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Research article

Drone-based assessment of microsite-scale hydrological processes promoted by restoration actions in early post-mining ecological restoration stages

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ABSTRACT

A successful choice of post-mining restoration activities in dry climates may depend on relevant features related to topographic characteristics, hydrological processes and vegetation development, which will determine functional recovery in these ecosystems. The combination of different restoration techniques to reestablish vegetation, such as sowing and plantation, implies the interspersion of bare-soil areas with vegetated areas in early plant development stages, which may result in an associated mosaic of hydrologic functioning. In this study, we conducted a drone-based assessment to disentangle the role played by microsite-scale hydrological processes (i.e., planting hole slope, sink volume capacity, individual catchment area, Flow Length Index) promoted by restoration actions in soil protection and vegetation development on the hillside scale. Based on two contrasting restoration scenarios (Steep hillside and Smooth hillside), the different applied restoration treatments conditioned the microtopographic processes on the planting hole scale and, therefore, resource redistribution. The main results showed higher planting hole functionality on the smooth hillsides than on steep hillside, which resulted in greater water availability and bigger vegetation patches.

By addressing the role of hydrological processes on the microsite scale, our study contributes substantially to prior knowledge on the relevant factors for ecosystem development and post-mining restoration success. It also demonstrates that high-resolution drone images can be a very useful tool for monitoring restoration actions, especially in large, inaccessible and unstable restored areas.

1. Introduction

Industrial-scale mining activities entail profound long-lasting landscape transformations (Beckett and Keeling, 2019). The direct impacts of open-pit mining usually involve topsoil removal and altered geomorphological landscapes, which promote erosive and modified hydrologic processes associated with land degradation (Drake et al., 2010). These new hostile environments are hardly recolonised by fauna and flora, which affects important ecosystem functions and services like carbon sequestration or biodiversity (Cooke and Johnson, 2002; Moreno-Mateos et al., 2017). In recent years, more efforts have been made to reduce, mitigate and offset such impacts. Ecological restoration may contribute to restore and recover essential ecological losses, and to promote positive impacts on society, even beyond the area directly affected by mining (Doley and Audet, 2015; Young et al., 2022). For this purpose, governments, international institutions and private companies are developing guidelines that define post-mining restoration objectives with varying degrees of detail and urgency (Bainton et al., 2018).

Starting from scratch, post-mining ecological restoration represents a good opportunity to analyse and monitor how the results of restorative-applied techniques are progressing towards recovery and integration in natural surrounding ecosystems (Vickers et al., 2012; Wortley et al., 2013). These recovery processes will depend on the suitability of the applied techniques by considering spatial heterogeneity, climate conditions and time. Effective actions in reclaimed mining areas with dry climates, such as the Mediterranean Basin, may depend on features related to water scarcity and soil erosion, which determine the vegetation dynamics in these ecosystems (Moreno-de Las Heras et al., 2008; Turrión et al., 2021).

The combination of different restoration methods to re-establish

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vegetation contributes to create spatial pattern heterogeneity and vegetation discontinuity. For instance, simultaneously implemented sowing and planting implies the interspersion of bare-soil areas and vegetated areas in early plant development stages, which may result in an associated mosaic of hydrologic functioning (Pariente, 2002; Bautista et al., 2007; Fuentes et al., 2017). In this patchy scenario, bare-soil areas are commonly characterised by exhibiting relatively low infiltration capacity that promotes water and sediment runoff (i.e., source areas), with vegetation patches acting as accumulation areas (i.e., sink areas) (Puigdefabregas et al., 1999; Ludwig et al., 2005). Furthermore, on the hillslope scale, the hydro-geomorphologic behaviour largely controlled by the above-mentioned surface processes will also be affected by other factors like slope and microtopography that, together with vegetation cover characteristics (i.e., vegetation patch size, bare-soil connectivity), will condition restoration success (Mayor et al., 2008; Urgeghe and Bautista, 2015; Smanis et al., 2021). On this microtopographic scale, planting hole quality may play an especially important role in restoration success. Suitable planting holes can help to ensure that the plants introduced during the restoration process receive enough water and nutrients to survive and thrive (Padilla and Pugnaire, 2007; Valdecantos et al., 2014). These sink areas can also initially act as vegetation cores where plant development is favoured, which has a positive effect on the slope scale. In this regard, planting holes and their collecting upslope surface area should be considered to maximise their functionality and effectiveness in resource retention, and might be key functional units when assessing restoration success in post-mining scenarios (Fuentes et al., 2017).

Due to the complexity involved in manually assessing all the ground parameters that affect hydrological processes and vegetation dynamics on the hillside scale, very little is known about the role played by these processes in mining restoration. Drone-based surveys offer high-resolution analyses that combine low cost and time efficiency to produce the results of many ecological indicators of interest on a large scale (Anderson and Gaston, 2013; Gillan et al., 2021). Drones have been previously used to study the recovery of peatland ecosystems (Harris and Baird, 2019) by determining microtopography through digital elevation models (DEM). LiDAR images have been applied to assess large-scale restoration success (Reis et al., 2019) in several ecosystems, such as meadows (Davis et al., 2020), bogs (Knoth et al., 2013) or degraded drylands (Pérez et al., 2019). In mining restoration, drones have been specifically employed to assess spatial changes (Carabassa et al., 2020) and soil erosion dynamics (Carabassa et al., 2021; Padró et al., 2022). However, to our knowledge they have been rarely used to analyse the role of ecohydrological processes on the microscale level in restoration success, and even less for contrasting post-mining restoration scenarios.

In this study, we conducted a drone-based assessment to disentangle the role played by the microsite-scale processes promoted by restoration actions in soil protection and vegetation development on the hillside scale. Based on two contrasting post-mining restoration scenarios (RS), Smooth hillside and Steep hillside, we aimed to test the hypotheses that: 1) the combination of topographic features on the hillside scale and the different restoration actions applied in each RS would condition microscale processes and would, therefore, influence restoration success on the entire restoration scale; in each RS: (2) the planting hole parameters, determined as the planting hole slope, the hole sink volume capacity, the individual catchment area and the associated Flow Length Index, would differently relate to one another as a result of the distinct applied restoration actions; 3) functional planting holes would act as sink spots from which to enhance plant development, measured as plant height and effective plant cover; 4) the individual influence of each ground parameter on plant response would differ among RSs.

2. Material and methods

2.1. Study area

The study was carried out in the restored Fortuna mine area located in Ademuz (Valencia Province, Spain) (40°06′50.38″ N, 1°09′32.21″ W). The area surrounding the mine shows two differentiated domains as part of the Mediterranean climate: subhumid located over 1100 m.a.s.l and dry-subhumid at around 950 m.a.s.l, which reflect a gradient under climate conditions. The mean annual temperatures range from 9.5 °C to 15.1 °C, and the mean annual precipitation values are between 443 mm and 627 mm, respectively. According to the bioclimatic classification, the natural vegetation in the area corresponds to: (i) the Supramediterranean (above 1000 masl), dominated by *Juniperus thurifera, Juniperus phoenicea* and *Quercus rotundifolia*; (ii) the Mesomediterranean (900–1500 masl), dominated by a community with the *Quercus coccifera*, *Ulex parviflorus* and *Cistus albidus* species that alternate with agricultural fields and old reforested areas with *Pinus pinaster* and *Pinus nigra* ssp. *salzmanii*. The geological profile in the restored area was characterised by the intercalation of successive layers of Kaolinite-feldspathic white sand separated by red clay levels. On these layers of industrial interest lie several well-organised strata ranging from calcarenitic sandstone to calcareous lithology. To fill the mining hole after mining exploitation, several clay and sand layers were placed in January 2019 by following the design of the land shapes that derived from the Geofluv™ method using the Natural Regrade software (Hancock et al., 2019).

2.2. Restoration actions

After remodelling, the restored area resulted in smoothed land shapes dominated mostly by slopes less than 15%, a smaller proportion of surface with slopes between 15% and 30%, and some steep areas with slopes exceeding 30%. According to these characteristics, we defined two different RSs for the present study: Smooth hillside (average slope 15–30%, restored area 1.08 ha containing 722 planting holes); Steep hillside (average slope >30%, restored area 0.74 ha containing 766 planting holes) (Fig. S1).

In February 2019, different restoration actions were applied to the remodelled area according to the RSs (Table 1). Restoration actions were designed according to the main physiographic characteristics of each area in the LIFE TECMINE Project context (Turrión et al., 2021) and previous experiments carried out by CEAM (Vallejo et al., 2012; Valdecantos et al., 2014). Firstly, the whole restored area was manually sown with native perennial herbaceous species. The seed blend consisted of 50% *Dactylis glomerata* and 50% *Lotus corniculatus*. Then composted sewage sludge (compost) mixed with pruning refuse (10%) was spread on the substrate surface of the Smooth hillside as an organic amendment supply. Planting holes (40 × 40 × 40 cm) were mechanically implemented with a retro-spider at different densities according to the RS. In the Smooth hillside areas, standard holes were improved by microcatchments to capture runoff water and to promote infiltration to seedlings' root zones. Microcatchments consisted of two small channels

Table 1
Main characteristics and treatments applied to each restoration scenario.

Restoration scenario	Surface (Doses)	Plantation (Density/Doses)
Smooth hillside Dry-mild areas, moderate slopes (15–30%)	- Sowing (100–150 kg seeds/ha) - Compost (20 Tn/ha)	- Standard holes + Microcatchments (600 holes/ha) (722 planting holes; 1.08 ha) - Compost (2 kg/hole; 125 Tn/ha)
Steep hillside Dry areas (sun-exposed), Steep slopes (>30%)	- Sowing (100–150 kg seeds/ha)	- Standard holes (1000 holes/ha) (766 planting holes; 0.76 ha) - Compost (2 kg/hole; 125 Tn/ha)

(1–1.5 m long) on both sides of the planting hole (Fig. S2). According to previous studies (Smanis et al., 2021), this technique was not implemented on the Steep hillside to avoid counterproductive effects. Compost was added in-depth to each planting hole before seedling plantation and was well mixed with substrate until complete substrate homogenisation. Finally for planting, we set out to restore four different habitat types by reintroducing 12 different species (see Turrión et al., 2021 for further details).

2.3. Soil water availability

Volumetric Soil Water Content (VWC) dynamics was continuously recorded during the study period (from August 2019 to June 2021). For that purpose, we installed soil moisture sensors 10HS (Decagon dev., Pullman, USA) at a depth of 30 cm in eight randomly selected planting holes in each RS. These sensors provided hourly soil moisture data. We also installed a meteorological station provided with a rain gauge (EML model ARG100), which supplied daily data on total and maximum precipitation.

2.4. Aerial survey

We established two repeated drone surveys (July-19 and May-21) to assess planting hole functionality on the microsite scale and its role in plant development changes, respectively. In July 2019, after a few months after restoration, we used coordinates from 25 high-quality ground control points by means of *Leyca GPS 1200* equipment to generate precise geospatial products in the image post-processing steps. We did a photogrammetric flight using a multirotor drone (type DJI, Phantom 4 Pro) equipped with two different sensors: a high-quality RGB sensor (1 inch) with a mechanical shutter and a high-resolution camera (20 MP); an infra-red (IR) sensor (1/2.3 inch) with near-infrared (850 nm) and red (660 nm) bands of 16 MP. Autonomous missions took place at a constant altitude of 47 m above the ground using an 85% forward overlap and a 65% side overlap, which gave 761/602 pictures when combining zenith and oblique angles. The *Agisoft Photoscan v.1.4* software was used to obtain high-resolution orthophotographs, with a ground sample distance (GSD) of 1.4, 1.8 and 2.7 cm per pixel for the RBG, IR and digital surface model, respectively.

2.5. Hydrological ground parameters

The first aerial survey was carried out after some mild rain events in the recently restored area (i.e., 67.5 mm distributed in eight rain episodes from Feb. 19 to July 19) and water runoff started producing incipient drainage channels. We combined the elevation data analysis to calculate the main hydrological microsite-scale processes related to planting hole functionality and resource redistribution: planting hole slope, hole sink volume, individual catchment area, the flow length index of each planting hole (Fig. S3). To calculate the slope of each planting hole, we included a 0.80 m radius from the centre of the planting hole to represent both the irregularity of the planting hole and the context around it.

Using the *Arc Hydro Tools* module of *ArcGis v.10.5*, a sink (depression) in the digital terrain model (DTM) was taken as a pixel or set of spatially connected pixels, whose flow direction could not be assigned to other surrounding pixels. Hole sink volume was calculated as the sink area multiplied by the mean depth of each pixel considered to be a sink in the planting hole. Then we employed it as a proxy of the water-holding capacity of the planting holes surfaces.

The individual catchment area of each planting hole was calculated using these sink areas as an entrance (*pour points*), together with flow direction. Hence this value represents the individual catchment area that would feed the planting hole after a rain event produced runoff. The calculated drainage network assumes that as sinks retain incoming water, flow length is interrupted. Finally, we calculated the Flow Length Index as a connectivity metrics proposed by Mayor et al. (2008) as the average of the runoff pathway lengths from all the cells on a raster-based map of an individual catchment area.

2.6. Vegetation analysis

The mean plant height of the ground vegetation (i.e., vegetation resulting mainly from sowing and marginally from natural colonisation) was obtained by subtracting the digital terrain model of 2019, where there was hardly any vegetation, from the digital surface model of 2021.

To quantify vegetation greenness, we calculated the Normalised Differenced Vegetation Index (NDVI) in both RSs. Based on the NDVI data, we then estimated plant cover as the area occupied by pixels with any NDVI value assigned to green vegetation. To specifically assess the role of the planting hole as a resources sink to enhance plant colonisation according to the ground parameters on the microsite scale, we considered the established vegetation in a gradual increasing radius of 0 m (growing over the initial sink), 0.8 m, 1.2 m and 1.6 m around the planting hole (Fig. S4). Finally, to assess the degree of variation in plant cover continuity with increasing distance to the planting hole, we calculated the coefficient of variation (CV) between the plant cover in the planting hole (i.e., maximum plant cover) in relation to the furthest radius (i.e., minimum plant cover) as the ratio of the standard deviation to the mean in each RS.

As this study focuses on the response of vegetation in early post-mining restoration stages, the planted seedlings were not considered in the vegetation analyses because until the end of 2022, they were protected by tree shelters (60 cm height x 15 cm diameter) without having exceeded their height and without showing their real plant cover.

2.7. Data analysis

To evaluate the combined effect of the topographic features on the hillside scale and the different restoration techniques applied to each RS, we conducted a linear model (ANOVA) analysis on the planting hole slope, hole sink volume capacity, individual catchment area and the Flow Length Index data by taking the RS as a fixed factor. The daily soil water content data obtained from August 2019 until June 2021 for each restoration scenario were averaged by seasons (i.e., winter, spring, summer, autumn) and analysed by a Repeated Measures ANOVA with the RS as a between-subject factor and season (S) as a within-subject factor. We calculated the pairwise Pearson's correlations between all the ground parameters in each RS to assess variations in the relations among them. To assess if plant response (i.e., mean plant height and variation in plant cover) responded linearly or non-linearly to each ground parameter, we fitted linear and quadratic relations by selecting the most parsimonious model in each case. For this purpose, the data of each ground parameter were sorted into different classes to establish data ranks and to facilitate data plotting. The planting hole slope data were sorted into eight different classes (17–21, 21–25, 25–29, 29–33, 33–37, 37–41, 41–45, 45–49%). The sink volume data were sorted into eight different classes (<3, 3–6, 6–9, 9–12, 12–15, 15–18, 18–21, >21 $m^3 \cdot 10^{-3}$). The individual catchment area data were sorted into six different classes (<3, 3–5, 5–7, 7–9, 9–12, >12 m^2). The Flow Length Index data were sorted into eight different classes (<0.35, 0.35–0.45, 0.45–0.55, 0.55–0.65, 0.65–0.75, 0.75–0.85, 0.85–95, >0.95 m).

We assessed the relative importance of predictors by applying boosted regression trees (BRT) models using the "gbm" R package (Ridgeway, 2017). The results of this analysis provided the relative influence (RI) of the predictors set on the response variables (mean plant height of the ground vegetation and variation in the plant cover from the sink (i. e., planting hole) up to a 1.6-m radius outwardly) at the planting hole level. The Relative influence (RI) measures the number of times that a predictor variable is selected for splitting and is weighted by squared improvement in the model as a result of each split, averaged over all the trees and scaled to sum 100% (Elith and Leathwick, 2017). The greater the RI, the stronger the influence of the predictor on the response variable. BRT models were set by considering Gaussian distribution families for both response variables, and learning rates of 0.001–0.0001, tree complexity of 10–15 and bag fractions of 0.5–0.75 were considered. The minimum number of trees was mostly above 1000. All the statistical analyses were performed using R (R Core Team, 2017).

3. Results

3.1. Ground parameters on the hillside scale

On the hillside scale, we found significantly contrasting mean values among the RSs for all the assessed ground parameters (Table 2). The mean planting hole slope measured on the microtopographic scale was significantly higher in the Steep hillside scenario than in the Smooth hillside one. Although the mean values on the hillside scale may not reflect the real view of the slope conditions, there were big differences in the planting hole distribution across the slope gradient (Fig. S5). The mean hole sink volume, as an indicator of the water holding capacity in the planting hole, significantly differed among the RSs. The hillside scale analysis showed more generalised higher hole sink volume values in the Smooth hillside scenario than in the Steep hillside one, where holes with a low sink volume capacity were mainly found (i.e., smaller green dots, Fig. S6). Microcatchment implementation in the planting holes of the Smooth hillside influenced the mean catchment size, which was 2-fold larger in the holes of this scenario than in the planting holes of the Steep hillside scenario. We obtained slightly higher mean Flow Length Index values in the Steep hillside scenario than in the Smooth hillside one. Finally, we found significant differences in soil water content among RSs (Table 2). For the first 2 post-restoration monitoring years, on the Smooth hillside we recorded minimum and maximum values that ranged from 0.21 to 0.34 m^3/m^3 in summer 2020 and winter 2020, respectively. On the Steep hillside, minimum and maximum values of 0.18 and 0.29 m^3/m^3 were also recorded during the same 2020 seasons (Fig. S7).

Relation between ground parameters on the microsite scale.

The relation between the ground parameters measured on the microsite scale differed among RSs, as shown in Fig. 1. In both scenarios, the Flow Length Index was positively related to the individual catchment area and negatively to sink volume. In the Smooth hillside, all the parameters significantly correlated to one another. Thus, the planting hole slope correlated positively with sink volume and the Flow Length Index, and negatively with the individual catchment area. In the Steep hillside scenario, planting hole slope correlated significantly with the Flow Length Index, and we found only a positive trend in the correlation of this ground parameter with the individual catchment area and a negative trend in the relation with sink volume.

The microsite-scale processes underlying the vertical vegetation structure: plant height response.

The mean plant height values of the ground vegetation occupying the planting hole and the surrounding area were higher in the Smooth hillside scenario than in the Steep hillside one, with values around 35 cm and 25 cm on average, respectively (Fig. 2). In the Smooth hillside scenario, the mean plant height linearly decreased with the increasing sink volume capacity of the planting hole (Fig. 2, B). The mean plant height in this RS linearly increased with the growing individual catchment area (Fig. 2, C). For the same response variable, we found a positive non-linear relation with the Flow Length Index, with maximum mean height values at flow lengths of about 0.75 m before stabilising with increasing flow length (Fig. 2, D). For the Steep hillside scenario, the mean plant height linearly decreased with the individual catchment area (Fig. 2, C) and was the only significant relation to be found.

3.2. The microsite-scale processes underlying the horizontal vegetation structure: plant cover response

The plant cover percentage surrounding the hole differed among RSs and was higher in the Smooth hillside scenario than in the Steep hillside one (Fig. 3). In both RSs, we found the same trend of lowering plant cover values as distance to the planting hole increased (Fig. 3).

The CV in the plant cover calculated for the maximum (plant cover in sink) and minimum (plant cover in 1.2–1.6 m ring) plant cover was twice as high in the Steep hillside scenario (53 % on average) than in the Smooth hillside one (24 % on average). In the Smooth scenario, plant cover variation linearly decreased with the increasing sink volume capacity of the planting hole (Fig. 4, B), and was the only significant relation to be found. For the Steep hillside scenario, plant cover variation linearly decreased with planting hole slope (Fig. 4, A), individual catchment area (Fig. 4, C) and the Flow Length Index (Fig. 4, D), but linearly increased with volume sink capacity (Fig. 4, B).

3.3. The influence of ground parameters on plant performance

The BRT models fitted for the mean plant height of ground vegetation yielded cross-validation (cv) correlations, which ranged between 0.57 for the Smooth hillside scenario and 0.61 for the Steep hillside one (Table S3). This means that the Steep hillside scenario was slightly better explained than the Smooth hillside one. For the RI of the ground parameters at plant height, we found differences among RSs (Fig. 5-A). In the Smooth hillside scenario, the individual catchment area proved to be the most important for plant height (19%), while the other ground parameters were equally important (~12%). In the Steep hillside scenario, the planting hole slope had the highest RI (20%) for plant height, followed by the Flow Length Index and sink volume. In this scenario, and unlike the Smooth hillside scenario, the individual catchment area presented the least importance (11%).

The BRT models fitted for the variation in plant cover yielded CV correlations that ranged between 0.57 for the Smooth hillside scenario and 0.76 for the Steep hillside one (Table S3). Once again, the Steep hillside scenario was better explained than the Smooth one. For the RI of each ground parameter on variation in plant cover, we found significant differences among RSs (Fig. 5-B). Planting hole slope and sink volume capacity were equally important (~22%) in the Steep hillside scenario,

Table 2
Mean values and statistical results, F (P-values), of the Linear Model ANOVA analysis on the planting hole slope, hole sink volume capacity, individual catchment area and Flow Length Index data by taking restoration scenario as a fixed factor, and from the Repeated Measures ANOVA on the soil water content data (at 30 cm soil depth) for the Smooth hillside and the Steep hillside RS. The numbers in italics indicate significant effects ($p < 0.05$).

		Hole slope (%)	Sink volume capacity (L)	Individual catchment area (m^2)	Flow Length Index (m)	Soil water content (m^3/m^3)
Restoration scenario	**Smooth hillside**	29,1 ± 0.2	12.6 ± 0.4	11.4 ± 0.3	0.59 ± 0.01	0.30 ± 0.00
	Steep hillside	37.7 ± 0.2	6.4 ± 0.2	6.9 ± 0.2	0.68 ± 0.01	0.23 ± 0.00
	F (p)	*865.02 (<0.001)*	*237.47 (<0.001)*	*144.37 (<0.001)*	*29.09 (<0.001)*	*12.72*[a] *(0.023)*

[a] Here we represent only the statistical results for restoration scenario as a between-subject factor. See Table S1 for the complete statistical information on soil water content.

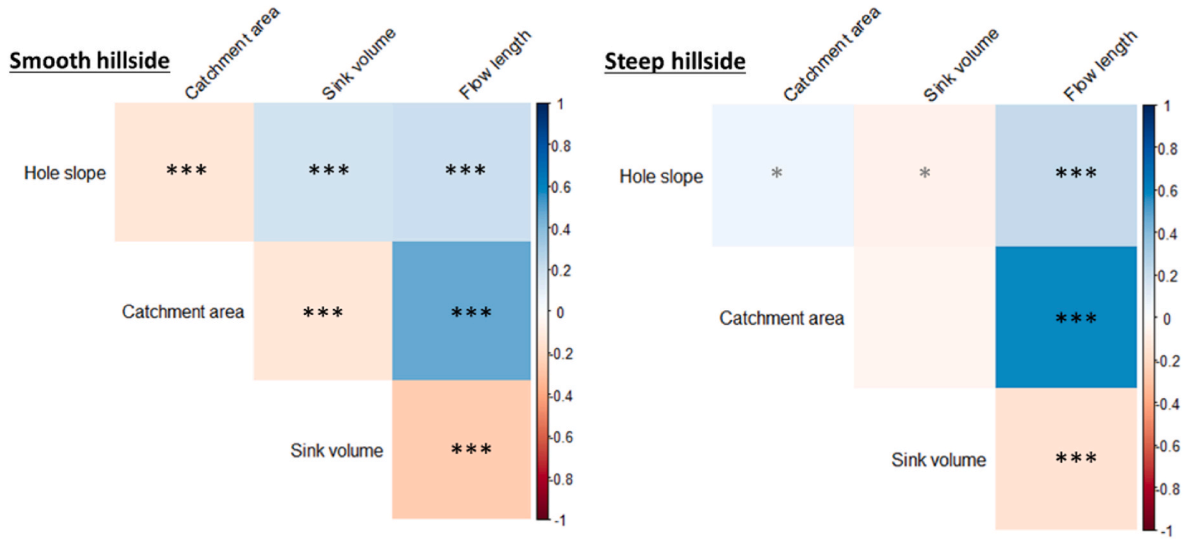

Fig. 1. Correlation matrix of the ground parameters for each restoration scenario. Colour intensity indicates the strength of the positive or negative correlations, with blue for positive and red for negative correlations. Significances are indicated as *p < 0.05, **p < 0.01, ***p < 0.001. Grey * shows trends (p < 0.06). Correlation coefficients can be found in Table S2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

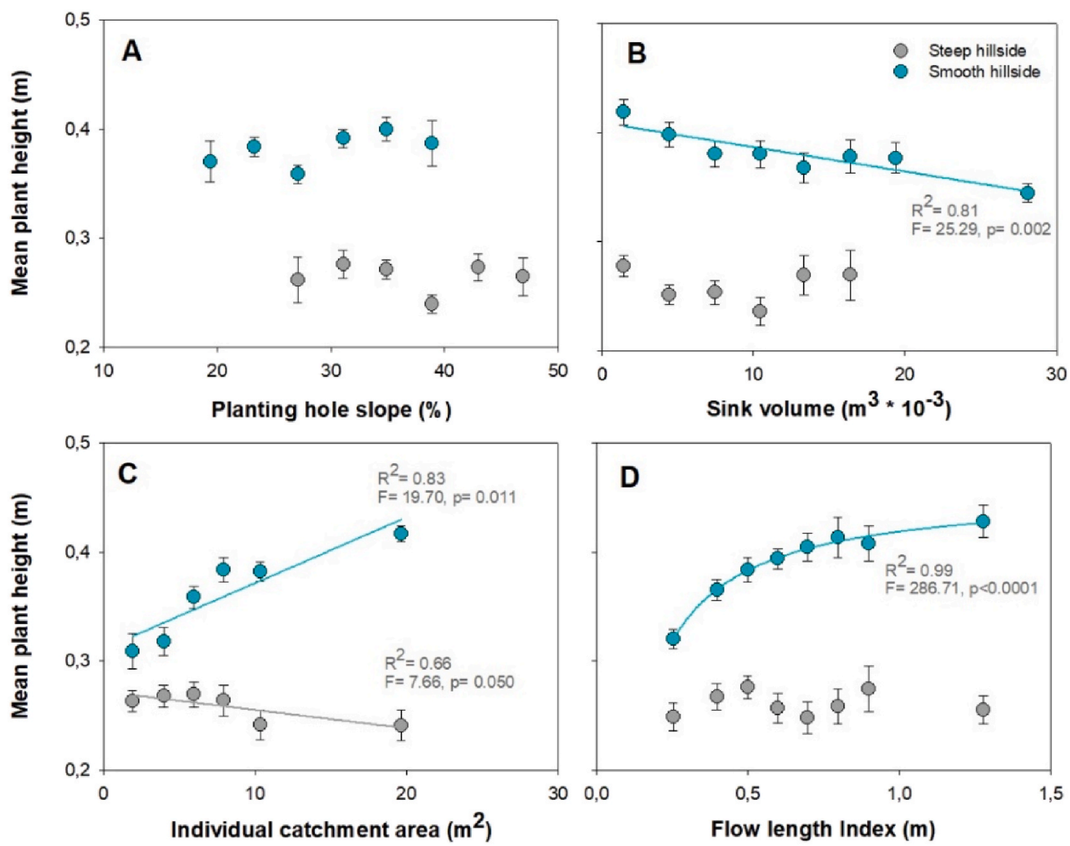

Fig. 2. Relation between the ground parameters and the mean plant height of the ground vegetation occupying the planting hole and the surrounding area in a radius of 0.8 m for each restoration scenario. The mean plant height according to the planting hole slope (A), hole sink volume (B), individual catchment area (C) and Flow Length Index (D). Each dot represents the mean ± SE of the values included in each defined class (see the M&ms section for information about data ranks). Blue- and grey-coloured dots and lines respectively depict the data and statistical relations for the Steep hillside RS and the Smooth hillside RS. Only significant relations (p < 0.05, solid lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

while the relevance of all the analysed parameters was similar for the Smooth hillside (12–16%).

4. Discussion

Our results demonstrate the effectiveness of drone-based assessments for monitoring restoration programmes compared to conventional

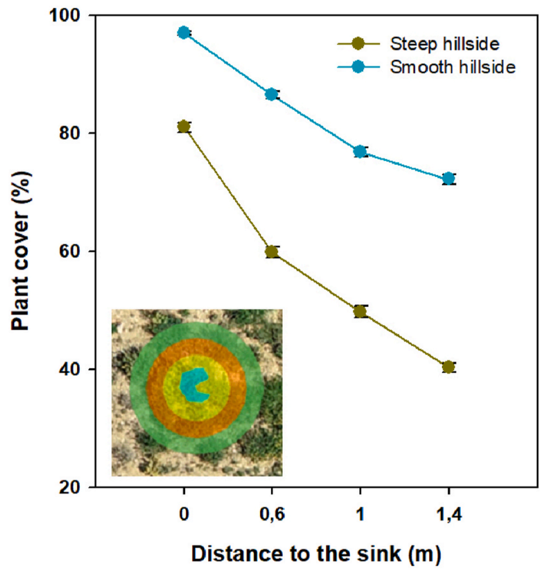

Fig. 3. The plant cover percentage according to distance to the sink (i.e., planting hole). Each distance labelled on the X-axis indicates the mean distance of each concentric ring measured to the sink (sink size is variable and corresponds to the blue area; sink-0.8 m yellow ring; 0.8–1.2 m orange ring; 1.2–1.6 m green ring; Fig. S4). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

fieldwork surveys, especially for large, inaccessible and unstable restored areas. The results are conclusive about the relevance of microtopographic factors on the related hillside scale for each RS.

Hillside slope: a main limiting factor for restoration success.

Hillside slope has been previously described as the main limiting factor for vegetation development in reclaimed landscapes (Vidal-Macua et al., 2020). Our results on the hillside scale showed clear differences among the evaluated ground parameters. When comparing both hillside scenarios, according to the recorded soil water availability data, the Smooth hillside favoured water retention. We also found a larger mean individual catchment area in the planting holes of the moderate slopes, which enhances the capacity of resources acquisition during a rainfall event (Urgeghe and Bautista, 2015; Fuentes et al., 2017). The average Flow Length Index revealed longer individual runoff paths on the Steep hillside, which underscores the crucial role played by topographic features on the connectivity of bare soil interpatches on hillslopes. According to Mayor et al. (2008), flow length used as a connectivity metric is linearly and positively related to runoff and sediment yields. In our study, this was reflected by the results obtained in the mean sink volume capacity of planting holes. The Steep hillside resulted in lower sink volume capacity, which is consistent with previous studies (Cantón et al., 2011 and references therein; see also Smanis et al., 2021). This was likely due to the larger amount of resources reaching planting holes which produce sink clogging and, in some cases, hole structure degradation.

Loss of infiltration capacity on the Steep hillside because of hole functionality loss, together with greater connectivity and lower resource retention capacity, imply more limiting abiotic conditions on the Steep hillside than on the Smooth one. Accordingly, the more favourable conditions found in the latter allowed ground vegetation to reach higher average plant cover and height than on the Steep hillside. Globally, our findings on the hillside scale, therefore, emphasise the importance of geomorphological remodelling prior to ecological restoration to ensure substrate stability and to avoid steep slopes dominating landscapes.

4.1. Role of planting holes as a sink to enhance vegetation development

Planting techniques aim to increase capture and retention by enabling seedlings to grow rapidly and more deeply explore soil horizons (Padilla and Pugnaire, 2007; Valdecantos et al., 2014). The longer the planting holes act as effective sink areas, the more likely seedling survival and plant development will be, which are especially important in early post-planting stages (Smanis et al., 2021). However, in this study we did not seek to evaluate plantation success, but the role of planting holes as a sink to enhance plant recovery and soil protection on the hillside scale.

The low-cost installation action of resource sinks in degraded areas has been widely tested in patchy drylands worldwide (Tongway and Ludwig, 2011; Kimiti et al., 2017; Cavallero et al., 2019; Urgeghe et al., 2021). In all cases, and regardless of the tested typology, which have varied from piles of branches and woody debris to synthetic sponges, installed resource sinks retain sediment and nutrients, and increase water infiltration by improving abiotic conditions for vegetation to establish and develop. In both the RSs evaluated in our study, planting holes acted as sink spots by obstructing runoff pathways and retaining resources. This was reflected by the decrease in plant cover with increasing distance to the sink. The sink effect was especially visible on the Steep hillside, where plant cover was arranged in a patchier pattern according to the high plant CV between the sink (~80% plant cover) and the most external measured ring (i.e., 1.2–1.6 m; 40% plant cover). This was not surprising because, as explained above, the hillside slope hinders resource retention and, consequently, a stronger effect of source-sink dynamics is expected (Puigdefábregas, 2005). We found that several local processes underlay our findings. On the Steep hillside, the plant CV correlated positively ($r^2 = 0.77$) with sink volume capacity, which emphasises the importance of preserving planting hole functionality to favour source-sink dynamics functioning. The plant CV was, nevertheless, negatively related to the individual catchment size and flow length and was, thus, when sediment yield was maximised. Although a low CV might *a priori* seem to be related to more homogeneous plant cover as observed on the Smooth hillside, on the Steep hillside it reflected low vegetation cover both inside and outside the planting hole. Therefore, our results suggest that this combination of a large individual microcatchment size and connectivity in Steep hillside scenarios should be avoided in future restorations to prevent sink clogging and cracking and, consequently, loss of planting hole functionality. Smanis et al. (2021) reached the same conclusion with their assessment 10 years after restoring a semiarid degraded area. In agreement with our results, those authors concluded that the bigger the individual microcatchment area, the lesser sink capacity in the medium/long terms. In contrast, such a combination of local processes maximising resources yields resulted in a different response pattern on the Smooth hillside. In this scenario, the plant CV was slightly related to sink volume, but unlike the Steep hillside, a major effect on plant height was observed. Plant height was linear and positively related to the increase in catchment area and was potentially related to flow length by showing on moderate slopes that resource arrival would benefit the role of planting holes when acting as a sink. These contrasting findings highlight the importance of designing specific actions according to each RS to optimise resource redistribution on the hillside scale and, therefore, plant performance.

4.2. Effectiveness of restoration actions in redistributing resources

According to the relative influence of each parameter that derived from the BRT models for both RSs, we can establish the most relevant influencing plant response among those measured. BRT models better fitted the Steep hillside scenario, which emphasises the existence of non-linear relations and interactions among microtopographic variables. In this RS, hole slope and flow length strongly influenced the plant height of the ground vegetation surrounding the planting hole. For plant cover variation (CV), hole slope and sink volume capacity were those with the strongest influence. In the Smooth hillside scenario, the individual catchment area stood out from the other variables in the plant height

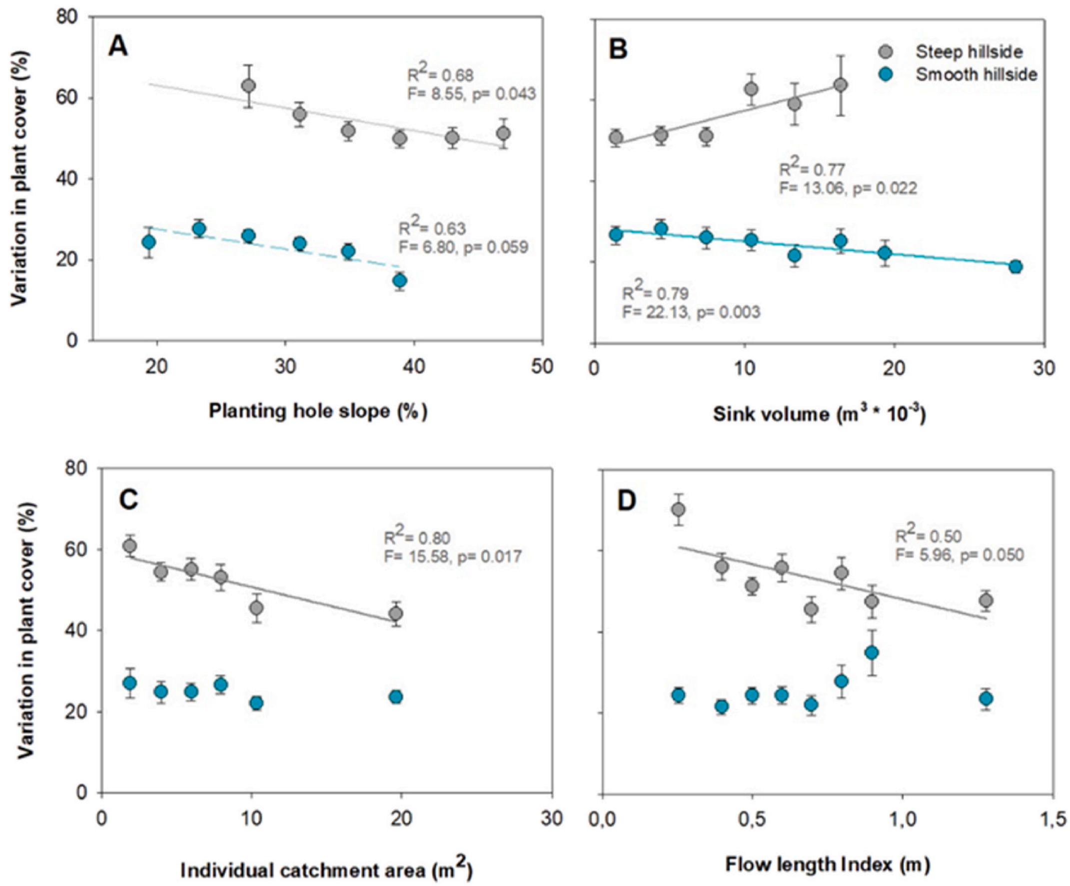

Fig. 4. The relation between ground parameters and plant cover variation (CV, coefficient of variation between sink plant cover and plant cover at the 1.6 cm distance). Plant cover variation according to the planting hole slope (A), hole sink volume (B), individual catchment area (C) and the Flow Length Index (D). Each dot represents the mean ± SE of the values in each defined class. The planting hole slope data were sorted into eight different classes (see the M&ms section for information about data ranks). Blue- and grey-coloured dots and lines show the data and statistical relations for the Steep hillside RS and the Smooth hillside RS, respectively. Only significant relations ($p < 0.05$, solid lines) and trends ($p < 0.1$, dashed lines) are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

response. In this regard, microcatchment implementation aimed to temporarily retain the rainfall and runoff water upslope of patches by slowing down the water flow and facilitating water infiltration (Fuentes et al., 2017), which proved appropriate for Smooth hillside scenarios. These constructions modified the individual catchment size and shape upslope of each planting hole (Fig. S8). Compared to regular planting holes conducted on the Steep hillside, on the Smooth hillside we found more shorter runoff paths associated with microcatchments, which ensured resource acquisition, while preventing planting hole functionality loss. However, according to our results and previous studies (Smanis et al., 2021), the implementation of this technique could be counterproductive on very steep slopes because of the above-explained negative relation observed between catchment size and plant development. These findings reinforce the design decision to not implement this treatment in the Steep hillside scenario.

The planting hole density applied to each RS (i.e., 600 and 1000 holes/ha on the Smooth hillside and the Steep hillside, respectively) may also play a significant role in connectivity and resource redistribution and, therefore, in preventing soil degradation. Sink density has been previously reported as being the primary hydrologic control factor of patchy landscapes through critical underlying mechanisms like rainfall interception and direct soil protection (Urgeghe et al., 2021). Therefore, modifying total vegetated patches by changes in planting hole density would also alter resource distribution on the hillside scale. Decreasing patch density may, for instance, entail global loss, but a local increase in the resources transferred from bare-soil areas to vegetation patches (Mayor et al., 2019). Considering our results, decreasing planting hole density in the Smooth hillside would allow to manipulate individual catchment size by implementing wider and/or longer microcatchments around the planting hole to maximise resource acquisition. Contrarily, increasing planting hole density (>1000 holes/ha) on steep slopes would help to increase sinks spots that break runoff pathways and therefore, would decrease connectivity. This action would prevent planting hole functionality loss in this scenario related to large individual catchment areas and long runoff paths. Nevertheless, establishing the proper planting hole density can be somewhat complicated because more is not always necessarily better, as some authors report (Berghuis et al., 2020). In addition, with the more limiting factors that are intrinsic to steep slopes, higher planting density may imply fiercer plant competition for resources, especially in the climate change context, which could result in negative effects for restoration success in the medium/long terms. Therefore, implementing empty planting holes or the intersperse installation of other low-cost barriers that act as functional resource sinks can be contemplated.

In any case, to ensure the development of vegetation and long-term restoration success, the selection of suitable restoration techniques must be designed by considering the limiting factors related to the different restoration scenarios to increase restoration efficiency and the minimising factors that hinder such success. Along these lines, some other important features previously reported, such as physical soil conditions (soil moisture index, soil quality), biological factors (distance from natural seed sources), climate factors (winter solar radiation, SPEI

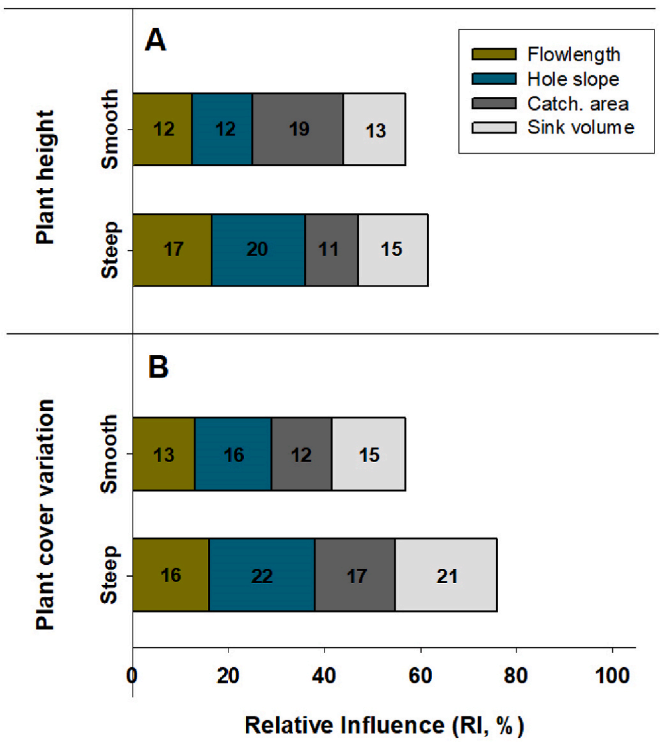

Fig. 5. The RI (%) that derived from BRT on (A) the mean plant height of the ground vegetation occupying the planting hole and the surrounding area in a radius of 0.8 m and (B) the plant cover variation (CV between sink plant cover and plant cover in the 1.2–1.6 m ring) in the Smooth and Steep hillside scenarios of the different ground parameters measured on the microsite-scale. The set of predictors for both the response variables in both scenarios includes the Flow Length Index, planting hole slope, individual catchment area and hole sink volume capacity.

Index) and adequate species selection, should be considered (Moreno-de Las Heras et al., 2008; Vidal-Macua et al., 2020; Turrión et al., 2021).

5. Conclusions

The use of high-resolution images has proven to be a very effective tool for assessing restoration actions. The drone images analysis applied from an ecological approach can help to refine the different stages of ecological restoration projects, from design to implementation and monitoring, and can provide low-cost powerful inputs for adaptive large-scale management.

Our findings provide useful information for modelling and understanding vegetation recovery dynamics, and for designing management and restoration measures that consider the critical role played by source-sink dynamics and hydrological connectivity in patchy landscapes. In this regard, it is crucial to underscore the importance of conducting geomorphological remodelling before ecological restoration after mining to ensure soil stability and to prevent the dominance of steep hillsides in the landscape.

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CRediT authorship contribution statement

Luna Morcillo: Writing – original draft, Writing – review & editing, Formal analysis, Data collection, Data curation. **Diana Turrión:** Writing – review & editing, Formal analysis, Data collection, Data curation. **David Fuentes:** Writing – review & editing, Formal analysis, Data collection, Data curation. **Alberto Vilagrosa:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119468.

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