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Chapter 5
Synthesis and Application of Spatial Strategies for Use of Vegetation to Minimise Connectivity

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Abstract The knowledge that has been acquired in the project RECONDES on critical conditions necessary for plants and on the occurrence of such conditions in the landscape is used in combination with the analysis of processes to develop strategies that could be applied at critical points and locations, identified by the connectivity mapping, to produce greatest effectiveness of the vegetation measures. This is achieved at the plot and land unit scale based on measurements of plant conditions, and at the catchment scale with the analysis of vegetation cover and conditions, both scales involving identification of erosion hotspots from connectivity mapping and modelling. These results have provided the framework for recommendations on spatial strategies and targeting of revegetation and restoration. The analysis of the effectiveness of different types of plants and species is used to select appropriate plants for different locations in the landscape. This has informed the development of practical guidelines produced for use by land managers and advisors. The research was developed in a Mediterranean environment but has wider applicability to drylands prone to erosion by water.

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5.1 Introduction

The knowledge that has been acquired on critical conditions necessary for plants and on the occurrence of such conditions in the landscape is used in combination with the analysis of processes to develop strategies that could be applied at critical points and locations, identified by the connectivity mapping, to produce greatest effectiveness of the vegetation measures. This is achieved at a number of scales: (1) at the plot and land unit scale based on measurements of plant conditions and identification of hotspots from detailed connectivity maps; and (2) at the catchment scale with the analysis of vegetation cover and conditions and identification of hotspots from the connectivity modelling. The outcomes of the work undertaken at each of these scales have been incorporated into the model EUROSEM, which has also been used to investigate the effect different measures have on connectivity. The analysis of the effectiveness of different types of plants and species is used to select appropriate plants for different locations in the landscape. This has also informed the development of practical guidelines (http://www.port.ac.uk/research/recondes/practicalguidelines/). *A copy of these guidelines can be found in the Extra Material associated with this volume.*

The following sections detail the outcomes of the analyses and the synthesis of the vegetation and connectivity components of the research to produce the spatial strategies for each type of land unit and at each scale. In each section we consider the criteria for selection of species, the conditions and constraints on implementation in that type of location, and the optimisation of location of the vegetation. The desirable characteristics of plants for greatest effectiveness in reducing erosion and sediment flux or encouraging infiltration of water were listed in Table 1.2 (Chap. 1) but are presented here again for reference (Table 5.1).

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Table 5.1 Desirable plant characteristics for erosion control

Properties
Native species
Germinates and/or propagates easily
Rapid growth rate
Perennial or persistent
Ability to grow in a range of substrates
Drought tolerant
Produces a dense root system
Has a high threshold to withstand forces of water flow
Ability to trap water and sediments

5.2 Application at Hierarchical Scales

5.2.1 Land Unit Scale

5.2.1.1 Reforested Lands

Extensive reforestation works using terracing to reduce runoff and improve soil water availability for plants have been carried out in Spain and elsewhere for more than three decades as the main method to control soil erosion in degraded areas. As a consequence, large areas of the Mediterranean landscape have been topographically altered and covered by a homogeneous, even-aged, and single-species planted forest, primarily *Pinus halepensis*. Landscape remodelling was undertaken using heavily mechanized techniques, such as bulldozer terracing and subsoiling, but the altered topography and vegetation cover have given rise to degradation processes which it is necessary to act upon. Terracing involves, to varying degrees, a modification of topography that can affect landscape connectivity. Defective terraces, which are not perpendicular to slope, act as fast runoff pathways. Local default in terraces seems to increase the hydrological connectivity. Finally, higher connectivity is favoring the collapse of old reforestation terraces and the migration upstream of the drainage network (Chap. 2).

Most reforestation works were carried out without considering the inherent spatial heterogeneity of conditions within Mediterranean landscapes. Thus, success of reforestations has been very varied depending on mesoscale environmental characteristics (climatic conditions, lithology, soil type and local water balance) and soil preparation techniques. Dense stands of planted trees exist alongside almost bare patches where only a few stunted plants have survived. A medium term survival rate of 50 % survival rate has been reported in studies on effectiveness of *P. halepensis* reforestations in semi-arid Mediterranean environment. Furthermore, data from Spanish National Forest Inventory revealed that the medium cover of >40-years old *P. halepensis* plantations is 30 %. It is generally hypothesised that through vegetation growth an improvement of soil properties in reforested lands will develop.

However, results of analysis of soil properties in *Pinus* plantations are contrasting. While some studies suggest that planted forest may improve soil properties in decades, others have found lower soil organic content and nutrient concentration under *Pinus* plantations than in adjacent shrublands. It can be concluded that edaphologenetic processes are not fostered fast enough to counterbalance the initial impact of plantation techniques. The duality terrace/sidebank created a system where vegetation colonization of the most exposed microenvironment is severely hampered. In Southeast Spain, after 30 years the bank is hardly colonized, bare soil is 12 times more frequent than on the terrace. On the other hand, the species pool is severely depleted and species richness is less than half that on original slopes. The poor colonization may also be a consequence of the development of a recalcitrant litter layer. In fact, *Pinus halepensis* litter decomposes with difficulty, especially under the dry conditions of a semi-arid environment. This fact leads to a layer of litter that physically and allelopathically affects the germination of seeds and the growth of seedlings that may hamper demographic recovery of the understorey layer. New restorations should aim to delineate the maximum potential for vegetation in the landscape and develop appropriate vegetation strategies. Knowledge of species interactions and demographic processes have to be incorporated into the design of the restoration.

In Reforested lands, focus is on plants which can be planted to strengthen side banks and reduce runoff from terraces that contribute to headwater development of rills and gullies. The following three vegetation strategies are recommended to correct negative impacts and reduce connectivity in Reforested Lands.

1. Vegetation should be planted where the rills originate, where terraces are collapsing or across terraces not perpendicular to slope as these will form zones of runoff during rainfall events.
2. Side banks are much more extensive structures. Massive plantations of vegetation are expensive, and mostly unsuccessful because of the harsh conditions. Encouraging spontaneous or induced colonization should be the focus of the works. Microstructures built with natural barriers like wood, debris and stones should be established on the side banks in order to promote the trapping of water, nutrients and seeds. Conditions could be further improved by local addition of organic amendments (to improve soil infiltration and nutrient status) and seeding with side-bank adapted species.
3. In mature forests, some manipulation of litter layer and seeding of shrubs and grasses should encourage understorey development. This should be especially targeted at areas between trees that function as contributing headwater areas of rills and gullies.

In terms of species which should be considered, a combination of grasses and shrubs are recommended to provide the understorey cover in reforested lands. Of the grasses these are *Stipa tenacissima*, *Brachypodium retusum* and *Helictotrichon filifolium*. Shrub species recommended are *Salsola genistoides* on the side-banks, while for other spots *Rosmarinus officinalis* and *Anthyllis cytisoides* should be planted first, followed by *Rhamnus lycioides* and *Pistacia lentiscus*.

5.2.1.2 Rainfed Croplands

In rainfed croplands, the focus has been on assessing the feasibility of using cover crops and vegetation strips in preventing desertification of rainfed agriculture with water deficits. In developing criteria for selecting suitable cover crops, in addition to the general criteria for desirable plants (Table 5.1) the following points need to be considered:

1. Limited rooting depth (<= 30 cm) to reduce competition for water with perennial crops (Meerkerk et al. 2008).
2. Dominates undesired weeds
3. Annual species – perennial species are undesirable because in most cropping systems considered, the cover crops can only be grown during a part of the year.
4. Leguminous species because they may reduce fertilisation costs (Bowman et al. 2000; Ingels et al. 1998).

Olive orchards have one extra selection criterion for cover crops compared to almond orchards that is related to harvest operations. The olive oil harvest, which involves 97 % of the olive production, takes place from December to early March. In southern Europe it is still common to harvest by hand, spreading nets on the floor and beating the olives off the trees with sticks. This makes tall cover crops impractical. Therefore, the additional criterion is a limited height of the cover crop, ideally <= 10 cm. An alternative is to restrict the cover crop to the lanes in between the tree rows, or to remove the cover prior to harvesting.

Apart from the role of water availability, additional criteria must be met for the successful application of cover crops in rainfed agriculture. In semi-arid areas in general, the presence of cover crops on the field must be tuned to cultivation practices like sowing and harvesting performed on the main crop. In orchards and vineyards, cover crops can be grown throughout the year if there is enough water, whereas in annual cropping systems like winter cereals, the growth of cover crops will be restricted to the fallow year. Olive and almond plantations that are harvested by hand require a clean soil below the trees during the harvest period. Two specific issues can identified for the application of grassed waterways in thalwegs. The first is that thalwegs cross field borders and may require the cooperation of several landowners. In addition, grassed waterways can complicate tillage operations: more turning is required to leave the grass undisturbed.

Different types of cover crops can be considered, including weeds, legumes and grass species (Fig. 5.1). Ingels et al. (1998) have presented a selection of potential cover crops consisting mainly of winter annuals and legumes: in the target areas in Tuscany and Murcia, cover crops in summer are undesirable with regard to rainfed production. In addition, only species with a moderate to high seedling vigour should be selected.

The advantages and problems of use of cover crops in cropland are summarised in Table 5.2.

The selection and application of specific vegetation measures should be done on (sub)catchment level, taking into account the local climate, landscape and

Fig. 5.1 Potential cover crops include weeds (*left*), legumes (*middle*) and grasses (*right*)

Table 5.2 Major benefits and drawbacks of vegetation measures in cropland

	Benefits	Potential drawbacks
Cover crops/ vegetation strips	Effective protection against soil degradation and loss of soil productivity	Competition for water between cover crop and main crop
	Increased infiltration of rain water	Increase in production and equipment costs, especially when specific vegetation species are sown
	Improvement of soil structure	The green soil cover may lower the soil temperature in spring and increase the risk of frost damage in orchards
	The mulch left after chemical weeding prolongs the period of soil protection and decreases water loss by soil evaporation	
Grassed waterways	Reduced risk of gully formation	May require the cooperation of several landowners
	Reduction of runoff volume and peak discharge at (sub)catchment level	Reduced trafficability of fields

cropping systems. Figure 5.2 shows the priority areas to be protected during the rainy season: terraced orchards/vineyards when competition for water is high (left), orchards on steep slopes (middle) and sloping cereal fields (right). The dip slope of earth terraces can be stabilised by natural vegetation. This is a common and quite effective practice in many areas. The effect of cover crops on production will be limited when their growth is restricted to the thalwegs, even in dry areas.

Several water harvesting techniques can be used to increase the water availability for vegetation growth. For perennial crops, a method to maximise production is to adapt the crop spacing to the local climate (Tubeileh et al. 2004a). The roots of trees like almond and olive are able to mine the soil around their trunk. If the climate is drier and water availability lower, individual trees need a greater 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. This explains the rationale behind traditional tree arrangements, with up to 24 m bare soil between rows of trees, as still present in Tunisia (Ennabli 1993). Another way to increase water availability and water use efficiency is to apply a mulch. The aim of the mulch is to reduce the soil evaporation.

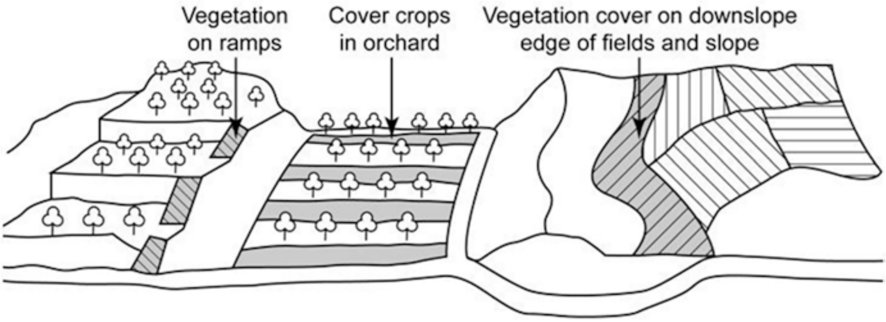

Fig. 5.2 Priority areas to be protected during the rainy season: terraced orchards/vineyards when competition for water is high (*left*), orchards on steep slopes (*middle*) and sloping cereal fields (*right*) (Hooke and Sandercock 2012)

5.2.1.3 Semi-Natural and Abandoned Lands

The *Criteria for selection of plant species* considered desirable for preventing terrace failure in semi-natural and abandoned lands are as identified in Table 5.1.

To mitigate soil erosion after agricultural land abandonment, and terrace failure specifically, the soil and water conservation practices can be divided into three groups: (1) maintenance of terraces and earth dams, (2) revegetation with indigenous species, and (3) restoring the original drainage pattern. The first option should include restoration of terrace walls after heavy rainfall and ploughing near the terrace wall to enhance the storage capacity and improve infiltration. This kind of management might even include subsidies for farmers who combine extensive agriculture with soil and water conservation. However, in the long term this option might not be very profitable, since the cost of subsidies will be high and when such a subsidy program stops the farmer might still abandon those fields, which means that erosion is only delayed.

For the second option of revegetation a distinction can be made between (i) revegetation on the terrace to improve infiltration and (ii) revegetation of terrace walls and zones with concentrated flow to prevent or mitigate gully erosion. Gyssels et al. (2005) conclude that for splash and sheet erosion vegetation cover is the most important parameter to control erosion, but for rill and gully erosion the effect of plant roots is at least as important. De Baets et al. (2006) demonstrate that especially grass roots are very effective in reducing soil detachment rates under concentrated flow. An increase in root density from 0 to 4 kg m^{-3} already decreases the relative soil detachment rates to very low values. Hence, vegetation species with a dense rooting system and good vegetation cover are most suitable for revegetation of terrace walls. Indigenous species that accomplish these characteristics are e.g. *Lygeum spartum*, *Brachypodium retusum* and *Stipa tenacissima*. However, other characteristics such as germination and growth rate are important as well for successful mitigation of terrace failure. From an ecological point of view the re-establishment of the indigenous shrub vegetation is a key step in the restoration of abandoned agricultural semi-arid lands (Caravaca et al. 2003). However, the use of native grass species in concentrated flow zones seems to be more effective to mitigate erosion. Quinton et al. (2002) provide a list of indigenous Mediterranean species that can be used for the revegetation of abandoned land, including specific bioengineering properties.

The last option of restoring the natural drainage pattern is rather drastic, since it entails a complete destruction of the terrace function. This will probably result in much erosion during the first years and loss of soil moisture due to increased runoff. However, in the long term less sediment might be lost and, in combination with revegetation, a natural and stable landscape might evolve earlier. Modelling might help to evaluate which of these options is more sustainable in the long term, as verification in the field is very problematic due to the diversity in topography, substrate and land use and the infrequent occurrence of extreme events. This makes it difficult to find field sites with similar conditions but with different land management. Modelling should elucidate which of the soil and water conservation practices will be most effective and sustainable in the long term in different locations, settings and environments.

5.2.2 Hillslopes and Gullies

To select species for gully erosion control, plant characteristics that influence the resistance to concentrated flow erosion must be selected. Traditionally, total plant cover and contact cover were used to evaluate species for controlling sheet and interrill erosion. However, for controlling concentrated flow erosion, new criteria have been investigated in more detail and quantified (Chap. 4) and are identified as:

Above-ground plant characteristics

- Stem density (SD, $m^2\ m^{-2}$)
- Sediment trapping efficiency (TE, $m\ m^{-1}$)
- Resistance to flow shear forces (MEI, N)

Below-ground plant characteristics

- Root density (RD, $kg\ m^{-3}$) for the 0–0.1 m topsoil
- The fraction of fine roots (<5 mm) relative to total root mass (FR, %)
- Root area ratio (RAR, fraction) for the 0–0.1 m topsoil
- Root tensile strength (T_r, mPa) for 2 mm thick roots

These criteria address directly two erosion sub-processes:

- Hydraulic erosion
- Shallow mass movements occurring on gully banks

De Baets et al. (2006) demonstrated that grass roots are very effective in reducing soil detachment rates under concentrated flow. An increase in root density from 0 to 4 $kg\ m^{-3}$ already decreases the relative soil detachment rates to less than 5 % of

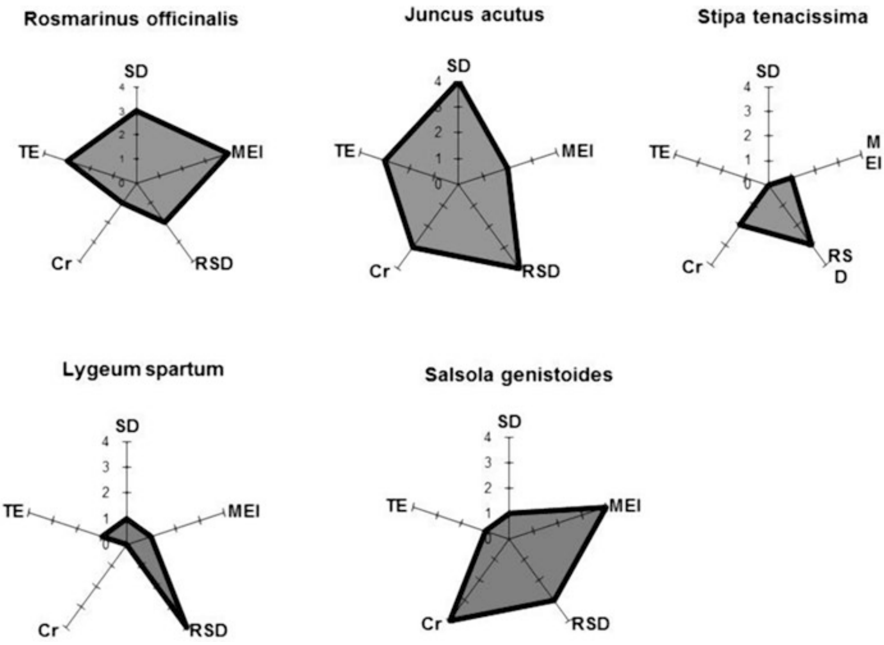

Fig. 5.3 Suitability of some Mediterranean plant species for rill and gully erosion control, based on their scores on the following criteria: Cr (kPa) is the root cohesion at 0.3–0.4 m soil depth, MEI (N) is the index of stiffness, SD ($m^2\ m^{-2}$) is the stem density, RSD (dimensionless) is the topsoil erosion reducing potential of plant roots during concentrated flow erosion and TE ($m\ m^{-1}$) is the trapping effectiveness (after De Baets et al. 2014)

the values for a rootless topsoil. Fine roots are found to be more effective in reducing concentrated flow erosion rates as compared to thick roots (De Baets et al. 2007a). The properties of some key plants suitable for use are shown in Fig. 5.3 in relation to the identified characteristics.

Planting species in rows perpendicular to the flow direction will provide an optimal resistance to erosion and a better ability to trap sediments and organic debris. Combining with the results of Rey (2003, 2004) it is recommended that on gully floors 50 % cover of low vegetation with high trapping effectiveness (e.g. *Juncus acutus*) in the gully floor renders the surface inactive (Rey 2003). Vegetation barriers can be established in gullies to further prevent soil loss; a downslope vegetation barrier covering only 20 % of this plot can be sufficient to trap all the sediments eroded upslope (Rey 2004) using species such as *Rosmarinus officinalis.* On terrace bank or gully walls planting species to prevent shallow mass movements should use deeply rooted shrubs such as *Anthyllis cytisoides, Salsola genistoides, Retama sphaerocarpa, Tamarix canariensis, Atriplex halimus* (De Baets et al. 2008).

5.2.3 Channels

Plant species were assessed on their potential use for restoration of ephemeral channels according to the list of desirable qualities in Table 5.1, plus the following additional characteristics:

- High threshold for removal
- Do not create large woody debris
- Not too obstructive/reduce capacity by large amount
- Perennial or persistent
- Salt tolerant
- Create even sward

The analysis of conditions and hydraulics (Chap. 4) forms the basis for assessing the potential of different plants for reducing erosion, the areas where plants are most likely to be effectively established and thresholds for removal. This is completed through a process of matching conditions for growth of plants with areas of erosion as demonstrated in Table 5.3. Suggested species within each plant functional group are listed. Conditions for growth of plants are outlined, as broken down into categories of 'substrate', 'water availability' and 'morphology' (derived from PCA). Field monitoring of impact of flows on vegetation, coupled with calculations of hydraulics is used to assess the 'ability to reduce erosion' and 'threshold for removal'. 'Areas of erosion' where plants may be established for the purpose of reducing erosion are indicated.

Of the grasses, *Lygeum spartum* is identified as having great potential for reducing erosion in channels. While it has been found to establish in a range of substrates, a preference for fines appears to exist. Extended monitoring indicates that this species is highly resistant to erosive floods, has the ability to trap sediments and contribute to the net aggradation of the channel bed. Within Cárcavo, these grasses are found in high density where there is a high supply of fine sediments along the channel network. This corresponds with two areas within the drainage basin, the first one in the upper part of the channel network in close proximity to gullies where there is a high supply of fine grained sediments; the second area is in the downstream zone immediately upstream of check dams where there are high rates of sedimentation. However, these latter areas also provide favourable conditions for other species, (ie Reeds and Tamarisk) that respond to greater water availability as water ponds behind these structures. It is suggested that *Lygeum spartum* is planted in close proximity to gullies contributing fines with the aim of trapping these incoming sediments.

As herbs have a very low resistance to erosion by channel flow, and are generally annuals, they are not considered to have potential for reducing erosion, although they may play a role in improving the organic matter content of the substrates which is beneficial for the establishment of other plants. Reeds, while they may be swept over by relatively minor flows, increase the resistance of the substrate to erosion and encourage sediment trapping. Their distribution is quite limited to low gradient

Table 5.3 Potential plants and identification of possible areas of erosion where they may be established in order to reduce erosion activity and sediment connectivity

Functional Group	Qualities		Conditions for Growth			Ability to Reduce Erosion	Degradation Processes	Areas of erosion
Plant species	Desirable	Undesirable	Water Availability	Substrate	Morphology		Threshold for removal	
Grasses								
Lygeum spartum	High resistance to erosion	Requires fine material	Perennial, tolerant to drought	Range of substrate, prefer fines	Thalweg, upper parts of channel network	Generally high, varies with substrate	Removal by flows > 4 m.	Close proximity to incoming gullies contributing fines
	Ability to trap sediments							
	Can form dense stands							
	Perennial and persistent							
Herbs								
Numerous species	Variable substrates	Annuals, not persistent	Annuals, not tolerant to drought	Range of substrates	Bed, bars and floodplain	Low	Removal by flows > 1 m	–
Reeds								
Phragmites australis	High resistance to erosion	Require high moisture content	High water requirement, ponded areas	Range of substrates, prefer fines	Scoured areas, thalweg, low gradient	Low-Moderate	Swept over by flows < 1 m	Low gradient reaches, thalweg in areas of ponding
Juncus sp	High thresholds	Invasive						
		Reduce biodiversity						
		Obstructive						
		Aesthetics						
		Fine sediment						

(continued)

Table 5.3 (continued)

Functional Group	Qualities		Conditions for Growth			Ability to Reduce Erosion	Degradation Processes	Areas of erosion
Plant species	Desirable	Undesirable	Water Availability	Substrate	Morphology		Threshold for removal	
Shrubs								
Dittrichia viscosa	Perennial	Low ability to trap sediments	Drought tolerant	Gravels	Bar surfaces	Low	Removed by flows > 1 m	Gravel beds, bars and raised surfaces
	Coloniser on gravel bars							
	Ability to trap sediment in dense stands							
	Can form quite dense swards							
	Resprouts easily							
	Moderate resistance							
Nerium oleander	High resistance to erosion	Highly poisonous	Drought tolerant	Gravels	Bar surfaces	Moderate	Removed by flows > 3 m	Gravel beds, bars and raised surfaces
		Ground cover usually limited						
	High thresholds for removal	Some limited woody debris						
	High resistance to drought	Low ability to trap sediments						
	Not invasive?							
	Perennial and persistent							
	Variable substrates							
	Sprouts easily but germination requires water							

Trees								
Tamarix canariensis	Very high resistance to erosion	Creates large woody debris	Drought tolerant	Fines, areas of sediment storage	–	High	High resistance to removal, flows > 5 m.	Thalweg and bars, close proximity to check dams
	High thresholds for removal	Invasive						
		Obstructive						
		Prefers fine sediment						
	Ability to trap sediments	May lead to excessive widening of channel, switching of flow, incision of non-Tamarisk part.						
	Perennial and persistent							
	Withstand drought							
	Can create even cover but high level canopy							
	Germinates and propagates easily							
	Salt tolerant							

reaches, where ponding occurs, this providing the extra water required for their survival. Experimental studies indicate that *Phragmites australis* has a marked effect in reducing erosion, with high stem densities increasing the retention of sediments and the finely distributed mat system protecting the surface against erosion (Coops et al. 1996). Even when swept over by floods, the recovery of reed communities can be rapid, with above ground biomass being replaced very quickly through the emergence and growth of new shoots. Establishment of reeds in low gradient reaches and thalweg where there are freshwater ponds may be effective in increasing the resistance of the bed to erosion and trapping sediments.

The two common shrub species that could have potential for erosion reduction, *Dittrichia viscosa* and *Nerium oleander* both have a preference to gravel substrates. However, *Dittrichia viscosa* has quite a low resistance to erosion and is generally removed by moderate sized floods (>1 m). Its ability to trap sediments is also quite limited due to its size and form. *Nerium oleander* can form a significant roughness element in the channel, serving to reduce the velocity of flows through a reach. Whilst its ability to trap sediments is considered quite low, its resistance to erosion is rated high. A major flood (>3 m) would be required to sweep over a mature individual, and, unless it is scoured out at its base through the removal of surrounding substrate, it is likely to recover. Individual bushes also add considerable roughness value to the channel and are therefore effective in reducing the velocity and power of floods along these channels. It is suggested that these be encouraged to grow in areas of sediment transport and storage (gravel beds, bars and raised surfaces).

Tamarix canariensis is by far the dominant native tree species present along these channels; its distribution has increased as a result of the construction of check dams. The large volumes of fine grained sediments stored upstream of the structures, and ponding of water that occurs in these zones provides favourable conditions for plant establishment. They also have high resistance to long periods of drought and high salinity levels, and are therefore well suited to the extremes of conditions that characterise these channels (DiTomaso 1998). Their ability to reduce erosion and resistance to removal is rated as high. Areas of erosion where they may planted include the thalweg and bars, and in close proximity to check dams. However, some concern exists about its use as they are highly invasive, can dominate the riparian community and in larger channels they have been associated with increased braiding and avulsion in south-western USA (Graf 1983). Further consideration is required on whether similar problems could be expected to arise within the ephemeral channels in Southeast Spain. The aesthetic quality has also been questioned. *Retama sphaerocarpa* has similar properties to Tamarisk and grows predominantly in schistose substrate channels of Southeast Spain.

The threshold for removal appears to be very high, though they can be removed by lateral incision, but if they are removed then they have the potential to form large woody debris, now considered beneficial on some channels, but long considered a flood hazard in some regions (e.g. Italy). Even if *Tamarix canariensis,* and similarly *Retama sphaerocarpa*, are severely damaged by high flows they have a strong capacity to resprout from damaged pieces and this may relatively quickly revegetate an area.

Within the channels, we have identified the following as goals to guide planting strategies: 1.minimise the delivery of sediments to the channel and maximise sedimentation within channel, but not to the extent that it causes problems (ie. erosion downstream by clear water flows); 2. minimise erosion along the channel through the effect vegetation has in reducing velocity of flows and increasing overall resistance of channel to erosion.

The following areas are identified as erosion hotspots in channels: incoming gullies; confluences; thalweg; areas downstream from check dams; valley walls undercut by the stream. Vegetation can potentially mitigate erosion and reduce sediment connectivity in all these sites with the exception of active valley walls, which are generally too steep. Valley walls represent a significant source of sediments. Channel widening through erosion of valley side walls is the most effective means a channel has to reduce its force. If this was to be restricted, then the channel will be forced to incise its bed at an accelerated rate. It is critical that planting strategies are based on a sound understanding of the local environmental conditions, particularly substrate and water availability and existing sediment connectivity, but also position within the channel and exposure to high forces. The likely influence that planted vegetation (and any associated measures) will have on future connectivity and possible sediment deficit also needs to be considered.

While the aim is also to minimise the amount of structural interventions, it may be advantageous to have some structural measures which will favour vegetation establishment. For example, construction of a small log/stone structure across incoming gully/thalweg of channel and planting of vegetation immediately upstream of the structure in an area where sedimentation is expected to occur could be effective. This may be necessary in the situation where there is insufficient substrate at a site for planting (i.e. site eroded to bedrock, high connectivity of sediments through reach). Sedimentation induced upstream by the structure and change(s) in moisture status may alter the conditions such as to improve seedling establishment. Such bioengineering measures have been trialled in marly gullies in the southern Alps, France, the improvement in soil water conditions increasing the capacity of the sediment deposits to allow germination (Rey 2006).

The following four areas are highlighted as areas where vegetation may be encouraged to mitigate erosion and reduce sediment connectivity. Possible bioengineering measures are proposed.

1. Incoming gullies, where the gully has incised to bedrock and is bare. Construction of small log/stone structure across floor of gully and planting of vegetation in sedimentation area upstream. Choice of planting depends on substrate, but if fines: *Lygeum spartum* and *Tamarix canariensis*.
2. Fan from gully/tributary, sediments are input to the channel and deposited immediately downstream from the confluence as a fan. Construction of stone bund around the edge of the fan and planting of vegetation in sedimentation area upstream. Choice of planting depends on substrate. If coarse gravels: *Dittrichia viscosa* and *Nerium oleander*, if fines: *Lygeum spartum* and *Tamarix canariensis*.

3. Small thalweg of channel. Construction of logs/stone structure across thalweg and planting of vegetation in sedimentation area upstream. Choice of planting depends on substrate, but if fines: *Lygeum spartum* and *Tamarix canariensis*.
4. Areas downstream of check dams. Very difficult to establish vegetation in these areas if there is no sediment. Suggest that vegetation is also planted in areas immediately downstream of check dam at time of construction. If coarse gravels: *Dittrichia viscosa* and *Nerium oleander*, if fines: *Lygeum spartum* and *Tamarix canariensis*. If it is an area where water ponding occurs, consider planting reeds such as *Phragmites australis* and *Juncus* species.

5.2.4 Catchment Scale and Synthesis

These various strategies can be put together at the small catchment scale in a spatially integrated strategy. An example of this is given for a small sub-catchment area of Cárcavo, SE Spain (Fig. 5.4), which includes field terraces and a track crossing the catchment. The area is mostly a mixture of almond and olive trees with a small area of abandoned land. Pathways of runoff and erosion occurring in several events (red arrows) and areas where sediments were deposited (grey areas) are shown. The steep uplands and area of abandoned land were a significant source of runoff. Many of the larger rills commenced immediately east of the road, with connecting pathways following the natural drainage line that exists in the landscape. There was also significant runoff along the elongated terraces as they are not constructed on the contour.

Figure 5.4 outlines suggested strategies that could be applied to the hotspot areas and pathways to reduce the potential connectivity in the landscape. These can be summarised as follows:

- Establish more vegetation on terrace banks. Suitable species include grasses like *Lygeum spartum, Brachypodium retusum* and *Stipa tenacissima* in combination with more deeper rooted shubs like *Anthyllis cytisoides, Atriplex halimus* or *Salsola genistoides*.
- Plant vegetation on flat terraces of abandoned lands and vegetate banks. Suitable species include *Lygeum spartum, Brachypodium retusum* and *Stipa tenacissima*.
- Plant cover crops in tree lanes of all fields in winter time (cover up to 50% of field area). Planted cover crops should follow the contour as much as possible. Planting winter annuals and weeds is recommended.
- Plant vegetation at sides of tracks. Suitable species include *Brachypodium retusum*.
- Plant vegetation along the natural drainage line (grassed waterway). Suitable grass species include *Brachypodium retusum*. Where water accumulates plant *Juncus sp*.

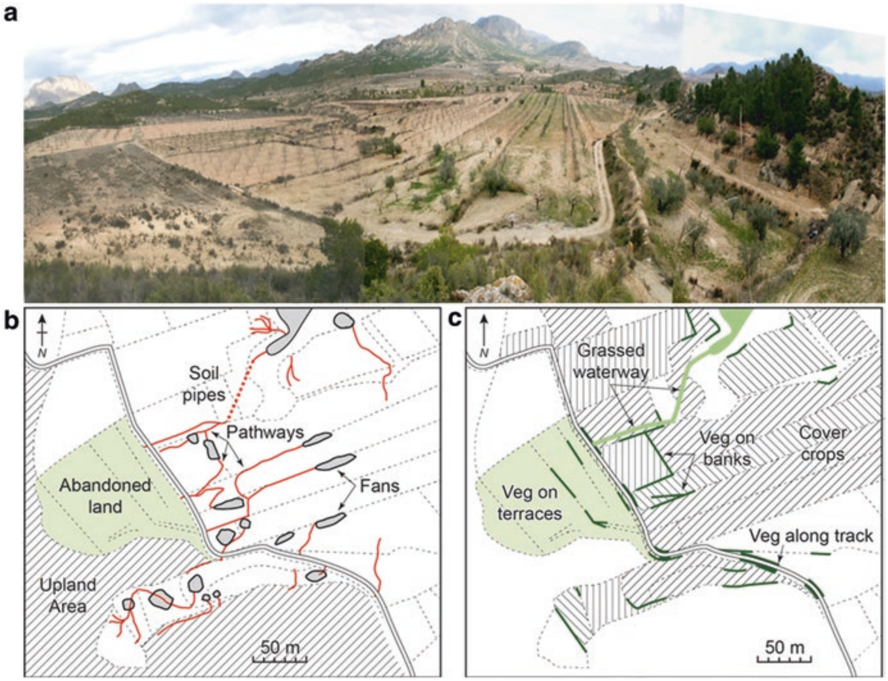

Fig. 5.4 (**a**) Photograph of a sub-catchment of Cárcavo, (**b**) Mapped connectivity pathways, (**c**) Suggested strategy for erosion reduction and increase of sedimentation by connectivity minimisation (after Hooke and Sandercock 2012)

5.3 Guidelines

A set of guidelines has been compiled based on detailed studies of vegetation and its positive effects in mitigating erosion and reducing connectivity at a range of scales. The purpose of these guidelines is to provide information on how problems of soil erosion and land degradation may be controlled by the application of innovative vegetation strategies with existing soil conservation measures. These strategies target specifically those hotspot areas in the landscape where erosion is a problem at present, or which, if improperly managed, will become a significant problem. The approach is different from other approaches in that it identifies hotspots and focuses on the application of appropriate vegetation species to these areas and their position in the landscape, whereas other approaches are applied across the entire landscape. These guidelines are suitable for dryland environments of the Mediterranean region of southern Europe, and they are based on research in Southeast Spain. These guidelines are presented in the Supplementary Material.

5.4 Summary

In this chapter a range of vegetation strategies has been suggested for mitigating erosion and reducing connectivity, and these are also communicated within the guidelines document which was disseminated to landowners, land managers and policy makers In Spain and Italy and is available at http://www.port.ac.uk/research/recondes/practicalguidelines/. These strategies can be summarised below as a series of recommendations, which apply to particular land units and hotspots, as listed below.

- In Reforested Lands, microstructures which trap sediments and nutrients could be applied to the side banks and on terraces the needle litter layer removed to improve vegetation establishment.
- On Abandoned Lands existing terraces should be maintained and failures repaired after events. Dense rooted grasses should be planted on reformed banks and in areas of concentrated flow.
- Consider correcting terraces that are not constructed on the contour and breaking up long terraces, as these concentrate runoff and contribute to erosion problems downslope.
- In croplands establish winter cover crops in access lanes between trees, but cover should not exceed 50 % of terrace. Cover crops should then be killed off at the end of the winter period.
- Plant vegetation cover along edges of tracks, particularly where these cross a drainage line or gradient changes such that the track begins to concentrate runoff.
- Where there are natural drainage lines crossing fields establish grassed waterways. Double drilling techniques should also be used when seeding these areas. Establish vegetation on gully floors.
- In small channels, revegetation efforts should focus on planting grasses in areas where there are fine sediment inputs. Small structures may be built to promote deposition and improve conditions for vegetation establishment.
- In larger channels, efforts should focus on establishing larger shrubs and trees as these will have a greater effect in reducing flow velocities and trapping sediments, therefore reducing sediment connectivity to areas downstream.

5.5 Wider Application and Global Implications

This approach of minimising connectivity and thus reducing soil erosion and sediment movement using vegetation in strategic spatial locations has been developed for the Mediterranean environment but is much more widely applicable. It is applicable to lands where the dominant degradation is by water. In such areas the patterns and locations of flow pathways and erosion hotspots can be identified and the contributors to connectivity targeted. Many traditional farming systems have recognised the need to minimise lengths and gradients of slope and have thus used terracing or similar techniques. However, increased mechanisation and need for efficiency has meant many of these structures and practices are being abandoned or removed. Similar principles of identifying patterns of flow lines and zones of erosion apply in non-terraced landscapes.

The strategies and recommendations have been developed in relation to marl bedrock areas. Areas of this soft rock are particularly vulnerable to soil erosion and land degradation. However, the approach would be applicable to other soft rock areas and zones with vulnerable soils. Local research would need to be undertaken to identify suitable local plant species and test their properties. In some areas the soil and soft rock is susceptible to piping, especially in clay soil, and this can be a major contributor to land degradation, as in many parts of southern Spain. The piping is frequently associated with rills and with drainage lines, and with terraces on abandoned land. Indeed, in the area illustrated in Fig. 5.4. there was some large piping in the lower part of the hillslope (Hooke 2006). The connectivity approach can be applied to understand the pathways (Marchamalo et al. 2016) and these can then be targeted.

Likewise, these ideas and approach could be transferred to other regions of the world but it would require investigation or application of knowledge of local plants and their suitability for various locations to ensure optimal effectiveness and to avoid use of invasive, exotic or unsuitable plants. The strategy has been developed in relation to agricultural areas but it may be applicable to grazed areas. However, this is challenging because of the consumption of plants by the animals. In some areas, e.g. Ethiopia, exclosures have been successful. A key advantage of the strategy advocated here is that it does not take up large areas of land and make them unproductive. The key locations for planting are on margins of fields, on structures, tracks etc. Patterns of animal movement may also need to be considered on grazing lands but their relation to drainage and runoff lines can be examined. Strategic fencing of key areas could still be used in grazing lands.

In terms of climatic regions, those most vulnerable to increased desertification and land degradation are the arid margins of deserts, semi-arid lands and to some extent sub-humid lands. As long as the native plants and the processes are examined then the approach can be used. It is not applicable in areas prone to wind erosion and aeolian land degradation. There are other locations in which vegetation is removed, leading to land degradation and there is a need for land restoration using vegetation, including contaminated and industrial land but the latter have been subject to much research. The approach and recommendations here have not been developed in relation to intensively irrigated land and extensive lowlands where salinisation may the major problem and cause of land degradation. Application in such environments needs further consideration of water balances, salt tolerant species and groundwater relations. If surface water flow is not the problem then the connectivity approach advocated here is less applicable.

Scenarios of both climate change and land use change and their combination all point towards likely increased desertification and land degradation in many parts of the world. This is at a time of increased population and concern about future food security so land degradation is likely to increase without such measures as recommended here being taken.

Any implementation of the approach and strategies suggested here requires the cooperation of the land users and owners. The ideas need to be introduced and discussed within communities and adopted by them. It is suggested that local people could be readily trained up to identify signs of flow lines and erosion and that simple systems of mapping using facilities such as GoogleEarth could be implemented in a wide range of environments and communities. The approach is dependent on identifying the connectivity and thus whole patterns in the landscape. Any scheme will entail cooperation between farmers in areas so that the whole connected system is considered. The consequences of any disconnection, especially on water supply, need to be considered. However, such an approach is likely to have multiple benefits because, if water infiltrates to a greater extent, it is likely to sustain local water supplies more effectively and is likely to reduce risk of flooding from excessive overland flow.

The key to application of these spatial strategies is adaptation to the particular landscape. This entails understanding of the processes and their spatial patterns and matching attributes of the soil and plants to these in optimal locations for land degradation reduction.