratios then determined. Inner and outer channels were defined in some cases and tests were made with mean and maximum depths and of widths at various heights.

One of the basic premises of the RECONDES project is that vegetation is influenced and in turn has an influence on the *connectivity* of flow and sediment transfers within the drainage basin. The potential connectivity of each site has been assessed through mapping of morphology, vegetation and connectivity along the channel using the methods described by Hooke (2003). This method of mapping is based on the interpretation of various morphological and sedimentological evidence. In this, the morphology of the channel is mapped, detailing changes in the dimensions of the channel bed and floodplain, bedrock exposures and the position of check dam/ groyne structures and road crossings. Particular attention is given to mapping the sources (gully/tributary, banks/valley walls) and storages of sediment (bar forms, accumulations behind check dams) along the channel. Using the combined map layers (channel morphology, sediment sources and storages) sediment source zones are identified and the channel is divided into areas of erosion, erosion and storage and net storage. The potential connectivity of sites along the channel network was then assessed and classified. Reaches that are classified as 'area of net erosion' are highly competent, material is likely to be flushed through the reach at high flows and there is minimal potential for sediments to be deposited within the reach. Within reaches classified as 'erosion and storage' there is considerable exchange of sediments along the reach. For example, sediments may be deposited and stored through the growth of one bar but a similar volume of sediments is then eroded from the next bar downstream. Within sections of the channel classified as 'areas of net storage' there is evidence of continued build up of sediments. Reaches with 'stable vegetation' typically extend upstream of check dams and represent reaches where the channel has been stabilised and vegetation now covers the channel floor.

The *hydraulics* of floods play an important role in influencing the distribution of vegetation. In-channel vegetation is affected by flood processes such as scour and deposition during flows and the characteristics of the landforms that are formed during floods (Bendix and Hupp 2000). Feedback relationships between vegetation, channel morphology and hydraulics exist, where the morphology of the channel and vegetation assemblages both influence and are influenced by flow hydraulics (Hooke and Mant 2000). Different landforms within the channel are characterised by a particular flow regime that has led to their development, and the flow regime associated with each landform may support a particular assemblage of plants (Bendix and Hupp 2000). Detailed cross-sections were surveyed for each of the sites using a Differential GPS (±2 cm) and recording changes in substrate and vegetation (species, height, condition) along the cross-sections. A longitudinal profile was also surveyed from which longitudinal distance, elevation and gradient at each site could be derived. Cross-sectional profile and gradients are used in conjunction with detailed surveys of vegetation to estimate hydraulics at sites for a selection of flows. The lack of multiple cross-sections at each site precluded use of software such as HEC-RAS. WinXSPRO (Hardy et al. 2005), was chosen for the calculation of hydraulics because of its ability to compute flow hydraulics for single cross-sections and the ability to divide a cross-section into a number of subsections on the basis of morphology or vegetation in which hydraulics could be calculated. The program has been recently used to compute hydraulics of flow in a study by Lite et al. (2005) examining the influence of flood disturbance and water stress on riparian vegetation along the San Pedro River in Arizona, a similar type of situation to that in the Spanish channels.

Cross-sections were divided into a number of subsections based on differences in vegetation and topography and Manning's n values were estimated for each subsection, according to the methods of Arcement and Schneider (1989). The program calculates the velocity and discharge of flows within each of the subsections for the increments of flow stipulated. Hydraulics of flows were calculated at selected sites for low, medium and high discharge events along Cárcavo (2, 10 and 40 $m^3 s^{-1}$) and Torrealvilla (10, 100 and 200 $m^3 s^{-1}$). These discharges were selected as having ecological and geomorphological significance. The low flow fills the thalweg/inner channel, the medium flood most closely resembles that of bankfull and the high flow is at least twice the magnitude of the medium flow. The bankfull stage is somewhat difficult to prescribe in some places and very sparse information is available on the frequency and magnitude of flows. Monitoring of flows within the Guadalentín Basin by one of the authors over the past 10 years also informed selection of these flows.

This method of calculating flow hydraulics provides the basis for evaluating the effect that different vegetation assemblages have on flow hydraulics, the conditions in which particular vegetation assemblages exist and flows they can withstand. The results can then be compared with surveyed effects of flows on vegetation to assess the thresholds of forces for plant damage and destruction. For this, we draw upon some earlier monitoring work that was completed in the region, in particular, the impact that floods in September 1997 and October 2003 within the Guadalentín Basin and November 2006 in Cárcavo Basin have had on vegetation and channel morphology.

Statistical analysis of the environmental data was carried out with the aim of identifying the conditions for the establishment and survival of different species and assemblages and thresholds. Principal Component Analysis (PCA) was used to eliminate redundant variables and determine which variables are more influential than others. PCA was carried out in a number of steps. In the first instance variables were grouped together according to whether they were considered to influence water availability, substrate, morphology and hydraulics. PCA was then carried out on each of these groups (Table 3.10). PCA was carried out on Cárcavo and Torrealvilla datasets separately, and also on the combined dataset. The analysis of the combined datasets gives considerably higher factor loadings so these results are presented.

The results of Principal Component Analysis (PCA) for water availability, substrate and morphology are shown in Fig. 3.7. For each PCA the set of variables has been reduced to two components, Component 1 and 2. Component scores are plotted on x and y axes according to the dominant plants. This is informative in revealing whether sites with the same vegetation plot together which would indicate similarity in required conditions for establishment and/or there are distinct differences in conditions associated with sites of contrasting vegetation types. The extent to which similarly vegetated sites are distributed in space is also informative in revealing the range of tolerances associated with each vegetation type. The amount of influence a variable has on each component is indicated by the value of its factor loading, listed in the Table 3.11 for water availability, substrate and morphology. The percentage variance explained by each PCA is also indicated in these tables.

For hydraulics, it is necessary to complete the PCA on the Cárcavo and Torrealvilla datasets separately as the low, medium and high flows computed are not the same for both channels. The Torrealvilla drains a much larger catchment area than Cárcavo and is able to generate significantly larger floods. Fig. 3.8 shows the output of PCA on the high flow computed for Cárcavo and Torrealvilla. There is a fairly clear grouping of *T. canariensis* and *N. oleander* together, this attributed in part to their comparable roughness values. Sites with no vegetation and grasses have comparably high flow velocities, these being located in high velocity areas, closer to the thalweg where flows reach greater depths.

Table 3.10 List of independent variables and groupings chosen for principal component analysis

Code	Description	Water availability	Substrate	Morphology	Hydraulics
Relev_site	Height above thalweg (m)	X	X	X	X
SDelev_site	Standard deviation of site (m)	X		X	X
Slope	Slope at site	X	X	X	X
Cd_up	Distance to checkdam upsteam (m)	X	X	X	X
CD_do	Distance to checkdam downstream (m)	X	X	X	X
BC_width/ V_width	Bankfull width/Valley width ratio			X	
IC_width/ IC_Adepth	Inner channel width/ Inner channel depth ratio			X	
BC_width/ BC_A depth	Bankfull width/depth ratio		X	X	
VWB_lith	Lithology of valley wall		X		
Chann_morph	Morphology of channel, position of site with respect to channel			X	
Substrate	Substrate – field textural classification (1–16)	X	X		
Re_Substrate	Simplifed substrate – fines dominant, gravels dominant, bedrock dominant	X	X		
D_bedrock	Depth to bedrock (m)	X			
D_water	Depth to water (m)	X			
Carbon	% Carbon from surficial sediments		X		
text_gravel	% Gravel		X		
Text_sand	% Sand		X		
Text_mud	% Mud		X		
So_d	Mean depth (section)				X
So_v	Velocity (section)				X
So_totp	Total Power (section)				X
So_unitp	Unit Stream Power (section)				X
So_br	Blockage ratio				X
So_ir	Inundation ratio – height of water/height of plants				X
So_ss	Shear stress (section)				X
To_q	Discharge across cross-section for flood stage (total)				X

(continued)

Table 3.10 (continued)

Code	Description	Water availability	Substrate	Morphology	Hydraulics
To_xsa	Total cross-sectional area (total)			X	X
To_v	Velocity (total)				X
To_totp	Total Power (total)				X
To_unitp	Unit Stream Power (total)				X
To_ss	Shear Stress (total)				X
Status	Index of connectivity		X		

Review of the PCA for water availability, substrate and morphology indicated that substrate (% sand, % gravel), index of erosion/connectivity, depth to bedrock, and height above thalweg were most important in explaining the variance of conditions (as indicated by their high factor loadings). A final PCA was conducted on these variables. This PCA showed very clear separations between *T. canariensis* and *N. oleander* dominated sites and the different density of grasses (Fig. 3.9). Reeds appear across a range of conditions, but a larger proportion of the sites with Reed dominated sites appear to coincide with areas of net storage, fine substrates, and greater depths to bedrock (these conditions are satisfied upstream of check dams).

In summary, Principal Component Analysis of the environmental dataset indicates that substrate is particularly important, but linked with this is also the index of potential connectivity/overall status of the reach. *T. canariensis* are rooted in fine substrates, sites where they are located are classified as areas of net storage, this coinciding with areas upstream of check dams where sedimentation of fines occurs. In contrast *N. oleander* are rooted in gravel substrates, and within the channel network these are mapped as areas of erosion, sediment transport and storage, tending to be part of a larger bar structure or former channel surface. Grasses do occupy a range of substrates. However, for a high density of grass cover to establish, fine sediments are important and these sites fall within reaches that are classified as areas of net storage. The second factor which is considered important is that of water availability, though the distinctions between the different vegetation types are not clear. This is probably in part, a problem of the difficulty associated with measuring this factor in the field. It is dynamic in nature, fluctuating considerably throughout the year in response to seasonal rains and flows. It is in the early stages of plant growth when water availability is most important but mapping and selection of sites is based on the distribution of mature vegetation assemblages. The variables we have measured and included in the PCA of water availability are an index of the potential for water to be available at a site. What is revealing from this PCA is the wide range in which *T. canariensis* dominated sites are found, extending into areas where depth to bedrock and water is greatest. This is supported by what is known from existing literature that *T. canariensis* has a

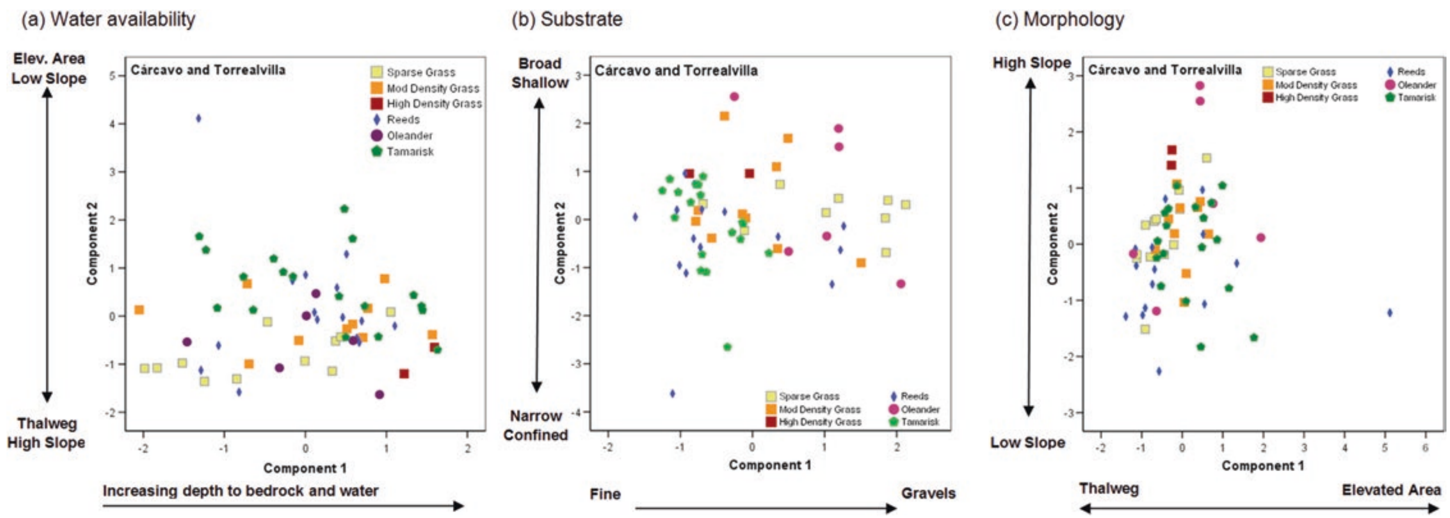
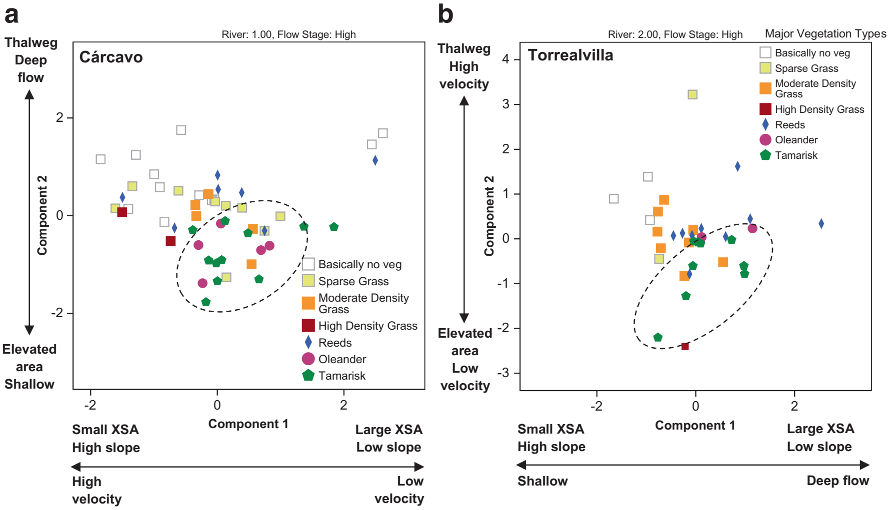


Fig. 3.7 Principal component analysis plots for (**a**) Water availability, (**b**) Substrate and (**c**) Morphology. Details of variables included in each PCA and their factor loadings are outlined below each scatterplot of components

Table 3.11 Table results of principal component analysis for (a) water availability, (b) substrate and (c) morphology

(a) Water availability				(b) Substrate				(c) Morphology			
Comp.[a]	% V.E.[b]	Variables	F.L.[c]	Comp.[a]	% V.E.[b]	Variables	F.L.[c]	Comp.[a]	% V.E.[b]	Variables	F.L.[c]
1	37 %	Depth to water	0.83	1	36 %	Substrate	0.87	1	35 %	S.D. of elevation	0.92
		Depth to bedrock	0.79			Status	−0.8			Height above thalweg	0.92
		Dist. to checkdam downstream	−0.69			% Gravel	0.78			Bankfull width/ valley width	−0.14
		Simplified substrate	−0.63			% Sand	−0.43			Bankfull width/ average depth	−0.11
						Slope	0.43				
2	26 %	Height above thalweg	0.78	2	17 %	Bankfull width/ average depth	0.76	2	27 %	Slope	0.8
		Slope	−0.59			Height above thalweg	−0.59			Bankfull width/ valley width	0.75
		Simplified substrate	−0.53			Slope	0.48			Bankfull width/ depth	0.3
		Depth to bedrock	0.47							Height above thalweg	−0.17
										S.D. of elevation	−016
KMO Statistic = 0.61, Total Variance Explained = 63 %				KMO Statistic = 0.71, Total Variance Explained = 53 %				KMO Statistic = 0.56, Total Variance Explained = 62 %			

[a]Component, [b]% Variance Explained, [c]Factor Loading



Com p.[1]	% V.E.[2]	Variables	F.L.[3]
1	40%	Cross-sectional area	0.86
		Slope	-0.83
		Average velocity	-0.77
		Height of flow in zone	0.567
2	35%	Height of bed above thalweg	-0.83
		Height of flow in zone	0.74
		Inundation ratio	0.62
		Average velocity	0.52

KMO Statistic = 0.67, Total Variance Explained = 75%

[1] Component, [2] % Variance Explained, [3] Factor Loading Explained, [3] Factor Loading

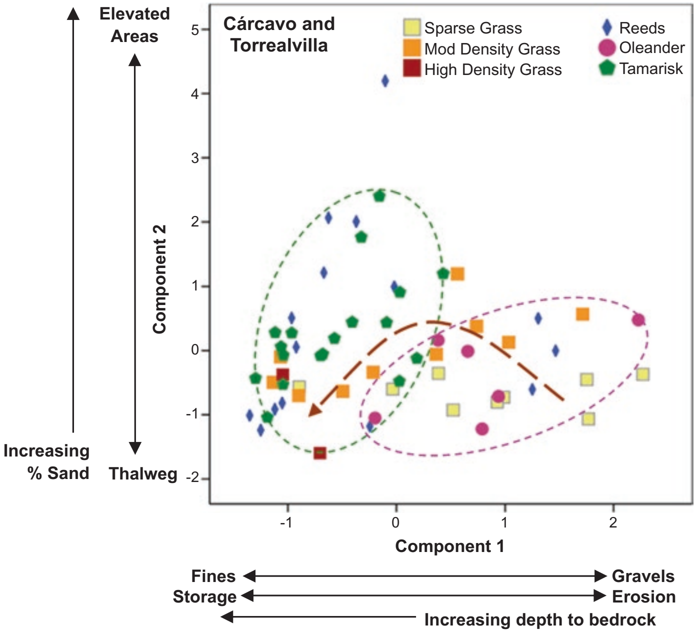
Comp.[1]	% V.E.[2]	Variables	F.L.[3]
1	43%	Cross-sectional area	0.93
		Slope	-0.92
		Height of flow in zone	0.67
		Average velocity	-0.65
2	29%	Height of bed above thalweg	-0.80
		Average velocity	0.62
		Height of flow in zone	0.61
		Inundation ratio	0.59

KMO Statistic = 0.67, Total Variance Explained = 72%

[1] Component, [2] % Variance

Fig. 3.8 Principal Component Analysis plots of hydraulic variables for (**a**) Cárcavo sites at high flow (40 $m^3\ s^{-1}$). (**b**) Torrealvilla sites at high flow (200 $m^3\ s^{-1}$). Details of variables included in each PCA and their factor loadings are outlined below each scatterplot of components

high tolerance to water stress (Levine and Stromberg 2001). The conditions required for reeds do not emerge clearly, and it is considered that perhaps the localised conditions where ponding occurs are not highlighted in the environmental variables measured.



Comp. [1]	% V.E. [2]	Variables	F.L. [3]
1	40	Substrate	0.92
		Status	-0.80
		Depth to bedrock	-0.77
		% Gravel	0.75
2	18	Height above thalweg	0.82
		% Sand	0.68

KMO Statistic = 0.74, Total Variance Explained = 58%

[1] Component, [2] % Variance Explained, [3] Factor Loading

Fig. 3.9 Principal component analysis of high scoring variables showing segregation of vegetation. *Arrow* shows trend of increasing density of grasses with greater proportion of fine sediments

3.4 Summary of Results on Required Conditions and Implications for Restoration

The conditions for the establishment and growth of vegetation at different spatial scales, levels of organization and mechanisms have been reviewed and analysed across the different land units. No one of the perspectives is complete but by assembling different aspects of them it is possible to get a more general picture of the necessary conditions for future restoration projects.

The availability of a detailed map of vegetation cover for the whole basin lets us study the effects of environmental variability on vegetation cover. It is confirmed that variations in vegetation cover are coupled to this variability. Slope gradient and unfavorable lithology as surrogates of hydric, nutritional and erodibility attributes of the ecosystems clearly limit the vegetation cover. The traditional approach of restoration has been to try to overcome these limitations. In fact this did not work well as limits to growth are intrinsic to nature. Extensive approaches like this should lead to delineate *maximum potential* cover for vegetation (or other attribute like LAI) and some progress has been made towards this. The methods here applied are not yet valid to establish this maximum potential as they are based on *mean* values of cover for a particular combination of environmental factors, in the sense that when modelling vegetation cover it is not taken into account possible effects of disturbance (human or natural), variability in other factors not accounted in our survey, etc. Basically, it is necessary to delineate a statistical methodology aimed to estimate maximum potentiality instead of mean values. However, results like those presented here could be a first operative tool to plan limits on the vegetation cover to be achieved in a restoration *given* some environmental *conditions*.

The potential pitfalls of a purely environmental approach is the unexpected behaviour of cover in shrubland and grasslands with respect to slope gradient and solar radiation. Availability of new better images and refined techniques of image analysis seem to suggest that: (i) environmental factors themselves could fail to explain vegetation cover if: human disturbance, present or past, is not accounted for; (ii) used surrogates can be useless in areas where dominant processes are singular like the strong erosive dynamics of Cárcavo catchments. Such is also the finding of the work on analysis of vegetation within abandoned and reforested lands, where the natural occurrence of vegetation species has been highly disturbed by human influences.

On these grounds we advocate the routine inspection of conditions for growth of areas to be restored using high-resolution images, using simple surrogates to model vegetation attributes and then inspecting what and why they are departing from previous assumptions. It will allow identification at the ecosystem and landscape level of where the conditions are adequate and above all, what limit the conditions impose on the possible development of vegetation.

The study of the relationship between conditions and planted *Pinus halepensis* and growth pointed out clearly how environment limits the possibilities of restoration of vegetation. Homogeneous treatment of a highly variable environment led to futile efforts as in unfavorable situations (high slope gradient, low infiltration and high runoff) mortality is very high, limiting establishment. On the other hand, those trees that survive have their growth clearly controlled by hydric stress and soil status as indicated by the significant effect of radiation and lithology. This large experiment provided by former management clearly indicates that conditions should be taken into account in any future planning. There are several ways of practical exploitation of this approach. Relationship between slope gradient and mortality can be used to establish limits to maximum gradient to be planted. Another similar approach is to estimate final densities, after differential mortality and to establish different densities of plantation according to slope gradient. Also, it can be established what combinations of environmental factors produce so slow growth that they are not considered viable for the objectives of restoration. These combinations of factors would be located in the field through GIS and will not be planted with the objective species. Comparing with whole scale basin analysis it could be apparent that a clear limit to vegetation development exists under these conditions, and then only very point-focused restoration would be carried out, for instance to short-circuit connectivity of the systems.

At the micro-scale physical and chemical attributes of litter layer have been shown to hamper soil development and germination dynamics. The litter layer of dominant species may be working as a physical barrier preventing the seedling establishment and the effective rain infiltration, but also can have significant allelopathic effects on the seed germination and early growth of plants. On the other hand, the planted vegetation had a negligible effect on the soil quality in the medium term due to the combination of poor litter decomposition and adverse climatic conditions. Also, increased soil organic carbon concentration of reforested areas was counteracted by higher rates of soil organic carbon erosion in well connected slope-channel areas (Boix-Fayos et al. in press).

Altogether, *a priori* approaches to semi-arid vegetation restoration that are based on simplistic assumptions that large scale afforestation will trigger secondary succession are risky if their effect is not previously tested; they are highly questionable and are doomed to failure. More finely targeted actions may be necessary to speed up soil quality improvement and secondary succession, for example choosing species with better litter quality, or managing the litter of pines by selectively removing it to facilitate the seedling establishment of subdominant species and spreading it on rills to increase rugosity and decrease connectivity of water and sediment flows. Many unexpected results may arise from the intrinsic complexity of the ecological relationships, which need to be addressed in detail.

Water availability is the main factor limiting the growth of cover crops in croplands. Soil type is also significant in influencing water retention capacity. Variations in soil type and topography at the field scale influence water availability for cover crops and orchards. The application of cover crops may be beneficial in decreasing erosion; however, their application needs to be adapted to the management and growing season of the main crop. The main concern is over the potential for competition for water between the cover crop and the main crop leading to subsequent reductions in yield.

In Semi-natural and Abandoned lands the vegetation on 134 plots were identified covering a range of substrates and types of land use, and a range of environmental variables were measured in the field and from a digital terrain model. Principal component analysis of main vegetation species and environmental variables revealed clear separation of species found in abandoned lands from those found in natural forest areas, difference between early and late succession species. Interpretation of the analyses requires careful consideration as a strong negative relation between a particular species and environmental variable does not necessarily mean that species will not grow in that environment. For example, *Pinus halepensis* has a very significant ($P<0.001$) negative association with abandoned land, but this can be explained by the slow secondary succession and the absence of reforestation on abandoned land.

Principal Component Analysis techniques has resolved the main factors that are important in influencing plant establishment, and the requirements for different types of vegetation along river channels. Substrate has been shown to be particularly important, but also linked to this is the degree of connectivity/overall sediment status of reach. Fines are particularly important for establishment of the perennial tussock grass *Lygeum spartum* and *Tamarix canariensis*, whilst on coarse substrates *Dittrichia viscosa* and *Nerium oleander* are more likely to establish. Water availability is also considered important. The distribution of check dams has a strong influence on conditions for different plants to establish in the channel.

In summary, a top-down, landscape approach in studying conditions for vegetation establishment and growth could be interesting in order to produce successively improved approaches to the restoration of an area. This successively improved approach goes from ecosystem attributes at catchment scale looking for deviations of a purely resource-based ecosystem functioning that could indicate operation of disturbances to physico-chemical conditions for dominant species to subtle biological controls. To conclude, it is important to have in mind that conditions themselves impose limits to vegetation development that simply cannot be overcome by any 'restoration'. Setting these limits is a priority task.