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EFFECTS OF TOPOGRAPHY AND SURFACE SOIL COVER ON EROSION FOR MINING RECLAMATION: THE EXPERIMENTAL SPOIL HEAP AT EL MACHORRO MINE (CENTRAL SPAIN)

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ABSTRACT

Mining reclamation tries to reduce environmental impacts, including accelerated runoff, erosion and sediment load in the nearby fluvial networks and their ecosystems. This study compares the effects of topography and surface soil cover on erosion on man-made slopes coming from surface mining reclamation in Central Spain. Two topographic profiles, linear and concave, with two surface soil covers, subsoil and topsoil, were monitored for two hydrologic years. Sediment load, rill development and plant colonization from the four profiles were measured under field conditions. The results show that, in the case of this experiment, a thick and non-compacted topsoil cover on a linear slope yielded less sediment than carbonate colluvium or topsoil cover on a concave slope. This study also shows that vegetation establishment, which plays an important role in erosion control, depends on topography. Plant cover was more widespread and more homogeneous on linear profiles with topsoil cover. On concave slopes, plant establishment was severely limited on the steepest upper part and favoured in the bottom. This study suggests that management of topography and surface soil cover should be approached systematically, taking three outcomes into consideration: (i) topsoil can lead to a successful mining reclamation regardless of topography, (ii) created concave slopes can lead to a successful mining reclamation and (iii) topography determines the vegetation colonization pattern. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: topographical design; topsoil; constructed slopes; concave slopes; water erosion; vegetation

INTRODUCTION

Mining, which supplies materials thought essential for our society, has serious environmental impacts. Opencast mining impacts all ecosystem components: substrata, topography, hydrology (surface and groundwater), soil, vegetation, fauna, atmosphere and landscapes (Osterkamp & Morton, 1996; Evans, 2000; Rivas *et al*., 2006). Often, mining impacts also have adverse effects on nearby ecosystems. Among these off-site effects, the hydrologic impact of mines on downstream fluvial ecosystems is one of the most detrimental (Toy & Hadley, 1987; Nicolau & Asensio, 2000).

Theoretically, mining reclamation should reduce these impacts. However, in spite of the significant development of mining reclamation techniques over the years, failures on mining reclamation are common (Haigh, 2000). Inadequate management of landform design at many reclaimed mining sites has been identified as the main reason for reclamation failures because of accelerated water erosion (Loch, 1997; Nicolau & Asensio, 2000).

To achieve effective control of water erosion, an integrated management of topography, surface soil cover and vegetation is required (Nicolau, 2003). Of these three factors, the management of topography and surface soil cover is considered an essential component of mining reclamation practices by many (e.g. Evans & Willgoose, 2000; Toy & Black, 2001; Moliere *et al*., 2002; Toy & Chuse, 2005).

For mine reclamation to be successful, efforts also must be directed towards the creation of biologically functional and stable soils that reduce soil erosion and facilitate the rehabilitation of post-mined lands (Bradshaw & Chadwick, 1980; Whisenant *et al*., 1995). Soil erosion negatively affects vegetation growth through several mechanisms: the removal of seeds and nutrients from surface soil, direct plant removal and the loss of water through surface runoff (Pimentel *et al*., 1995; Espigares *et al*., 2011). Indeed, seeds removal is sometimes a negligible reason to explain the lack of vegetation even in bare surfaces (see Cerdà & García-Fayos, 1997). The most common soil surface used is topsoil (cover soil) spread on the slope surface; this approach is considered essential in most cases (Power *et al*., 1981; Kapolka &

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Dollhopf, 2001). Additionally, a wide range of modifications can be applied to improve physical and chemical soil properties (Bradshaw & Chadwick, 1980). Armouring surface with rocks is a convenient and cost-effective measure to decrease soil erodibility (Toy *et al.*, 2002).

The most common approach of topography management consists of terraced landforms, graded spoil banks comprising alternating short constant-gradient slopes and benches. Artificial ditches commonly drain off the concentrated runoff (Bugosh, 2006). Without maintenance, many terraced landforms succumb to water erosion in the long term (Loch, 1997). Linear slopes can be unstable, especially if the base level is continuously changing by ditch incision, which causes the slopes to respond by eroding or mass failure (e.g. Haigh, 1980, 1985). Erosion problems also arise because of ponding or exceeding the storage capacity of the terraces (Sawatsky *et al.*, 2000). According to Hancock *et al.* (2003), linear slopes erode and increase sediment loss until achieving a stable profile, which is usually concave. Additionally, we have reported how terraced spoil heaps in this physiographic setting of the Upper Tagus are not stable within a decadal span time, and they evolve to gullied landforms (see Sanz *et al.*, 2008).

Arguments have frequently been raised in favour of topographic designs that replicate “natural” landscapes. This geomorphic approach is based on knowledge of geomorphic processes, mostly fluvial processes operating for an extended time. The objective of these designs is the construction of steady-state landscapes (Riley, 1995; Schor & Gray, 2007).

Application of truly geomorphic approaches (Sawatsky & Beckstead, 1996; Toy & Chuse, 2005) depends very much on the exploitation method and timing. Implementing a geomorphic approach is more difficult and expensive in active mines that already have terraced landforms. Often, only basic modifications of individual slopes (contour berm or contour linear steep slope) can be cost-effective. Geomorphic approaches are easier to implement before mining activities start or at abandoned mines. These two situations highlight the success of Bugosh’s approach, a computerized method (GeoFluv) of mining reclamation based on fluvial geomorphic principles (Bugosh, 2004). His approach seeks hydrologic balance in reclaimed minescapes and is perfectly tuned with the approach of Toy & Chuse (2005) who suggested that constructed landscapes should include hydrologic basins, composed of slopes and watercourses. When basic modification of individual slopes is the only possibility, the GeoFluv method plays an important role to decrease the slope length factor. This is carried out by building first-order and second-order channel drainage density, so that frequent small subwatersheds transform long slopes in shorter ones, making the resultant landforms more resistant to erosion.

The topographic profile of individual constructed slopes has been discussed for long in the field of mining reclamation (Haigh, 1985; Toy *et al.*, 2002; Hancock *et al.*, 2003). Many studies have reported a relationship between soil erosion and slope shape. These include the first studies in geomorphology related to soil erosion on individual slopes (Meyer & Kramer, 1969), laboratory experiments (D’Souza & Morgan, 1976) and the application of erosion models. For example, Hancock *et al.* (2003) and Priyashantha *et al.* (2009) applied the SIBERIA model to demonstrate the greater stability of concave slopes compared with linear ones. However, no field experimental studies have been conducted to assess the reclamation benefits of concave slopes compared with linear slopes.

Because less sediment exportation occurs on concave slopes compared with other shapes (linear, convex or S-shape) (Meyer & Kramer, 1969), these studies have led to the belief that concave slopes are very stable. Although watershed size and runoff increase downslope, the slope gradient decreases, and this reduces runoff velocity and erosion ability (Toy *et al.*, 2002).

Martín-Duque *et al.* (2010) explained how a holistic geomorphic approach to mining reclamation, using both topographic and surface soil cover management, led to a successful mining reclamation in a quarry of Central Spain. The current study is based on that work and describes a field experiment carried out at the El Machorro kaolin mine of Central Spain. The objective of this study was to compare the erosion response of two constructed slopes, linear and concave, with two different surface soil covers. These soil covers were (i) subsoil (carbonate colluvium), a natural superficial sediment that drapes the sandy sedimentary rocks underlying the original slopes around the mine and (ii) topsoil, soils developed originally on top of the carbonate colluvium. A linear slope of overburden material with no cover was used as a control for linear slopes. A concave slope of overburden material with no cover could not be constructed, because the experimental layout had to be adapted to pre-existing topographic conditions. Therefore, a total of four different combinations of topography and surface soil cover, that we call “reclamation treatments”, and one control (overburden linear slope), were monitored in this study. A core objective of this study was to compare the response of both topographies and both surface soil covers, to acquire know-how for efficient mining reclamation at similar sites. Our working hypothesis was that concave slopes would yield less sediment than linear slopes. We also expected a dramatic reduction in soil loss from topsoil and carbonate colluvium compared with overburden material.

MATERIALS AND METHODS

Study Area

El Machorro is an active contour mine with an ongoing terraced reclamation approach. It is located in the buffer zone of the Upper Tagus Natural Park (*Parque Natural del Alto Tajo*, in Spanish) in Central Spain (40°39′29″N, 2°2′26″W, datum World Geodetic System 1984, WGS84) (Figure 1). This protected area was established in 2000

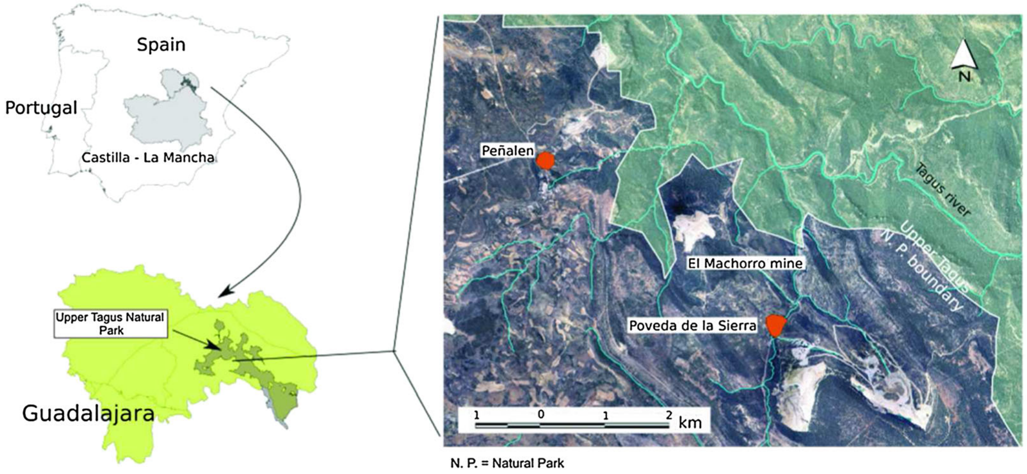

Figure 1. Location of the study area within the Iberian Peninsula and within the province of Guadalajara. The experimental spoil heap is located at El Machorro mine. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

by a regional law (DOCM, 2000) because of its outstanding biodiversity, specifically regarding aquatic ecosystems. It is also very diverse geologically (Carcavilla *et al.*, 2008) and biologically (DOCM, 2000).

The Upper Tagus landscape is characterized by plateaus and mesas capped by Cretaceous carbonates, with their slopes and canyon scarps underlain by sandy sediment that hold the kaolin (*Arenas de Utrillas* formation) exploited in several mines (Olmo & Álvaro, 1989; González Amuchastegui, 1993).

On mesa tops, the soils are chromic luvisols, calcaric cambisols, mollic leptosols and rendzic leptosol. On slopes, carbonate colluvia with calcaric cambisols are common (IUSS Working Group WRB, 2007). The vegetation is representative of Mediterranean-continental environments, with communities dominated by *Juniperus thurifera* on the highest plateaus and pine (*Pinus nigra* subsp. *salzmanii*) and gall oak (*Quercus faginea*) in valleys (MARM, 1997–2006).

The climate of this area is temperate mediterranean with dry and mild summers (Csb, according to Köppen, 1918) but with a noticeable continental influence. The moisture regime is dry mediterranean (Papadakis classification) (CNIG, 2004). Mean annual precipitation is 780 mm and mean annual temperature is 10 °C (AEMET, 2012). Seasonally, this area is characterized by long and cold winters with snow common and short, dry summers with high intensity rainstorms. The spring and fall are usually wet. The rainfall erosive factor, *R* (equivalent to the *R* factor of RUSLE), is estimated to be about 800 MJ mm ha^{-1} h^{-1} yr^{-1} (ICONA, 1988).

Rainfall and Temperature Monitoring

To measure rainfall quantity and intensity, a tipping-bucket automatic rain gauge (0·2 mm/pulse) (Davis Instruments, 2005) with a HOBO Event data logger was installed 100 m away from the experimental spoil heap, at 1230 m asl. Rain gauge data were downloaded at the same time as the sediment collection. Total rainfall volume (mm) and maximum rainfall volume in 24 h (mm) were calculated. In addition, the return period of annual precipitation for each year was estimated using the CHAC software (CEDEX, 2004). Each year, temperature data were obtained from a nearby weather station (AEMET, 2012).

Experimental Design

An experimental spoil heap was built by the mining operator company of El Machorro mine, CAOBAR, in the summer of 2008, on the foundations of an existing spoil heap. Two different topographic slope shapes, linear and concave, were constructed with spoils (overburden materials) and

Table I. Slope code and starting month and year of measurements for each treatment

	Treatment			
Code	Topographic profile	Surface soil cover	Month	Calendar year
SCS-TS	Short concave slope	Topsoil	November	2008
LCS-TS	Long concave slope	Topsoil	October	2009
LCS-CC	Long concave slope	Carbonate colluvium	October	2009
LS-TS	Linear slope	Topsoil	November	2008
LS-CC	Linear slope	Carbonate colluvium	November	2008
LS-OM	Linear slope	Overburden material	November	2008

Measurements did not start in October 2008 because the spoil heap was built that month.

covered with two surface soil covers: subsoil (carbonate colluvium) and topsoil (Table I). Additionally, to these four reclamation treatments, one linear slope of the spoil heap with overburden material (spoils) was left uncovered as a control (Figure 2). The four “reclamation treatments” and the control were monitored for two hydrologic years (2009 and 2010) starting from 6 November 2008.

At the experimental spoil heap, articulated dump trucks built the terraced spoil heaps by directly unloading materials, and a bulldozer compacted and finished the benches. The dump trucks could not drive on the linear slopes because of their high slope gradient, so the trucks drove on the benches and unloaded the two surface soil covers directly downslope. The concave slope was built by a bulldozer that drove on the concave slope reshaping it and spreading the surface soil covers at the same time. Summing up, the experimental spoil heap had two parts. The first one was a terraced system with two linear slopes and one intermediate bench. Each linear slope had the two surface soil covers (carbonate colluvium and topsoil) and the exposed overburden material (control); the second part was a concave slope with the two surface soil covers; therefore, five different slopes were monitored (Figure 2).

Mining and reclamation operations within the mine prevented the construction of the upper part of the concave slope during the first hydrologic year of the study. During this period, the concave slope consisted of its half-lower part, equivalent in height to a single linear slope plus its bench. Additionally, run-off from the upper slope formed an alluvial fan on the concave slope covered with carbonate colluvium. Therefore, data could not be collected on this treatment during the first year. The concave slope was fully constructed in the second year to have the same width and length as a set of two linear slopes with an intermediate bench. This modification could be considered a limitation of this study.

Linear slopes had a mean length of 11 m (standard deviation 0·6), with a slope gradient of 32 degrees. The bench was 5 m wide with a reversed-slope gradient of 14 degrees in cross-section and 2 degrees in longitudinal section. Concave slopes had a slope length of 25 to 30 m during the first year and 35 to 40 m during the second year. Their gradient increased from bottom to top from 4 to 26 degrees (first year) and from 4 to 32 degrees (second year) (see Table II for details). The concave slope curvature was described using the equation proposed by Stefano *et al.* (2000):

$$y = H\left(1 - \frac{x}{\lambda}\right)^n$$

Where:
x = horizontal abscissa
y = the corresponding elevation
H = difference of level
λ = slope length measured along the horizontal axis
n = exponent that varies according slope shape, following Stefano *et al.* (2000)

Short concave slopes (first year) had an n value between 1·34 and 1·32, whereas long concave slope values (second year) were between 1·40 and 1·47 (Figure 3). A differential global positioning system (model number Leica 1200) was used to survey the concave slope profiles. Slope surveys were conducted once a year (12 May 2009 and 1 July 2010).

Three composite samples were taken from each soil cover to characterize their physical properties (shown in Table III). The thickness of both carbonate colluvium and topsoil ranged between 30 and 75 cm on linear slopes. This wide

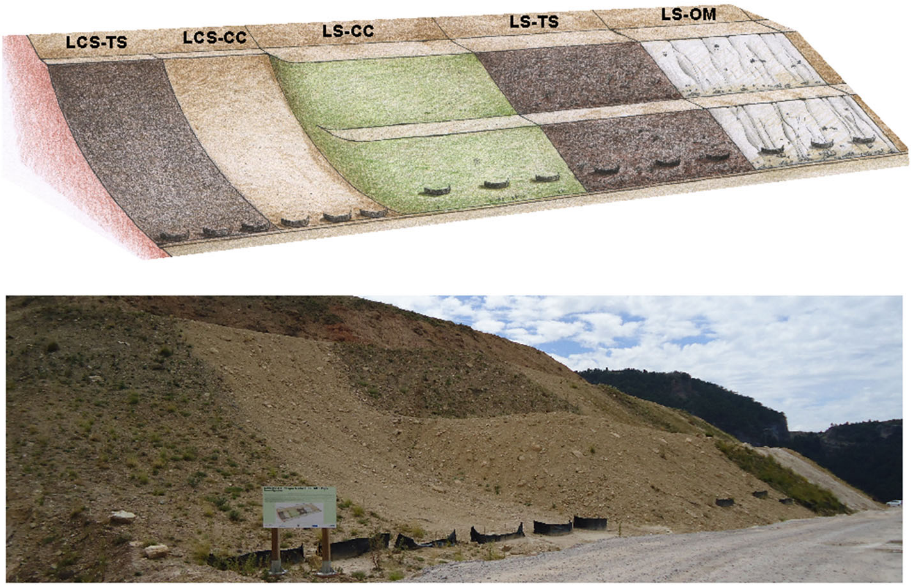

Figure 2. Experimental spoil heap of El Machorro mine, during the second study year, after conversion of the short concave slopes to long concave slopes. Top, treatment scheme; bottom, photograph taken on October 2011, one year after experiment finished. LCS-TS, long concave slope with topsoil; LCS-CC, long concave slope with carbonate colluvium; LS-CC, linear slope with carbonate colluvium; LS-TS, linear slope with topsoil; LS-OM, linear slope with overburden material. The long concave slope with overburden material (LCS-OM) could not be constructed. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Table II. Experimental treatments and their characteristics

Treatment	Open plot number	Topographic profile	Surface soil cover	Surface soil cover thickness (cm)	Slope length (m) Year 1	Slope length (m) Year 2	Slope gradient (°) Year 1	Slope gradient (°) Year 2	Area (m^2) Year 1	Area (m^2) Year 2
SCS-TS and LCS-TS	1	Concave	Topsoil	20 to 30	33	40	4 to 26	4 to 32	83·7	91
	2	Concave		20 to 30	33	40	4 to 26	4 to 32	82·9	104
	3	Concave		20 to 30	33	40	4 to 26	4 to 32	73·2	100
SCS-CC and LCS-CC	4	Concave	Carbonate colluvium	20 to 30	33	40	4 to 26	4 to 32	58·7	106
	5	Linear		30 to 75	11		32		70·3	124
	6	Linear		30 to 75	11		32		61·5	100
LS-TS	7	Linear	Topsoil	30 to 75	11		32		30·9	
	8	Linear		30 to 75	11		32		35·5	
	9	Linear		30 to 75	11		32		45·7	
LS-CC	10	Linear	Carbonate colluvium	30 to 75	11		32		27·5	
	11	Linear		30 to 75	11		32		23·5	
	12	Linear		30 to 75	11		32		43·2	
LS-OM	13	Linear	Overburden	30 to 75	11		32		31·3	
	14	Linear		30 to 75	11		32		43·5	
	15	Linear		30 to 75	11		32		31·3	

range resulted from directly unloading material from upslope without spreading it. Carbonate colluvium and topsoil on concave slopes were 20–30 cm thick and were spread by a bulldozer.

The core of this study is based on the field measurement of the sediment amount yielded by each reclamation treatment and the control. Three open plots were set up for every slope. Sediment amount was recorded using silt fences (Robichaud & Brown, 2002), with a width of 3 m, placed across the toe of the slopes. Silt fences trap sediment while allowing water to pass through. According to Robichaud & Brown (2002), the trap efficiency of silt fences is 68% to 98%. Because sediment could fill and overload silt fences, possibly resulting in a loss of sediment, periodic cleaning of silt fences was necessary (Robichaud & Brown, 2002).

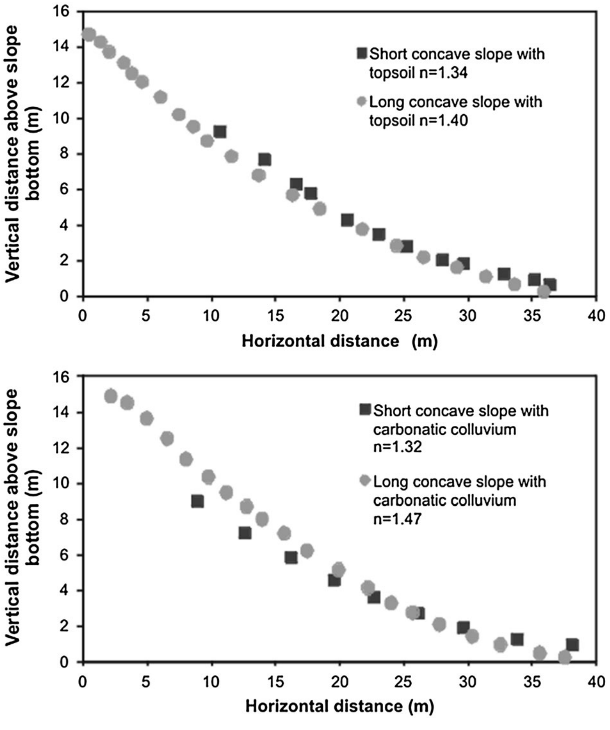

Figure 3. Concave slope shapes and their *n* values. The *n* value is an exponent that varies according to slope shape, following the equation of Stefano *et al*. (2000). The original, short concave slopes were converted to long concave slopes at the end of the first year.

Sediment yield was measured at the toe of the concave slope and at the toe of the lower single linear slope of the set of two linear slopes (Figure 2). Sediment from the upper linear slope were not measured, but they did not run onto the monitored lower linear slope, as they were deposited on the intermediate reversed sloped bench and drained out of the monitored lower linear slope (Figure 2). The short reversed slope of the terrace bench was not counted in the balance, as it was observed that it did not yield any sediment.

Therefore, a total of 12 (first year) and 15 (second year) sets of “open” plots (plots without artificial boundaries) with silt fences were monitored. Because the plots were open, there were differences in plot size due to different drainage areas. The area of each open plot, measured using differential global positioning system, ranged between 23·5 and 83·7 m^2 (first year) and between 23·5 and 124 m^2 (second year) (Table II).

Sediment Yield

The protocol for monitoring the open plots consisted of collecting the sediment trapped by the silt fences and weighing the sediment in the field, using a portable weight scale. The sediment from a single plot was mixed, and a portion of the mixed sediment was taken to calculate the percentage of moisture, using the method by Ramos-Scharrón & MacDonald (2007). The erosion rate was calculated, and the results were expressed as $Mg\,ha^{-1}yr^{-1}$. Annual sediment yields and standard deviations were also calculated for each treatment.

Table III. Surface soil cover characteristics and vegetation cover

Treatment	Sand (%) 2–0·05 mm	Silt (%) 0·05–0·002 mm	Clay (%) <0·002 mm	Organic matter (%)	Bulk density (g cm^{-3})	Textural classification (USDA)	Soil structure	Rock cover (%)	Vegetation cover (%)
LCS-TS	49·7	29·8	20·5	2·3	1·06	Sandy clay loam	Medium or coarse granular 2–5 mm	20	30
LCS-CC	39·8	47·2	13·1	0·6	1·26	Loam	Medium or coarse granular 2–5 mm	40	0
LS-TS	39·2	40·8	20·0	3·3	1·09	Loam	Fine granular 1–2 mm	20	50
LS-CC	51·1	36·9	12·1	0·6	1·27	Loam	Fine granular 1–2 mm	25	0
LS-OM	68·4	16·1	15·5	0·2	1·41	Sandy-loam	Fine granular 1–2 mm	10 to 5	0

Values are means. Vegetation survey was carried out in May 2010.

Rill Development

Overburden materials at El Machorro mine are mainly sandy, with very low clay content. The very low cohesion makes the overburden material vulnerable to detachment by runoff, so that gully formation is common.

To monitor the landform evolution of the four different reclamation treatments and the control, photographs were taken of each open plot before sediment was collected. Rill networks were measured after they formed. Width and depth were measured in at least 80% of all rills in three slope positions (top, middle and bottom).

The length, width and depth of rills and gullies were measured with a tape, following the method described by Morgan (2005). Rill volume was estimated by multiplying the rill cross-sectional area—“U” shape for carbonate colluvium and “V” shape for overburden material—by their mean rill length. This rill volume was then divided by the treatment area, to obtain estimated values for sediment removed by rill erosion ($m^3 m^{-2}$). This value was then transformed to sediment weight per area ($Mg\,ha^{-1}$) by multiplying the volume by the mean bulk density of each surface soil cover that was calculated by the core method (Sobek *et al.*, 1978). Three soil core samples were taken from each slope treatment for bulk density calculations. The sediment amounts resulting from rill measurements and from the silt fences were then compared.

Vegetation Colonization

Vegetation cover was measured using digital photographs and a point-frequency method (Brakenhielm & Liu, 1995; Vanha-Majamaa *et al.*, 2000) 1 year after the end of the second year of the study (October 2011). Because no seeding was applied in any of the reclamation treatments, we therefore measured spontaneous vegetation colonization.

Statistical Analysis

To compare the effects of topography and surface soil cover on sediment yield, paired *t*-tests were conducted comparing sediment yield from treatments with the same topography but with different surface soil cover (i.e. linear slope with carbonate colluvium (LS-CC) versus linear slope with topsoil (LS-TS)) and sediment yield from treatments with same surface soil cover but with different topography (i.e. concave slope with topsoil versus LS-TS). Analyses were conducted separately for each study year. For linear slopes, data were also analysed for both years combined, because the plots were not modified during the second year. Statistical analyses were made using Statgraphics Centurion XVI.I software, version 16·1.17 (StatPoint Technologies, Inc., 2012). The significance level was $\alpha = 0{\cdot}05$.

RESULTS

Rainfall and Temperature

A total of 324 rain days were registered during the study period, accounting for a total rainfall of 1426 mm. Annual rainfall for the second year (992 mm) was approximately twice that of the first year (434 mm), with return periods of 5 and <2 years, respectively. Climatic characteristics of each study year are shown in Table IV. Monthly rainfall ranged from 1 mm (July 2009) to 290 mm (December 2009). The maximum rainfall recorded in 24 h was 49 mm. Frost-free days were slightly more common in the second year.

Sediment Yield

During the 2 years of study, open plots were sampled approximately once a month, resulting in a total of 21 samples: 10 samples during the first year and 11 samples during the second year. Mean sediment yield and standard deviation of each reclamation treatment are shown in Table V, along with rainfall characteristics for the period between two consecutive sediment collections. The sediment yield rates for the three plots within the same treatment did not differ significantly ($p > 0{\cdot}05$, paired *t*-test).

Significant differences were found when sediment yield rates from reclamation treatments with the same topography, but different surface cover were compared (Table VI). For the first year, the comparison between LS-TS and linear slope with overburden material (LS-OM) showed a significant difference ($p = 0{\cdot}01$, *t*-test). For the second year, the comparison of these two treatments also showed a significant difference ($p = 0{\cdot}003$). Regarding the two-year data analyses, significant differences were found between all tested pairwise treatments on linear slopes ($p < 0{\cdot}05$, paired *t*-test). When slopes with the same surface cover but different topography were compared, no meaningful significant differences were found.

Regarding annual sediment yield rates, the short concave slope with topsoil (SCS-TS) had lower sediment yield values than any linear slope during the first year, regardless of surface soil cover (Figure 4 and Table V). The sediment yield rates of linear slopes depended on the surface soil cover: the slope with topsoil had the lowest rate (12 $\mathrm{Mg\,ha^{-1}yr^{-1}}$), one order of magnitude less than that with carbonate colluvium (120 $\mathrm{Mg\,ha^{-1}yr^{-1}}$) or overburden material (282 $\mathrm{Mg\,ha^{-1}yr^{-1}}$). In the second year, the LS-TS produced the lowest erosion rate (3 $\mathrm{Mg\,ha^{-1}yr^{-1}}$). The other two linear slopes had the higher values: 126 $\mathrm{Mg\,ha^{-1}yr^{-1}}$ with carbonate colluvium and 347 $\mathrm{Mg\,ha^{-1}yr^{-1}}$ with just overburden. The effect of surface soil cover was not found for the long concave slopes. The slope with topsoil (LCS-TS) yielded 20 $\mathrm{Mg\,ha^{-1}yr^{-1}}$ of sediment and the slope with carbonate colluvium (LCS-CC) yielded 16 $\mathrm{Mg\,ha^{-1}yr^{-1}}$ (Figure 4).

Rill Development

Rill development was different on concave and linear slopes. Concave slopes developed a rill network in the upper part, lacking rills in its lower part. Linear topography allowed a continuous rill network along the slope length. In both cases, rill development depends on the surface soil cover characteristics.

Rill development on concave slopes

The SCS-TS did not develop rills during the first year, which was dryer than the second one. Indeed, this treatment resisted the most intense rainfall in 24 h of the first year (38·4 mm), which occurred just after building the experimental spoil heap and spreading the surface soil cover but before the silt fences were installed. During the second year, small rills formed in the steepest area of the concavity, near the top of the slope, but they were small and disappeared downslope. These rills were not measured, because we assumed the sediment eroded from them was deposited within the slope.

Plots on the concave slope with carbonate colluvium surface soil cover could not be monitored during the first year, because run-on from upslope formed noticeable alluvial cones within the open plots. In the second year, the upper parts of both concave slopes were reconstructed, making them longer. During the second year, the concave slopes behaved similarly, regardless of their surface soil cover: rills were formed at the top of the slope and disappeared downslope. On the long concave slope with carbonate colluvium, these rills were discontinuous, with a "U" shape, and mean length of 6 m. The estimated sediment volume eroded from these rills over the two-year period was 1·4 $\mathrm{m^3}$, or 0·004 $\mathrm{m^3\,m^{-2}}$, based on an area of 330 $\mathrm{m^2}$ on the LCS-CC. No mass movements, such as mudflows, occurred on the concave slope with carbonate colluvium. The calculated bulk density for carbonate colluvium was 1·26 $\mathrm{g\,cm^{-3}}$, so the estimated weight of sediment from the concave slope with carbonate colluvium was 50 $\mathrm{Mg\,ha^{-1}}$. Because 80% of rills were measured, the estimated total mass of sediment was 63 $\mathrm{Mg\,ha^{-1}}$. Two-year sediment yield measured in the open plots of this same slope was 16 $\mathrm{Mg\,ha^{-1}}$. The estimated amount of sediment determined from rill development has

Table IV. Rainfall and temperature characteristics of each study year

	First year	Second year
Annual rainfall (mm)	434	992
Maximum rainfall (month year/mm)	December 08/125	December 09/290
Minimum rainfall (month year/mm)	July 09/1·00	August 10/4·20
Maximum rainfall in 24 h (mm)	38·4	49·0
Average annual temperature (°C)	10·1	10·3
Maximum average temperature (month year/mm)	August 09/21·0	July 10/20·5
Minimum average temperature (month year/mm)	December 08/2·00	January 10/1·60
Frost-free days per year	223	267

Table V. Rainfall characteristics and sediment yield on sampling dates

				Mean sediment yield (Mg ha^{-1})/standard deviation (SD)									
Sampling date	No. of rain days	Total rainfall (mm)	Maximum rainfall 24 h (mm)	S/LCS-TS		LCS-CC		LS-TS		LS-CC		LS-OM	
01Oct2008–6Nov2008	9	82·6	38·4	Open plots were not yet installed									
19Dec2008	16	138	19·2	0·003	/0·003	0·02	/0·03	0·00	/0·00	0·00	/0·00	0·00	/0·00
23Jan2009	14	17·4	4·80	0·00	/0·00	0·00	/0·00	0·00	/0·00	6·38	/9·02	3·27	/4·62
30Jan2009	3	10·6	6·20	0·00	/0·00	—	—	0·00	/0·00	29·5	/41·7	44·2	/62·6
12Feb2009	6	11·6	7·60	0·00	/0·00	—	—	10·0	/14·2	60·4	/40·3	102	/42·2
13Mar2009	6	3·20	1·00	0·00	/0·00	—	—	0·39	/0·29	3·48	/4·14	14·9	/12·3
21Apr2009	16	75·6	12·6	0·00	/0·00	—	—	0·32	/0·29	0·78	/0·46	35·4	/45·8
09Jun2009	14	52·8	28·8	1·25	/1·23	—	—	0·31	/0·03	14·7	/2·81	43·3	/4·80
24Jun2009	6	6·40	3·60	0·00	/0·00	—	—	0·10	/0·05	0·14	/0·02	0·49	/0·14
12Aug2009	6	8·20	6·40	1·30	/0·89	—	—	0·34	/0·13	4·90	/1·47	30·0	/2·18
01Oct2009	16	27·6	10·6	0·04	/0·03	—	—	0·07	/0·03	0·12	/0·01	8·56	/0·83
First year total	112	434	—	3		—		12		120		282	
Mean	10·2	39·5	12·7	0·26		—		1·16		12·0		28·2	
Median	9·00	17·4	7·60	0·00		—		0·20		4·19		22·4	
SD	5·04	43·2	11·6	0·54		—		3·12		19·3		31·1	
07Oct2009	3	5·80	4·00	0·03	/0·02	0·00	/0·00	0·00	/0·00	0·23	/0·12	3·13	/0·47
29Oct2009	8	43·0	25·0	0·47	/0·44	0·00	/0·00	0·14	/0·10	1·20	/0·56	15·2	/11·8
12Nov2009	9	6·80	2·80	0·00	/0·00	0·00	/0·00	0·00	/0·00	0·00	/0·00	0·20	/0·05
10Dec2009	13	51·6	20·2	0·50	/0·43	0·00	/0·00	0·00	/0·00	0·73	/0·12	19·4	/16·0
18Jan2010	29	328	49·0	8·39	/1·56	7·38	/5·62	0·61	/0·43	23·8	/17·4	102	/12·5
02Mar2010	30	153	24·8	1·29	/0·80	2·35	/1·97	1·67	/1·15	74·6	/34·0	38·1	/7·18
05Apr2010	25	79·4	24·4	0·18	/0·15	1·82	/2·19	0·07	/0·08	2·56	/2·48	16·4	/2·27
19May2010	27	156	26·0	2·04	/1·05	1·97	/2·81	0·09	/0·13	1·44	/0·83	43·0	/16·4
01Jul2010	23	56·8	20·4	2·10	/1·18	2·27	/3·93	0·18	/0·19	5·50	/1·54	67·8	/30·5
30Sep2010	28	35·8	4·20	3·28	/1·06	0·00	/0·00	0·32	/0·11	14·1	/2·94	29·7	/11·2
03Nov2010	17	76·6	22·4	1·90	/0·77	0·00	/0·00	0·00	/0·00	1·42	/0·66	11·8	/3·36
Second year total	212	992	—	20		16		3		126		347	
Mean	19·3	90·2	20·3	1·84		1·44		0·28		11·4		31·6	
Median	23·0	56·8	22·4	1·29		0·00		0·09		1·44		19·4	
SD	9·67	93·2	13·2	2·42		2·23		0·50		22·2		30·5	
2-year total	324	1426	—	23		16		15		246		629	

Total values are also included by hydrologic year. S/LCS-TS, short/long concave slope with topsoil; LCS-CC, long concave slope with carbonate colluvium; LS-CC, linear slope with carbonate colluvium; LS-TS, linear slope with topsoil; LS-OM, linear slope with overburden material.

Table VI. Results of paired *t*-test

Study year	Treatments compared	*t*-test results *p*-value
2009	SCS-TS versus LS-TS	0·38
	LS-TS versus LS-CC	0·09
	LS-TS versus LS-OM	0·01*
	LS-CC versus LS-OM	0·18
2010	LCS-TS versus LCS-CC	0·69
	LCS-TS versus LS-TS	0·05*
	LCS-CC versus LS-CC	0·15
	LS-TS versus LS-CC	0·11
	LS-TS versus LS-OM	<0·01*
	LS-CC versus LS-OM	0·09
2009 + 2010	LS-TS versus LS-CC	0·02*
	LS-TS versus LS-OM	<0·01*
	LS-CC versus LS-OM	0·03*

Statistical significance level: *$\alpha = 0{\cdot}05$. S/LCS-TS, short/long concave slope with topsoil; LCS-CC, long concave slope with carbonate colluvium; LS-CC, linear slope with carbonate colluvium; LS-TS, linear slope with topsoil; LS-OM, linear slope with overburden material.

the same order of magnitude as that measured at the silt fences, for the two-year period (Figure 6).

Rill development on linear slopes

The LS-TS did not develop perceptible erosive forms during the 2 years. The LS-CC was subject to small mudflows in the first year. Additionally, an incipient rill network developed. After this initial geomorphic evolution, the plots remained very stable throughout the two-year period, with only small mudflows and minor rills. At the end of the second year, rills were discontinuous, with a "U" shape, with an average width of 30 to 40 and depth of 10. The estimated average length was 7 m, and the estimated sediment volume eroded from rills was 0·4 m^{3}. The estimated sediment removed by rill erosion was 0·004 m^{3} m^{-2}. Considering the corresponding bulk density (1·27 g cm^{-3}), the estimated sediment yield was 51 Mg ha^{-1} (from 80% of rills), corresponding to a total sediment of 64 Mg ha^{-1} (for 100%). This estimated sediment yield is one order of magnitude lower than that measured at the silt fences (246 Mg ha^{-1} for the two-year period) (Figure 6).

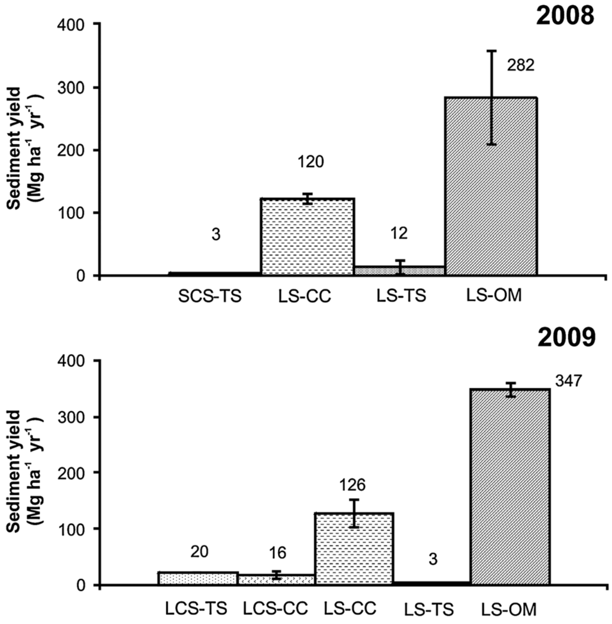

Figure 4. Mean annual sediment yield (Mg ha^{-1}) by treatment and study year. The error bars represent the standard deviation. SCS-TS, short concave slope with topsoil; LCS-TS, long concave slope with topsoil; LCS-CC, long concave slope with carbonate colluvium; LS-CC, linear slope with carbonate colluvium; LS-TS, linear slope with topsoil; LS-OM, linear slope with overburden material. The short concave slope with carbonate colluvium (SCS-CC) was not monitored during the first year.

The linear slope covered with overburden material (LS-OM) developed an evenly defined rill network. These rills were deeper and much more numerous than those formed on the carbonate colluvium. The rills were 20 cm wide on average and had an average depth of 20 to 30 cm, maximum 50 cm, at the end of the first year (Figure 5). Small alluvial cones were formed at the bottom of the slopes. A progressive disintegration of sand clods on the linear slope surface was also observed during the 2 years. During the second year, the rill-erosion process continued, leading to the formation of gullies, being these landforms defined in the same way that Brice (1966, p. 290): "a recently extended drainage channel that transmits ephemeral flow, has steep sides, a steeply sloping or vertical head scarp, a width greater than about 1 foot, and a depth greater than about 2 feet". At the end of the second year, the rills were continuous, "V"-shaped, with an average width and depth of 45 and 25 cm, respectively. Gullies with a maximum width of 200 cm and depth of 150 cm were also measured. Rill length was the same as on the linear slope, 11 m. The estimated sediment volume eroded from rills was 4·75 m^{3}, and 0·045 m^{3} m^{-2}, the highest of the slopes monitored (Figure 6). The estimated sediment eroded by rill processes, calculated using the bulk density of 1·41 g cm^{-3}, was 793 Mg ha^{-1} (considering 100% of rills). The estimated sediment yield quantified from rill development was higher than that measured at the silt fences (629 Mg ha^{-1} for the two-year period).

Vegetation Colonization

At the start of the study period, all plots were bare, without any vegetation. As geomorphic evolution progressed, natural plant colonization occurred. Concave and linear slopes covered with topsoil showed plant establishment in the following spring (spring of 2009). In October 2011, plants covered 30% of the concave slope and 50% of the linear slope (Table III). Plants spatial pattern was not homogeneous on the concave slope with topsoil, so that plants were not evenly distributed along the slope, but the linear slope showed a uniform vegetation distribution. On the concave slope, vegetation cover was more extensive in the lower part of the slope than at the top. Table VII shows the plant species identified in each topsoil-covered slope. Although species richness is similar in both slopes (14), species composition is quiet different (being

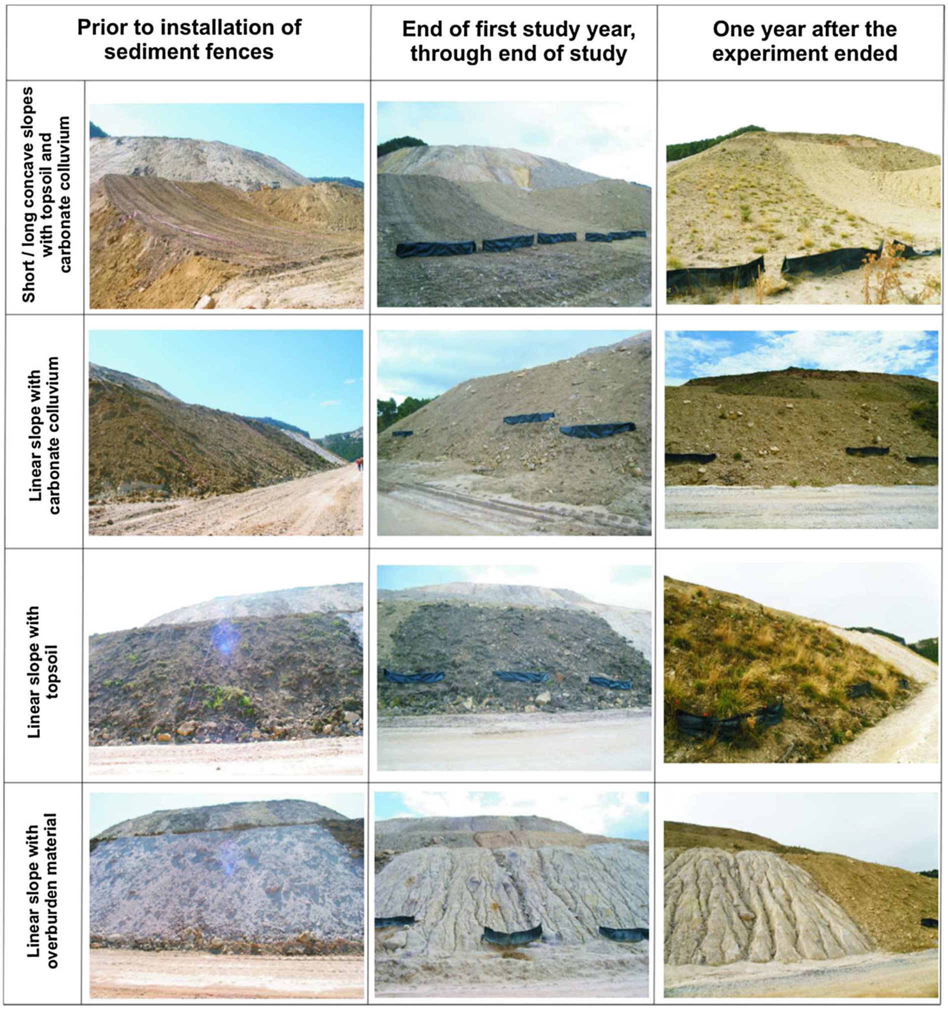

Figure 5. Photographs showing geomorphic evolution and vegetation colonization at the experimental spoil heap. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

only five species common among to the two slopes). No vegetation was observed on carbonate colluvium or overburden material.

DISCUSSION

Sediment Yield

Our results suggest that surface soil cover controls sediment yield on linear slopes more than on concave ones. This is supported by the fact that linear topography has no mechanisms to control sediment fluxes, whereas concave topography is able to store sediment at the toe (Stefano *et al*., 2000; Toy *et al*., 2002). On linear slopes, control of erosion could be improved by using a different surface soil cover. Our results are consistent with previous findings: topsoil was the best surface soil cover, providing better conditions for soil development and plant establishment than other materials (Power *et al*., 1981; Haigh, 2000).

Similar erosive response was observed in the first year for the topsoiled slopes, whether short concave (SCS-TS) or linear (LS-TS), indicating that, under favourable soil conditions, the role of topography was not evident. During the second year, topsoiled slopes behaved differently. Although sediment yield from the LS-TS was reduced, sediment yield from the long concave slope (LCS-TS) was greater than the yield from the SCS-TS. The increased length and drainage area could explain the increase in sediment yield. In agreement with this, several authors have reported that, under the same environmental conditions, shorter slopes produce less sediment than longer ones

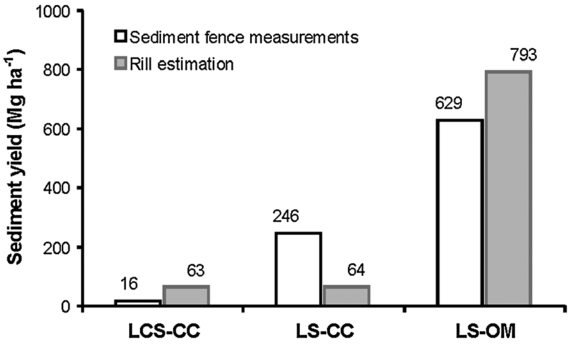

Figure 6. Comparison of sediment yield measured from silt fences with sediment yield estimated from rill erosion, for the two-year study period. LCS-CC, long concave slope with carbonate colluvium; LS-CC, linear slope with carbonate colluvium; LS-OM, linear slope with overburden material.

Table VII. Plant species established in the slopes with topsoil

Concave slope with topsoil	Linear slope with topsoil
Family Compositae	
Cuprina crupinastrum	*Hieracium pilosella*
Leucanthemum vulgare	
Family Euphorbiaceae	
Euphorbia sp.	*Euphorbia* sp.
Family Gramineae (Poaceae)	
Arrhenatherum elatius subsp. bulbosum	*Brachypodium phoenicoides*
Festuca gr. rubra	*Bromus erectus*
Family Lamiaceae	
Sideritis hirsuta	*Thymus vulgaris*
Family Leguminosae (Fabaceae)	
Coronilla repanda	*Coronilla repanda*
Genista scorpius	*Lotus corniculatus*
Medicago lupulina	*Medicago lupulina*
	Family Liliaceae
	Aphyllanthes monspeliensis
Family Plantaginaceae	
Plantago sp.	
Family Rosaceae	
Filipendula vulgaris	*Rosa* sp.
Sanguisorba minor	*Sanguisorba minor*
Family Rubiaceae	
Asperula montana	
Galium lucidum	*Galium lucidum*
	Family Resedaceae
	Reseda alba
	Reseda phyteuma

(Toy & Foster, 1998; Liu *et al*., 2000; Toy *et al*., 2002; Toy & Chuse, 2005).

Another aspect must be considered: constraints existed for combining soil surface covers and topography. The depth, uniformity and quality of surface soil cover were determined by reclamation operations. On linear slopes, the surface soil cover was spread out by direct unloading of trucks, which provided a more homogeneous and less compacted layer. However, on concave slopes, the spreading out process had to be carried out with a bulldozer, which compacted the soil (Barber & Romero, 1994; Chong & Cowsert, 1997). Soil compaction has been reported to reduce the land's capacity to absorb rainwater, accelerating runoff and erosion (Haigh & Sansom, 1999). The greater thickness and porosity of linear slopes with topsoil, as well as a better spatial distribution of surface soil cover, could explain lower rates of sediment yield than for the concave slope. This means that slope topography affects surface soil cover depth and quality in reclaimed landscapes (Hancock *et al*., 2003; Priyashantha *et al*., 2009) (Table VIII).

The smaller second-year sediment yield from the long concave slope (16 $\mathrm{Mg\,ha^{-1}yr^{-1}}$) compared with LS-CC (126 $\mathrm{Mg\,ha^{-1}yr^{-1}}$) suggests that concave topography helps to reduce sediment yield. The yield was smaller even though the concave slope was longer than the corresponding linear slope, and even though the concave slopes had been recently constructed.

To assess the validity of the sediment yield measurements, it is important to take into account that, although the plots were open, the length and area of the linear slopes were similar. Because of this, we consider that converting sediment yield to per unit area, and comparing them, was justified. However, the long concave slopes had larger open plots. A larger contributing area implies a higher erosive power, but the fact that the slope was concave implies a lower erosive power. The combined consequence of these effects could not be separated and quantified. Therefore, converting sediment yield to per unit area for concave slopes, and comparing them with linear slopes, has an evident uncertainty. Despite of that, the comparison was made because they are real alternatives of reclamation, both for this site and elsewhere: concave slopes or terraced ones as a topographic possibility of regarding spoil heaps.

Rill Development

In our experiment, rill development on linear slopes showed clear differences depending on the surface soil cover. Whereas no rills were formed on the LS-TS, a widespread rill network was developed on overburden material (LS-OM), and only few rills and mudflows occurred on carbonate colluvium (LS-CC). This very different geomorphic behaviour indicates that soil cover is dominant in controlling erosion processes on linear slopes. Topsoil resists erosion (Sawatsky *et al*., 1996), because its higher infiltration rate decreases runoff and, therefore, soil detachment (Haigh & Sansom, 1999). On the other hand, rill erosion is very common in overburden materials, because higher bulk density promotes overland flow (Soulliere & Toy, 1986; Moreno-de las Heras *et al*., 2010). Two additional factors favoured rill formation in overburden material: the low rock cover and the sandy texture (Quansah, 1981; Porta *et al*., 1989) as described in Table III.

Generally speaking, rills grow by incision and by side-wall sliding (Nicolau, 2002). The different cross-sections—V-shaped versus U-shaped—and size could be explained as a consequence of different surface soil covers. Rills developed on overburden material were V-shaped and larger than those on carbonate colluvium. This was likely due to the sandy texture and lower cohesion of overburden, favouring more effective incision and side-wall collapse, and causing rill widening. Rills developed on carbonate colluvium were observed to be U-shaped and smaller. This could be interpreted as a result of higher cohesion in carbonate colluvium because of lower sand and higher silt content than in overburden material. The carbonate colluvium also has a higher surface roughness (because of the abundance of rock fragments), which would also contribute to a smaller rill size development. Roughness decreases overland flow and runoff because of surface ponding and increased hydraulic roughness that reduces the effective flow shear stress (Darboux *et al*., 2002; Toy *et al*., 2002; Gómez & Nearing, 2005).

Sediment yield estimated to have been eroded from rills differed from sediment yield measured in silt fences. At least

Table VIII. Concave and linear profile characteristics related to sediment yield, rill development and establishment of vegetation

Topographic profile	Runoff control	Sediment yield control	Soil surface cover	Natural plant colonization
Concave slope	Watershed size and runoff increase downslope, whereas slope gradient decreases	Sediment accumulates at lower, flat part of slope	↑ compaction	Heterogeneous distribution
	Decrease of energy downslope		↓ thickness Heterogeneous distribution	Plant colonization more difficult in steep upper part of slope than in the lower part
Linear slope	Watershed size and runoff increase downslope, whereas slope gradient is constant	None	↓ compaction	Homogeneous distribution
	Increase of energy downslope		↑ thickness Homogeneous distribution	

two factors affect the interpretation of the results. Sediment yield estimated from rills assessment represented only rill erosion. For all comparisons, it is important to consider that rill assessment has some limitations, and it is an estimation. At the same time, silt fences trap sediment from rill, inter-rill erosion and mudflows, and it is necessary to take into account how efficiently the silt fences trap sediment. According to Robichaud & Brown (2002), the total values for sediment yield could be 2% to 32% higher. One might expect then that rill erosion estimates were probably low and silt fence measurements could be higher.

For the LS-CC, sediment yield estimated from rills assessment was one order of magnitude lower than sediment yield measured at silt fences (64 Mg ha^{-1} and 246 Mg ha^{-1} respectively, Figure 6). This difference could be explained by the fact that small mudflows occurred on this slope. For the LS-OM, the estimated sediment yield from rills was 164 Mg ha^{-1} (21%) higher than the sediment yield measured in silt fences. This could be explained by the fact that small alluvial cones were formed at the bottom of the slope and also because sediment overloaded the silt fences on some occasions. For the concave slope with carbonate colluvium (LCS-CC), the difference between the two values was 47 Mg ha^{-1}, being 75% higher the sediment yield estimated from rills. This was likely due to some sediment that was deposited downslope and did not fill the silt fences.

Vegetation Colonization

In our study, the plant establishment pattern was quite different on the linear versus the concave slope (always regarding topsoiled treatments).

The linear profiles allowed more widespread and homogeneous plant cover. This could be because their abiotic characteristics: slope angle and surface soil cover depth and compaction which were very homogeneous, so that its environmental heterogeneity is not remarkable. In fact, species associated to worse soil conditions—i.e. *Thymus vulgaris*, *Brachypodium phoenicoides* or *Aphyllanthes monspeliensis*—appear only in the linear slope.

The concave profile includes two very different environments (upper steepest part and lower flatter part). Plant colonization occurred mainly in the lower and flatter one, where water availability as well as the seed bank richness should be higher. In addition, woody species have been identified here (*Genista scorpius* and *Sideritis hirsuta*).

These facts are interpreted as the development of a more "structured" plant community in the concave slope than in the linear one. In turn, we consider this as a result of a more heterogeneous environment on the concave slope. Of course, given the very few years of vegetation colonization, these are preliminary results, and a larger time-span is needed for more conclusive results, as far as the vegetation development is concerned.

The greater amount of continuous vegetation cover on the linear slope could be another explanation for the lower sediment yield rates for linear versus concave slopes. In this respect, the value of 50% of vegetation cover reached by this LS-TS and the decrease of sediment yield amount seems to be in agreement with the literature. Indeed, the role of vegetation cover in sediment yield control is well known. Several authors have observed that, in mediterranean environments, erosion rates are greatly reduced when vegetation cover rises up above 30% (Thornes, 2004; de Luís *et al*., 2001; Gimeno-García *et al*., 2007). Andres & Jorba (2000) and Moreno-de las Heras *et al.* (2009) confirmed empirically the drastic reduction of soil loss with a 30% plant cover for slopes constructed for mining reclamation in central and northeast Spain. They recommend a 50% plant cover in practice as a conservative target. For man-made slopes, there is considerable evidence that the restoration of 50% cover with herbaceous vegetation is decisive for site stabilization. And this is what our experiment seems to show. The literature reflects, however, that it is not only a question of cover, but also a matter of how the vegetation cover is distributed, such as in natural ecosystems (Cerdà *et al*., 2010).

CONCLUSIONS

These conclusions are addressed for mining scenarios similar to the one described, active mines that already have terraced landforms, with possibility of being improved either by limited topographic modifications (concave slopes) or by different use of surface soil covers. However, the long-term instability of terraced spoil heaps has been proved, with special emphasis in arid and semi-arid climates, as the mediterranean one (see Introduction for references). Therefore, wherever mining reclamation is less conditioned by previous mining works, we recommend a mining reclamation based on a geomorphic approach, instead of terraced slopes.

The effect of topography (linear or concave) on soil erosion was prominent when slopes were covered by carbonate colluvium. Without topsoil, concave slopes yielded much less sediment than linear slopes, with deposition occurring primarily at the flatter bottom part of the slope, reducing off-site sediment exportation. Therefore, building concave topographies could be considered advisable when no topsoil is available.

The interaction between vegetation establishment and topography is complex. Natural plant cover was more widespread and more homogeneous on linear slopes than on concave ones. In the latter, natural plant colonization on the steepest part of the concavity was severely limited. The bottom of the concavity provided more favourable conditions for plant growth.

The three main activities involved in mining reclamation (slope construction, use of surface soil cover and plant establishment) did not operate independently in reducing sediment yield and erosion. This study suggests that the debate about the management of topography and surface soil cover, and their relationship with vegetation, should be approached under a systemic perspective. The main trade-offs between major variables should be considered: (i) topsoil can lead to a successful mining reclamation regardless of the two types of topography considered in our experiment; (ii) managing topography by creating concave slopes can lead to a successful mining reclamation when the use of topsoil is limited; and (iii) topsoil and topography determine the plant colonization pattern.

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