



# Floristic and vegetation successional processes within landslides in a Mediterranean environment



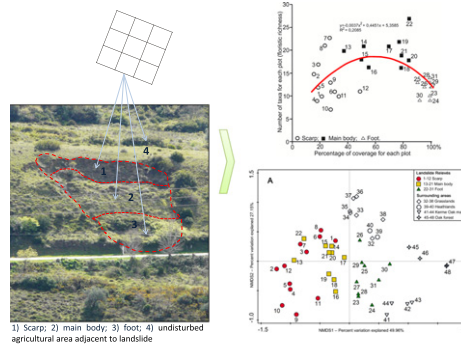
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## HIGHLIGHTS

- A method to understand successional processes in disturbed landslide areas is presented.
- A floristic and vegetation analysis is performed considering different landslide sectors.
- A gradient in the seral vegetation stage is observed from landslide scarp to foot.
- Landslide disturbed areas can be biodiversity reservoirs.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Floristic and vegetation analysis in seven Mediterranean landslides led to the understanding of the successional processes occurring in different landslide disturbed sectors. Our study showed that in landslides that occurred between 1996 and 2010 there is a clear differentiation between the three main landslide sectors (scarp, main body and foot) concerning floristic composition, vegetation structure, floristic richness, successional processes and plant functional type. Additional differences were found between landslide areas and undisturbed agricultural areas adjacent to landslides. In this study 48 floristic relevés were made using a stratified random sampling design. The main landslide body exhibits the highest floristic richness whereas the landslide scarp has the lowest coverage rate and the highest presence of characteristic species from ruderal and strongly perturbed habitats. Finally, the landslide foot shows a late stage in the succession (maquis or pre-forest stage) with a high dominance of vines. We further discuss the importance of landslides as reservoirs of biodiversity especially for Mediterranean orchids.

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## 1. Introduction

Disturbances caused by natural disasters such as earthquakes, typhoons, landslides, floods and forest fires, among others, change the biological organization of ecosystems (del Moral and Walker, 2007).

These events often lead to primary or secondary succession, depending on whether the disturbance involves species changes on substrates with little or no biological legacy (primary succession) or the succession begins with some biological legacy (secondary succession) (Franklin et al., 1985; Walker and del Moral, 2003; Geertsema and Pojar, 2007; Walker and Shiels, 2013). The study of environmental disturbances has a long research tradition focusing on different impacts, restoration and succession process (White and Jentsch, 2001; Restrepo et al., 2009). Landslides

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are major phenomena responsible for natural disturbance on ecosystems removing organic matter and topsoil, exposing bare rock and shallow subsoil and generating extreme environmental gradients (Myster and Fernández, 1995; Myster, 1997; Pearson et al., 2013). These natural disturbances provide new substrates for plants and community development and alter the landscape (Elias and Dias, 2004, 2009). The mobilization of soil mass (engineering perspective) takes place when a landslide occurs allowing the study of the successional processes, as well as the analysis of the competition processes among colonizing plants.

The principle of ecological succession on landslides is well established with the nature and rate of succession being determined by changes in soil type, available nutrients, light, wind and hydrology (Walker et al., 1996; Myster and Walker, 1997; Stokes et al., 2007; Shiels and Walker, 2013). However, the ecological characteristics of habitats created by the landslide are not homogeneous and a longitudinal gradient (from upper to lower landslide zone) of the chemical and physical properties may exert a big influence on the spatial distribution of flora and vegetation and on the successional process (Lundgren, 1978; Adams and Sidle, 1987; Guariguata, 1990; Reddy and Singh, 1993; Francescato et al., 2001; Shiels et al., 2008). According to Guariguata (1990) the lower zone of the landslide (the landslide foot) has higher concentration of carbon and total organic nitrogen exchangeable cations than the upper landslide rupture zone. On the other hand, the changes in soil structure and texture induced by the soil mass mobilization leads to a spatial differentiation of water-holding capacity and root penetrability among the different landslide zones. The spatial mosaic of habitats provided by the soil mass mobilization leads to different plant strategies and functional types of colonization of the main landslide sectors.

Worldwide studies on how landslides alter the structure of populations, communities and ecosystems relate to the soil characteristics and floristic and structural comparison between the landslide and the undisturbed adjacent area (Lundgren, 1978; Zarin and Johnson, 1995a; Restrepo and Alvarez, 2006; Elias and Dias, 2009). Some studies, however, explore plant succession on landslides (Flaccus, 1959; Mark et al., 1989; Dalling, 1994; Zarin and Johnson, 1995b; Francescato and Scotton, 1999; Gers et al., 2001; Elias and Dias, 2009; Walker et al., 2009; Walker and del Moral, 2009; Walker et al., 2010a, 2010b; Walker et al., 2013). However, only a few studies focus on the differentiation of flora and vegetation within different landslide sectors, especially the scarp, the main body and the foot (Sakai and Ohsawa, 1993; Velázquez and Gómez-Sal, 2008, 2009; Velázquez et al., 2014).

Our study aims: (i) to identify the flora and vegetation differences between the three main sectors of a landslide (scarp, main body, foot) as a consequence of the different habitat characteristics created by the moving soil mass (longitudinal gradients); and (ii) to find out whether the differences in floristic composition and vegetation structure are reflected in the succession process; (iii) to find out if the three landslide sectors of landslides of similar ages are now in the same seral stage or if the succession process has produced different seral stages along the longitudinal gradients and compare these seral stages with those of the undisturbed areas adjacent to the landslides but submitted to agricultural processes that have not taken place in the landslide area; and concerning the floristic composition (iv) to find out the contribution of landslides towards the formation of nodes or hotspots of non-forested or non-shrubby habitat and biota (Geertsema and Pojar, 2007) that in the Mediterranean region are fundamental to the preservation of many protected plants, mainly of the *Orchidaceae* family, some of which are rare.

## 2. Study area

As test site we selected a set of seven landslides (Fig. 1; Table 1) that occurred within a 4.5 km<sup>2</sup> study area north of Lisbon, specifically, along the small catchment of the Pequeno River. The study area is

characterized by the existence of a monocline structure with lithological layers dipping south from 5° to 25°. The dominant lithological outcrops are: carbonated rocks of Jurassic age, volcanic dykes and alluvial deposits filling the valley bottom. The carbonated rocks are essentially associated to a lithological complex of limestones and marls. The northern section of the study area comprises two minor outcrops of pelites, sandstones, marls and limestones. The elevation ranges from 120 m in the southern central part of the study area along the channel of the Pequeno River to 310 m in the Alrota hill. The major slopes are part of the Pequeno River valley that flows from the north to the south following the dip of the geological layers.

The differential erosion during the Quaternary generated a hilly landscape that includes structural landforms (cuestas) and large erosional depressions such as the Arruda dos Vinhos basin located 10 km northwards of the study area. Additional elements on the geomorphology of the area north of Lisbon can be found, for example, in Ferreira and Zêzere (1997), Zêzere et al. (1999) or Zêzere et al. (2008).

The natural vegetation in the studied territory is dominated by Portuguese oak forests and the respective substitution communities as presented in Table A1. According to the national cartography of land use cover (COS-Soil Occupation Map from 1990 and 2007) the majority of the studied landslide test sites underwent substantial changes between the early 1990's and 2007, in particular reverting from agricultural to shrub areas (Table 1) due mainly to the progressive abandonment of agricultural activities.

The climatic characteristics of the study area are defined based on the climate profile obtained from the São Julião do Tojal meteorological station, located 10 km south of the study area and with a Mean Annual Precipitation – MAP of 730 mm (Zêzere and Trigo, 2011). The contrast between the wet period (October to May) and the drier period (June to September) is clear. Shallow landslides are typically triggered by intense rainfall accumulating within a 1 to 15-day period (Zêzere et al., 2005; Zêzere et al., 2015).

### 2.1. Landslide data

Data on landslides in the study area (Fig. 1) was acquired through detailed field geomorphological mapping. All the landslides occurred within the lithological unit composed by limestones and marls dated from the lower Tithonian. Table 1 summarizes the main characteristics and morphometric properties of the seven landslides that make up the test site. With the exception of landslide #5, all studied landslides occurred within a similar time span (1996–2010), 6 to 20 years ago. Their position on the slopes is mainly associated with elevations ranging from 158 to 253 m and on moderate to steep slopes (22° to 36°). This slope variation is related to the lithological variations along the lower Tithonian lithological formation (Fig. 1) where steeper slopes are typically associated to limestones layers or interbedded limestones and marls, which originate rock halls on the slope top or along the middle slope. The landslide areas are mainly oriented to the E, NW and W. With respect to the landslide magnitude, defined by landslide area, length and width, landslides are essentially small (maximum landslide area ± 3300 m<sup>2</sup>).

## 3. Methods

In order to answer the initial question about the floristic and physiognomic-structural differentiation between the vegetation on the different landslide sectors (landslide scarp, main body, foot and undisturbed area adjacent to landslide) seven landslides and seven landslides strata were selected. Thus we ensure that the results are not influenced by a substantial age difference between landslides or by a considerable human influence (agricultural activities or fire impact).

In order to understand the floristic differentiation between the different landslide sectors seven landslide strata were defined (Fig. 2):

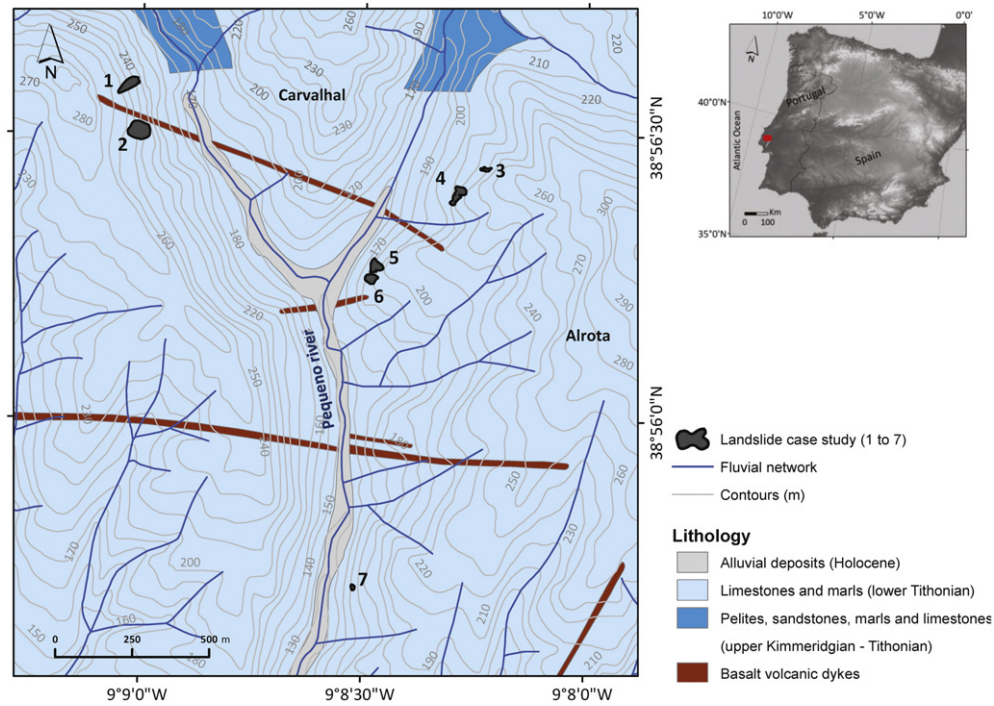


Fig. 1. Location of study area and landslides case study.

1 - Scarp; 2 - Main body; 3 - Foot; 4 - Undisturbed area adjacent to landslide, and for the latter 4 sub-divisions were considered: 4a - Oak forest; 4b - Maquis of *Quercus coccifera* in mosaic with *Brachypodium phoenicoides* grasslands; 4c - Heathland in mosaic with *Brachypodium phoenicoides* grasslands; 4d - *Brachypodium phoenicoides* grasslands. Forty-eight relevés were considered in this study using a stratified random sampling design. The random distribution and spatial position of relevés within landslide sectors and undisturbed area adjacent to landslides was further obtained randomly using the ArcGIS Geostatistical Analyst tool. For that purpose, a grid layer (5 × 5 m) was created and superimposed onto each landslide and to 200 m outside the landslide delineation. In this study, the 200 m buffer areas outside the landslides delineation were considered as the undisturbed area adjacent to landslides. Finally, a numeric ID was assigned to each square grid centroid and a random selection was performed. In this process we try to guarantee, in an iterative way, that approximately 60% of the relevés are uniformly distributed within the different landslide sectors (approximately 10 relevés for each landslide sector: landslide scarp, main body and foot) and the remaining 40% of relevés distributed along the undisturbed area adjacent to landslides (landslide strata defined previously from 4a to 4d). The final distribution of relevés by landslide strata was defined according to the distribution shown in Table 2.

In the relevés we used a quadrat size of 1 m<sup>2</sup> for annual and perennial herbaceous vegetation (grasslands), 5 m<sup>2</sup> for low shrubby

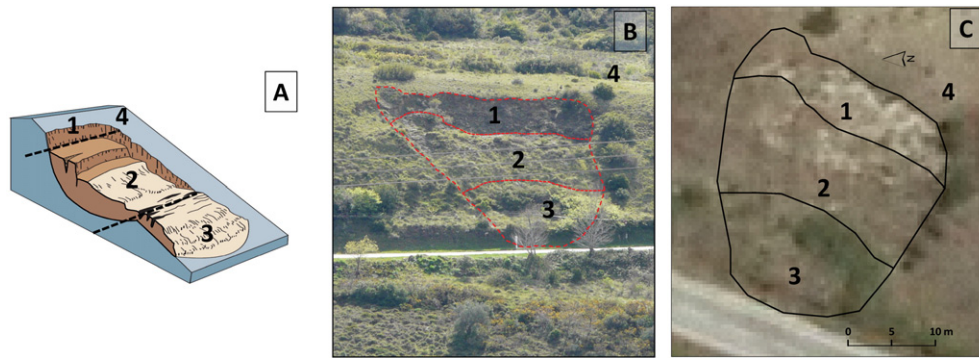
vegetation (garrigues), 25 m<sup>2</sup> for medium to high shrubby vegetation (maquis) and 100 m<sup>2</sup> for arboreal vegetation (marcescent oak forest of *Quercus faginea* ssp. *broteroi*, leaves wither in autumn but remain dry on the branches until spring). The quadrat area for each type of vegetation was determined by the minimal area quadrat method (species area curve/asymptotic curve) as described by Mueller-Dombois and Ellenberg (1974), Westhoff and van der Maarel (1978), and are in agreement with standard dimensions for different types of vegetation proposed by Chytrý and Otýpková (2003) and van der Maarel (2005).

Square size was kept constant within the same type of vegetation (annual and perennial herbaceous vegetation (grasslands); low shrubby vegetation (garrigues); medium to high shrubby vegetation (maquis); arboreal vegetation) according to Otýpková and Chytrý (2006) and Dengler et al. (2009). We used a 1 m × 1 m frame for herbaceous and a 2.5 m × 2.5 m frame for low shrubby vegetation. For the high shrubby vegetation the same 2.5 m × 2.5 m frame was used for each quadrant of the 25 m<sup>2</sup> square. In the forest area the 100 m<sup>2</sup> square was bounded by four poles and a rope and the abundance calculated based on the vertical projection for all species. In each relevé we recorded the cover area (with a tape-metric and a distance meter Leika DISTO™ D5 with 1 mm accuracy) of the different taxa and represented it in a 2D graphic model (field map). Also, the height of each plant was recorded using a tape-metric in the case of herbaceous and shrubby vegetation and with the distance meter Leika DISTO™ D5 for trees. Lastly, all field

Table 1  
Landslide characteristics: morphometric parameters and location.

ID #	Typology	Max. Length (m)	Max. Width (m)	Slide area (m <sup>2</sup> )	Date	Mean slope (°)	Aspect	Elevation (m)	Land use "COS"	
									1990	2007
1	Shallow Translational Slide	81	30	1804	2006	22	E	253–221	Pinewood forest	Sparse shrubs
2	Shallow Rotational Slide	73	64	3301	2006	26	E	249–213	High shrubs transition area	Sparse shrubs
3	Shallow Translational Slide	37	9	272	2006–2010 <sup>a</sup>	23	W-NW	233–223	Annual crops; Vineyard	Sparse shrubs
4	Shallow Translational Slide	40	67	1464	2006–2010 <sup>a</sup>	27	W-NW	230–208	Mainly agricultural areas	Sparse shrubs
5	Shallow Rotational Slide	43	50	1219	1996–1997 <sup>a</sup>	27	NW-W	193–176	Annual crops; Vineyard	Burned areas
6	Shallow Rotational Slide	42	33	937	1996–1997 <sup>a</sup>	28	W	197–176	Annual crops; Vineyard	Burned areas
7	Shallow Translational Slide	14	19	179	2010	36	W	165–158	Broadleaved forest	Resinous and broadleaved forest

<sup>a</sup> It was not possible to establish an absolute date of occurrence for these cases and only an estimated age is reported.



**Fig. 2.** Example of a rotational slide sectors scheme (A) (adapted from Highland and Bobrowsky, 2008); (B) and (C) Rotational slide #6 and different landslide sectors individualization. Numbers represent the different landslide sectors: (1) Scarp; (2) Main body; (3) Foot; (4) undisturbed area adjacent to landslide (including: 4a - Oak forest; 4b - Maquis of *Quercus coccifera* in mosaic with *Brachypodium phoenicoides* grasslands; 4c - Heathland in mosaic with *Brachypodium phoenicoides* grasslands; 4d - *Brachypodium phoenicoides* grasslands).

maps were vectored in ArcGis in order to calculate the percentage of study area occupied by each *taxa* within the square plot.

The dominance concept is used throughout the work in the sense of basal area (Begon et al., 2005; Kercher et al., 2009). Dominance and relative dominance of each species in a plot was obtained by Eqs. (1) and (2), respectively:

$$D.b.a. = \frac{\text{b.a. for each taxa}}{\text{Area of the plot}} \times 100 \quad (1)$$

where D.b.a. is the Dominance or proportional basal area in plots; and b.a. is basal area.

$$R.D.b.a. = \frac{D.b.a. \text{ for each taxa}}{\sum \text{dominance of all taxa}} \times 100 \quad (2)$$

where R.D.b.a. is the Relative Dominance or basal area.

The height of each species within a plot is the average height of all individuals. We used Eq. (3) to compute the average height of vegetation in each plot:

$$A.h. \text{ of vegetation in a plot} = \sum_{i=1}^n \left( \frac{R.D.b.a. \text{ for each taxa}}{100} \times A.h. \text{ for each taxa} \right) \quad (3)$$

where A.h. is the Average height.

The total of 48 plots was submitted to a Non-metric multidimensional scaling (NMDS) with Bray-Curtis coefficient using CANOCO 5.5 software (Ter Braak and Šmilauer, 2012).

A polynomial regression based on landslide relevés (scarp, main body, foot) was made between floristic richness (in the sense of number of *taxa*) and the percentage of coverage for each plot. A Bartlett's test for homogeneity of variances was performed as was an ANOVA test (with the richness values).

We used the original classification of Raunkiær plant life-form (Raunkiær, 1934) subsequently revised and modified by Braun-Blanquet (1964) and Mueller-Dombois and Ellenberg (2003): Phanerophytes - woody plants with resting buds >50 cm or more above soil

level (nanophanerophytes 0.5–2 m; microphanerophytes 2 m–8 m; mesophanerophytes 8 m–30 m; megaphanerophytes >30 m high). Chamaephytes - woody plants with perennating buds borne between ground and 50 cm above the soil surface. Hemicryptophytes - herbaceous plants with buds at or near the soil surface. Cryptophytes - herbaceous plants resting buds lying either beneath the surface of the ground as a rhizome, bulb, corm, etc., or a resting bud submerged under water (geophytes resting in dry ground, helophytes resting in marshy ground, hydrophytes resting by being submerged under water. Therophytes - annual seed plants.

Raunkiær plant life-forms classification (Raunkiær, 1934) was performed based on the abundance of each plant life-form in the scarp, in the main body, in the foot and in the group of Landslide Surrounding areas, respectively. We calculated the relative abundance of each plant life-forms for each sector using the following formula:

$$RaPLF = \frac{\sum \text{dominance of each life form in the sector} \times 100}{\sum \text{dominance of all plant life forms in the sector}} \quad (4)$$

where RaPLF is the Relative abundance of a Plant Life-Form within a sector.

We performed an indicator value (IndVal) analysis of the *taxa* present in the studied areas based on Table A2 (species in rows and samples in columns). IndVal method developed by Dufrêne and Legendre (1977) combines measurements (abundance and frequency of occurrence in samples assigned to each landslide strata) of the degree of specificity of a species to an ecological state. The IndVal of each *taxa* and the respective significance levels (performing 50,000 randomizations) were obtained using the “indval” function from “labdsv” package (Roberts, 2015), using R Statistical Software (R Core Team, 2015). IndVals were calculated and the results are shown in at Table A3 under supplemental material.

The nomenclature of vascular plants follows the works of Castroviejo (1986–2012), Franco (1971, 1984), Franco and Afonso (1994, 1998, 2003). For the Orchydaceae family we follow Tyteca (1998) nomenclature. All specimens collected were identified in João de Carvalho e Vasconcellos Herbarium (Code: LISI) University of Lisbon, where all material is deposited.

**Table 2**  
Distribution of the 48 relevés for each of the seven landslide environments.

Sample strata	Landslide sectors			Undisturbed area adjacent to landslide			
	Scarp	Main body	Foot	Oak forest of <i>Quercus broteroi</i>	Maquis of <i>Quercus coccifera</i> in mosaic with <i>Brachypodium phoenicoides</i> grasslands	Heathland in mosaic with <i>Brachypodium phoenicoides</i> grasslands	<i>Brachypodium phoenicoides</i> grasslands
# relevés	12	10	9	4	4	2	7

4. Results

The analysis of the relevés from the different landslide sectors showed that there is a clear differentiation in the floristic composition, in the dominance of the Raunkiaer plant life-form and in the seral stages between the different landslide sectors. Table A2 show the dominance or basal area of the *taxa* in the study area for all the relevés organized into the different strata according to the selected sampling design. The average plant cover in the landslide scarp plots has the lowest value of all sectors (26%). The main landslide body reaches a much higher (67.6%) average plant cover and the landslide foot has the highest value (97.7%). There is a clear gradient between the highest and the lowest sectors of the landslide. Furthermore, the average height of the plants in the landslide scarp is the smallest of all sectors. Concerning the relationship between the average height and the percentage of vegetation cover Fig. 3 shows that the landslide scarp plots have the lowest values of coverage and the lower average height of the individuals.

Regarding the richness of floristic species, the plots in the landslide scarp have a lower number of *taxa* per plot (mean = 13.3; variance = 23.8) than the landslide main body (mean = 19.8; variance = 10.6) and at the landslide foot the number of *taxa* per plot is lower again (mean = 11.9, Variance = 4.1) (Fig. 4). Comparing the floristic species richness with the relative coverage for each plot, the lowest values of species richness are recorded in the landslide foot with higher coverage rates and the highest values of species richness are recorded in the landslide main body with medium coverage rates (Fig. 4). Similar pattern of floristic richness distribution within landslides had also been carried out by Velázquez and Gómez-Sal (2009) in a tropical dry climate in Nicaragua.

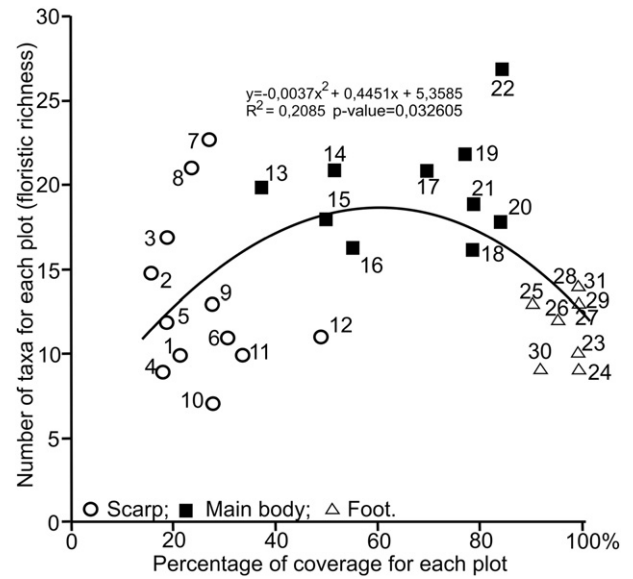


Fig. 4. Relationship between floristic richness and % of coverage for plots included in landslide sectors. Bartlett's test for homogeneity of variances (floristic richness) with P-value = 0.049 and ANOVA (floristic richness) with P-value = 0.00011925.

The Non-metric multidimensional scaling (NMDS) of all the relevés clearly separated the three sectors of the landslides, based on their floristic composition (Fig. 5A and B). The landslide scarp is dominated by species characteristic of disturbed areas, ruderal areas and abandoned

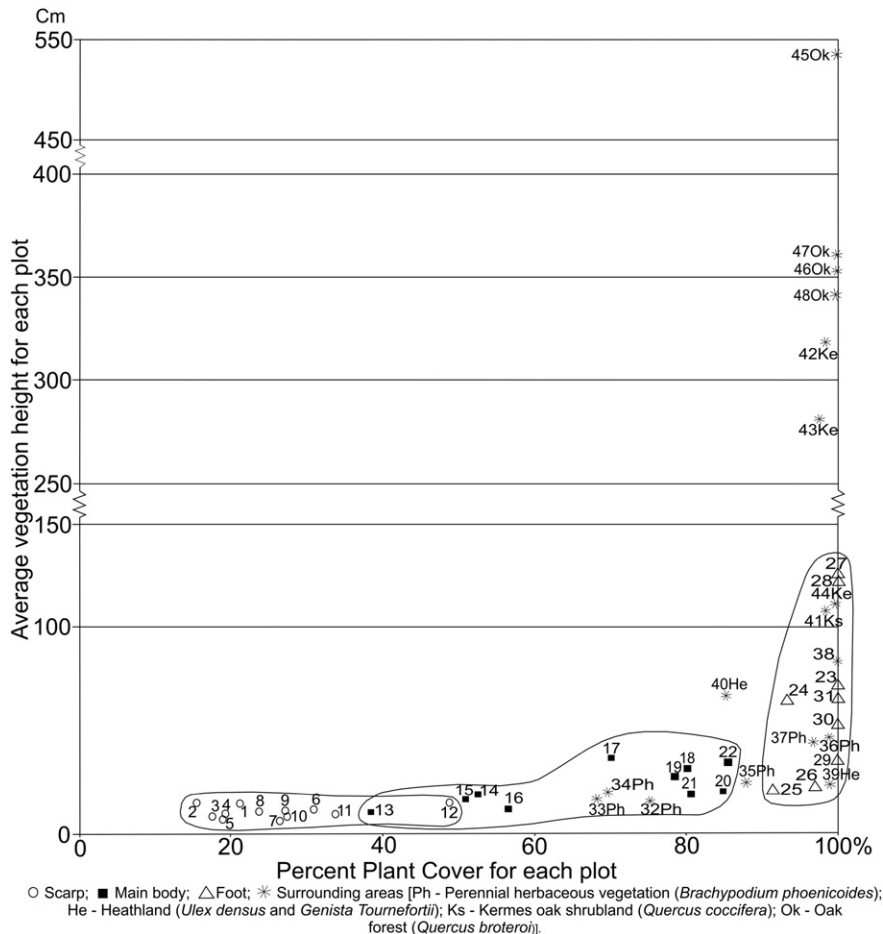


Fig. 3. Relationship between the average vegetation height and the coverage rate (percentage) for all plots.



bushes increases steadily from the landslide scarp to the landslide foot. Fig. 5B and Table 3 shows that the foot sector and the relevés from surrounding *Q. coccifera* maquis are close together and the taxa more linked to these two groups are medium to high scrubs and climbers (*Pistacia lentiscus* (Pi), *Quercus coccifera* (Qc), *Rubia peregrina* (Rp), *Lonicera hispanica* (Lh), *Arum italicum* (Ai). The relevés from Oak forest are positioned on the opposite side relatively to the scarp relevés in the axis 1 along which the communities are positioned from the basal communities in the scarp then the main body, the foot and finally the oak forest at the right end of the axis (Fig. 5A and B).

As the main regional indicator of strongly disturbed habitats, the *Ononis ramosissima* is common in the landslide main body and dominant in the landslide scarp. The Asteraceae, Poaceae and Fabaceae are the most represented families in the three landslide sectors. The Poaceae and Asteraceae (predominantly formed by heliophytic, thermophilic and oligotrophic species) show the highest percentage of coverage or dominance on the landslide scarp and declines dramatically towards the landslide main body and landslide foot where the increasing vegetation density and height does not allow for favorable light and temperature conditions. The Asteraceae plant family is one of the most common ones in landslides areas due to the great capacity for dispersal of most species (Dalling, 1994; Myster and Sarmiento, 1998; Shiels and Walker, 2003).

Concerning the Raunkiaer plant life-form (Fig. 6) we observe that: i) concerning therophytes (annual plants) and hemicryptophytes the relative dominance is maximal on the landslide scarp and decreases towards the landslide foot; ii) the relative dominance of chamaephytes is maximal on the landslide main body; iii) there is a high relative dominance of climbing phanerophytes on the foot and the nano, micro and mesophanerophytes are absent on the landslide scarp and have a high relative dominance on the landslide foot; iv) the mesophanerophytes appear only in the landslide foot with a low relative dominance and are dominant on the undisturbed areas adjacent to landslide due to the presence of Oak forests.

Finally, our work demonstrates the importance of the landslides as biodiversity reservoirs. Table 4 shows the presence of orchids in the studied landslides. However, the abundance of orchids is higher in the landslide main body, lower in the landslide scarp and absent in the landslide foot. Regarding the undisturbed area adjacent to landslide the orchids survive only in the perennial grasslands, but less abundantly than in the landslide areas.

## 5. Discussion

### 5.1. Flora, vegetation and seral stage differences between landslide sectors

Given that the studied landslides have similar ages and based on the above mentioned differentiation between different landslide sectors it can be stated that there is a clear gradient in the seral vegetation stage from the landslide scarp to the landslide foot.

The landslide scarp usually displays the C horizon (mineral horizon) at the surface and consequently has extreme conditions concerning nutrients, moisture and stability, which evolve very slowly allowing a sluggish development of the vegetation (Beguiría, 2006). That fact may explain in the case of the landslide scarp the lowest percentage of plant coverage or dominance, the lowest average height of the vegetation and a clear dominance of taxa characteristic of anthropic perturbed habitats (Table 3). The latter regionally occurs in habitats created by anthropogenic disturbances such as road embankments, clear cuts and construction zones that provides habitats similar to landslides (specially the scarp and main body) (Walker and Shiels, 2013). The occurrence of chamaephytic to nanophanerophytic scrubs in the landslide scarp (Fig. 5A and B), although rare, is possibly related to the permanence of parts of the radicular system of these plants on the C horizon which was cut during the mass movement. The recorded highest relative dominance of annual plants (therophytes) in the landslide scarp is possibly

due to extreme ecological conditions, mainly dryness and high temperatures during the dry season.

The landslide main body is the store area of the soil that moves downslope from the landslide scarp. In this case the amount of propagules (roots, rhizomes, bulbs) that are moved with the soil mass could be very significant which facilitates the rapid development of the small shrubs (chamaephytes) (Table 3). For relatively recent landslides of approximately the same age it is clear that the vegetation attains a later succession stage in the landslide main body than in the landslide scarp (in early succession stages). This difference may be explained by the presence of a large number of fissures (tension cracks) in the soil of the landslide main body zone as a consequence of differential deformation patterns associated to the main rotational soil rupture. These fissures facilitate the infiltration of air and water into the soil (Novák et al., 2000) and according to the work of Song et al. (2012) it accelerates vegetation recovery. This may explain the increasing dominance of plants of the Fabaceae family belonging to *Ulex* and *Genista* genus, from the landslide scarp to the landslide main body which increases again towards the landslide foot (*Ulex densus*, *Ulex latebracteatus* and *Genista tournefortii*) (Table A3). The Fabaceae family is known for their ability to fix atmospheric nitrogen through N-fixing nodules (Thomas and Spurway, 2001; Kraus et al., 2003; Gupta and Mukerji, 2006; Schatzl and Thompson, 2015). Nodulation was found to require well aerated media while poor aeration in the soil inhibited nodule formation (Thomas and Spurway, 2001). According to Walker and Shiels (2013) nodular nitrogen fixing symbionts colonize landslides frequently and they are less numerous on other types of primary succession (Walker, 1993).

The high dominance of grasses (mainly *B. phenicoides* and *D. hispanica*) on the landslide scarp (21.1%) and landslide main body (21.4%) of the studied landslides is in line with the values obtained by other authors (Walker and Boneta, 1995; Myster and Sarmiento, 1998; Restrepo and Vitousek, 2001; Velázquez and Gómez-Sal, 2009; Elias and Dias, 2009) and may be related with the ability of these plants to rapidly colonize disturbed habitats and dominate landslides for several years after landslide occurrence. Several studies show that when the disturbance exceeds the tolerance threshold of sprouters, seeders have an advantage because of their higher growth rates and their greater colonization capacity (Vesk and Westoby, 2004; Guerrero-Campo et al., 2006). Perennial grasses like *B. phenicoides* and *D. hispanica* have a fasciculate root system with a higher fine-root density that maximizes the capacity of water and nutrient uptake (Kummerow, 1981; Fitter, 1991; Caldwell and Richards, 1986). In Mediterranean climates this kind of root structure has a particular advantage (Canadell and Zedler, 1994) because of the irregularity of the precipitation and of the characteristics of the landslide scarp and main body which facilitates the drainage and promotes dryness. The fasciculate root system of the grasses also allows for greater stability of the plant, which is particularly important in the scarp, and further provides soil stabilization and decreases the risk of erosion (Velázquez and Gómez-Sal, 2009).

In regard to successional processes, the landslide foot clearly appears as the most evolved sector. The fact that it could receive a large amount of material slipped with propagules allows a rapid development of the aerial part of the shrubs that reach total coverage of the soil after 15 years. The occurrence of the water table near the surface is also important for the rapid development of shrubs due to the water that infiltrates in the soil fissures at the landslide main body, and also to weak slope that facilitates the water accumulation. This may explain the presence of mesophilic species like *Prunus insititoides* and especially the high dominance of hygrophilous such as *Rubus ulmifolius* (Fig. 6). The frequent occurrence of vines (0.89% on landslide scarp, 1.41% on the landslide main body and 6.31% on the landslide foot) indicates that we are on a pre-forest environment. On the other hand, the landslide foot is also characterized by the presence of middle-sized shrubs *Quercus coccifera*, *Daphne gnidium*, *Myrtus communis*, *Ulex latebracteatus* which become

**Table 3**  
Taxonomy, physiognomy, disturbance preferences, and % of coverage of each taxa within the landslide sectors and surrounding areas (The complete name of each taxon is provide in the supplemental dominance Table A2).

	Acronym of the species		Landslide (b)			Surrounding areas (b)				
			Scarp	Main body	Foot	Oak forest	Maquis Q. coccifera	Garrigue	Grasslands	
			(a)	% of total coverage			% of total coverage			
<i>Ononis ramosissima</i>	Or	Leguminosae	Sub	26.99	17.03	0.30	0.00	0.00	0.00	0.02
<i>Cistus salvifolius</i>	Cs	Cistaceae	Sh	12.57	5.39	1.28	0.00	1.23	0.00	0.00
<i>Dirtrichia viscosa</i>	Dv	Asteraceae	Sh	5.16	0.00	0.10	0.03	0.00	0.00	0.00
<i>Phagnalon saxatile</i>	Ps	Asteraceae	He	2.37	0.06	0.00	0.00	0.00	0.00	0.00
<i>Carex hallerana</i>	Cha	Cyperaceae	He	1.79	0.94	0.00	0.00	0.00	0.00	0.00
<i>Antirrhinum linkianum</i>	Al	Plantaginaceae	He	0.91	0.00	0.00	0.15	0.00	0.00	0.00
<i>Polygala monspeliaca</i>	Pm	Polygalaceae	He	0.68	0.00	0.00	0.00	0.00	0.00	0.05
<i>Reichardia picroides</i>	Rpi	Asteraceae	He	0.63	0.17	0.01	0.00	0.22	0.00	0.00
<i>Origanum virens</i>	Ov	Lamiaceae	He	0.63	0.42	0.01	0.00	0.00	0.21	0.11
<i>Trisetaria panicea</i>	Tp	Poaceae	He	0.24	0.00	0.00	0.00	0.00	0.09	0.01
<i>Salvia sclareoides</i>	Ss	Lamiaceae	Sh	0.22	0.18	0.00	0.00	0.19	0.00	0.00
<i>Eryngium dilatatum</i>	Ed	Apiaceae	He	0.13	0.00	0.00	0.00	0.00	0.00	0.00
<i>Klasea monardii</i>	Km	Asteraceae	He	0.02	0.00	0.01	0.00	0.00	0.02	0.00
<i>Centranthus calcitrapae</i>	Cc	Valerianaceae	He	0.02	0.00	0.00	0.00	0.00	0.00	0.00
<i>Pulicaria odora</i>	Po	Asteraceae	He	4.72	1.53	0.00	0.00	0.02	0.00	0.74
<i>Dactylis hispanica</i>	Dh	Poaceae	He	4.17	2.77	1.22	0.00	0.09	27.93	44.59
<i>Daucus carota</i>	Dc	Apiaceae	He	3.55	0.65	0.21	0.13	0.11	0.00	2.06
<i>Centaurium erythraea</i>	Ce	Gentianaceae	He	1.32	0.05	0.04	0.00	0.00	0.00	0.36
<i>Blackstonia perfoliata</i>	Bpe	Gentianaceae	He	1.04	0.18	0.00	0.00	0.00	0.00	0.19
<i>Bellis perennis</i>	Bp	Asteraceae	He	0.04	0.00	0.00	0.00	0.00	0.00	0.15
<i>Sanguisorba balearica</i>	Sb	Rosaceae	He	0.38	0.17	0.01	0.00	0.01	0.00	0.22
<i>Leontodon taraxacoides</i>	Lt	Asteraceae	He	0.12	0.05	0.00	0.00	0.01	0.00	0.04
<i>Achillea ageratium</i>	Aag	Asteraceae	He	0.10	0.00	0.00	0.00	0.00	0.00	0.14
<i>Anagallis monelli</i>	Amo	Primulaceae	He	0.72	0.58	0.03	0.00	0.00	0.01	0.38
<i>Carlina hispanica</i>	Ch	Asteraceae	He	0.10	0.01	0.01	0.00	0.01	0.00	0.01
<i>Brachypodium phoenicoides</i>	Bph	Poaceae	He	16.70	18.56	11.70	1.18	1.22	0.00	33.70
<i>Sideritis hirsuta</i>	Sh	Lamiaceae	Sub	5.34	10.67	0.15	0.00	0.01	0.00	1.20
<i>Asparagus aphyllus</i>	Aa	Asparagaceae	Sh	0.03	0.27	0.01	0.13	0.28	0.00	1.41
<i>Lathyrus angulatus</i>	La	Fabaceae	Sc	0.01	0.12	0.00	0.00	0.00	0.01	0.09
<i>Ophrys scolopax</i>	Os	Orchidaceae	He	0.05	0.10	0.00	0.00	0.00	0.00	0.12
<i>Aceras anthropophorum</i>	Aan	Orchidaceae	He	0.06	0.07	0.00	0.00	0.00	0.00	0.03
<i>Taraxacum obovatum</i>	To	Asteraceae	He	0.06	0.07	0.00	0.00	0.00	0.00	0.05
<i>Pallenis spinosa</i>	Psp	Asteraceae	He	0.00	0.02	0.00	0.00	0.00	0.00	0.01
<i>Genista tounefortii</i>	Gt	Fabaceae	Sh	2.32	20.88	13.05	0.22	2.61	47.82	0.00
<i>Trifolium campestre</i>	Tca	Fabaceae	He	0.16	1.44	0.00	0.00	0.00	0.00	0.24
<i>Linum strictum</i>	Ls	Linaceae	He	0.81	1.27	0.00	0.00	0.00	0.00	0.03
<i>Orchis italica</i>	Oi	Orchidaceae	He	0.05	0.74	0.00	0.00	0.00	0.00	0.04
<i>Anacamptis pyramidalis</i>	Ap	Orchidaceae	He	0.13	0.58	0.00	0.00	0.00	0.00	0.04
<i>Bupleurum paniculatum</i>	Bpa	Apiaceae	He	0.38	3.86	0.01	0.00	0.00	0.15	0.07
<i>Convolvulus althaeoides</i>	Ca	Convolvulaceae	He	0.60	0.61	0.00	0.02	0.08	0.08	0.00
<i>Pistacia lentiscus</i>	Pl	Anacardiaceae	Sh	0.00	0.28	0.00	3.51	3.49	9.03	4.74
<i>Avena barbata</i>	Aba	Poaceae	He	0.00	0.09	0.00	0.00	0.00	0.03	0.00
<i>Mantisalca salmantica</i>	Ms	Asteraceae	Sub	0.00	0.05	0.03	0.02	0.00	9.06	0.00
<i>Elaeoselinum foetidum</i>	Ef	Apiaceae	He	0.00	0.24	0.00	0.00	0.00	0.00	0.00
<i>Daucus muricatus</i>	Dm	Apiaceae	He	0.00	0.23	0.00	0.00	0.00	0.00	0.00
<i>Anthyllis maura</i>	Am	Fabaceae	He	0.26	0.38	0.00	0.00	0.00	0.00	0.00
<i>Carduus broteroi</i>	Cbr	Asteraceae	He	0.00	0.11	0.00	0.00	0.00	0.00	0.00
<i>Rosa sempervirens</i>	Rs	Rosaceae	Sc	0.00	0.08	0.00	0.00	0.00	0.00	0.00
<i>Centaurea pullata</i>	Cp	Asteraceae	He	0.06	0.08	0.00	0.00	0.00	0.00	0.00
<i>Thapsia villosa</i>	Tv	Apiaceae	He	0.05	0.07	0.00	0.00	0.05	0.00	0.00
<i>Hyacinthoides hispanica</i>	Hhi	Asparagaceae	He	0.00	0.07	0.00	0.37	0.09	0.00	0.14
<i>Bartsia trixago</i>	Bt	Orobanchaceae	He	0.00	0.06	0.00	0.00	0.00	0.00	0.00
<i>Ophrys bombyliflora</i>	Ob	Orchidaceae	He	0.00	0.06	0.00	0.00	0.00	0.00	0.00
<i>Stachys ocymastrum</i>	So	Lamiaceae	He	0.00	0.05	0.00	0.00	0.00	0.00	0.00

Table 3 (continued)

	Acronym of the species			Landslide (b)			Surrounding areas (b)			
				Scarp	Main body	Foot	Oak forest	Maquis Q. coccifera	Garrigue	Grasslands
				(a) % of total coverage			% of total coverage			
<i>Calamintha nepeta</i>	Cn	Lamiaceae	He	0.00	0.03	0.00	0.00	0.00	0.00	0.00
<i>Ophrys fusca</i>	Of	Orchidaceae	He	0.00	0.03	0.00	0.00	0.00	0.00	0.12
<i>Euphorbia exigua</i>	Ee	Euphorbiaceae	He	0.03	0.01	0.00	0.00	0.00	0.00	0.00
<i>Reichardia intermedia</i>	Ri	Asteraceae	He	0.00	0.01	0.01	0.00	0.00	0.00	0.00
<i>Cistus crispus</i>	Cc	Cistaceae	Sh	2.37	5.22	0.05	0.00	2.64	0.00	0.02
<i>Ulex densus</i>	Ud	Fabaceae	Sh	1.03	0.60	18.09	0.00	1.17	0.00	0.25
<i>Rubus ulmifolius</i>	Ru	Rosaceae	Sh	0.00	0.48	13.24	0.68	6.20	0.00	0.61
<i>Lonicera hispanica</i>	Lh	Caprifoliaceae	Sc	0.00	0.33	4.84	1.04	2.18	0.00	0.09
<i>Euphorbia characias</i>	Ec	Euphorbiaceae	Sh	0.00	0.00	2.91	0.00	0.37	0.00	0.00
<i>Quercus coccifera</i>	Qc	Fabaceae	Sh	0.00	0.00	2.39	5.99	63.82	4.48	0.01
<i>Rubia peregrina</i>	Rp	Rubiaceae	Sc	0.10	0.87	0.92	0.47	2.04	0.00	0.01
<i>Galactites tomentosus</i>	Gto	Asteraceae	Sub	0.05	0.00	0.06	0.00	0.17	0.00	0.00
<i>Conyza bonariensis</i>	Cb	Asteraceae	He	0.00	0.00	0.02	0.00	0.01	0.00	0.00
<i>Ulex latebracteatus</i>	Ul	Fabaceae	Sh	0.00	1.18	13.73	0.00	0.00	0.00	0.00
<i>Daphne gnidium</i>	Dg	Thymelaeaceae	Sh	0.00	0.05	1.87	0.62	0.56	1.08	0.19
<i>Gladiolus illyricus</i>	Gi	Iridaceae	He	0.00	0.00	0.70	0.03	0.00	0.00	0.00
<i>Arrhenatherum baeticum</i>	Ab	Asteraceae	He	0.00	0.00	0.03	0.00	0.00	0.00	0.00
<i>Lagurus ovatus</i>	Lo	Asteraceae	He	0.00	0.00	0.01	0.00	0.00	0.00	0.00
<i>Prunus insititioides</i>	Pi	Rosaceae	Sh	0.00	0.00	0.27	0.00	0.00	0.00	0.00
<i>Galium verrucosum</i>	Gv	Rubiaceae	He	0.00	0.00	0.01	0.00	0.00	0.00	0.00
<i>Gaudinia fragilis</i>	Gf	Asteraceae	He	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Lapsana communis</i>	Ic	Asteraceae	He	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Coronilla glauca</i>	Cg	Fabaceae	Sh	0.00	0.00	7.87	1.10	0.00	0.00	0.00
<i>Quercus broteroi</i>	Qb	Fabaceae	Tr	0.21 (*)	0.00	0.68	34.59	2.27 (**)	0.00	5.37 (*)
<i>Smilax aspera</i>	Sa	Smilacaceae	Sc	0.77	0.00	0.54	20.18	6.09	0.00	2.22
<i>Myrtus communis</i>	Mc	Myrtaceae	Sh	0.00	0.00	3.61	4.25	0.00	0.00	0.00
<i>Geranium purpureum</i>	Gp	Geraniaceae	He	0.00	0.00	0.01	0.22	0.00	0.00	0.00
<i>Rhamnus alaternus</i>	Ra	Rhamnaceae	Sh	0.00	0.00	0.00	0.55	0.42	0.00	0.02
<i>Quercus gadihana</i>	Qg	Fabaceae	Tr	0.00	0.00	0.00	0.45	0.00	0.00	0.00
<i>Osyris alba</i>	Oa	Santalaceae	Sh	0.00	0.00	0.00	13.04	0.50	0.00	0.00
<i>Arisarum simorrhinum</i>	As	Araceae	He	0.00	0.00	0.00	0.45	0.18	0.00	0.00
<i>Tamus communis</i>	Tc	Dioscoreaceae	Sc	0.00	0.00	0.00	0.16	0.00	0.00	0.00
<i>Olea sylvestris</i>	Os	Oleaceae	Tr	0.00	0.00	0.00	3.67	1.30	0.00	0.00
<i>Hedera hibernica</i>	Hh	Araliaceae	Sc	0.00	0.00	0.00	3.43	0.00	0.00	0.00
<i>Phillyrea latifolia</i>	Pla	Oleaceae	Tr	0.00	0.00	0.00	1.08	0.00	0.00	0.00
<i>Ruscus aculeatus</i>	Rac	Asparagaceae	Sh	0.00	0.00	0.00	0.90	0.00	0.00	0.00
<i>Erophaca baetica</i>	Eb	Fabaceae	Sh	0.00	0.00	0.00	0.63	0.00	0.00	0.00
<i>Osyris lanceolata</i>	Ola	Santalaceae	Sh	0.00	0.00	0.00	0.33	0.00	0.00	0.00
<i>Crataegus monogyna</i>	Cm	Rosaceae	Sh	0.00	0.00	0.00	0.18	0.00	0.00	0.00
<i>Vicia sativa</i>	Vs	Fabaceae	Sc	0.00	0.00	0.00	0.10	0.00	0.00	0.00
<i>Arum italicum</i>	Ai	Araceae	He	0.00	0.00	0.00	0.00	0.23	0.00	0.00
<i>Margotia gummifera</i>	Mg	Apiaceae	He	0.00	0.00	0.00	0.00	0.15	0.00	0.00
Total of taxa adapted to perturbed areas (%)				91.22	72.95	15.27	2.21	6.32	37.38	84.18
Herbaceous				43.29	36.68	14.04	2.56	2.66	28.52	83.77
Subshrub				32.38	27.74	0.53	0.02	0.18	9.06	1.22
Shrub				23.48	34.35	78.47	32.19	83.30	62.41	7.26
Scandent				0.89	1.41	6.31	25.38	10.31	0.01	2.41
Tree				0.00	0.00	0.00	39.34	3.57	0.00	0.00

Sh - shrub; Sub - subshrub; Sc - scandent; He - herbaceous; Tr - Tree. (a) - squares in dark gray correspond to taxa adapted to perturbed areas (ruderal species - species characteristics of roadsides, of abandoned agricultural land, of embankments) according to Franco (1984, 1981) and Franco and Afonso (1994, 1998 and 2003) and flora-on. (\*) seedling; (\*\*) shrub. (b) squares in light gray correspond to highest values of relative dominance of each sector.

dominant and higher in the adjacent maquis (Table A3). The mesophanerophytes do not occur in the studied landslides because a maximum of 20 years has elapsed since the occurrence of the landslides which is not long enough for the development of forests.

5.2. The floristic and physiognomic differences between landslide sectors

The floristic and physiognomic-structural differences between the vegetation in the three landslide sectors, evidenced by this work, and

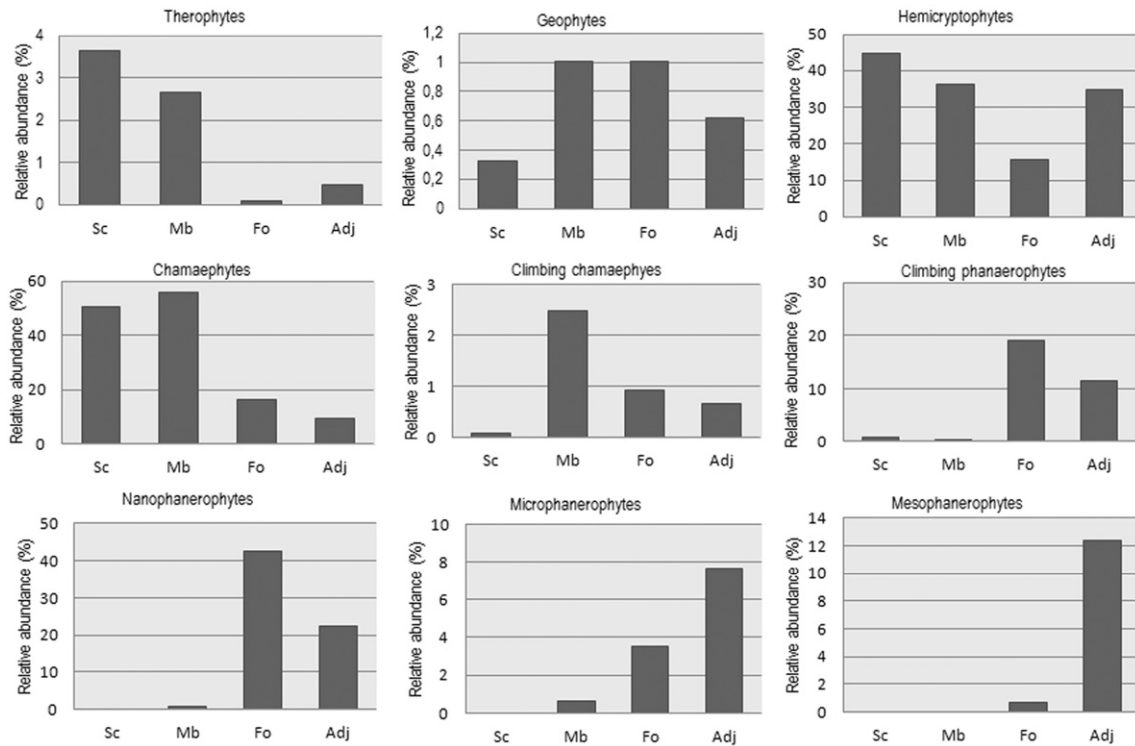


Fig. 6. Raunkiaer plant life-forms (sc - Scarp; Mb - Main body; Fo - Foot; Adj - Landslide surrounding areas).

between these and the undisturbed areas adjacent to the landslide justify the excellent separation between groups shown by the NMDS (Fig. 5A and B). The analysis of Fig. 4 show a spatial organization of the plots following a gradient of perturbation intensity which is subject to the differences found in structure and chemical composition of the soil by Guariguata (1990) and Wilcke et al. (2003) among others authors (Lundgren, 1978; Adams and Sidle, 1987; Reddy and Singh, 1993; Zarin and Johnson, 1995a, 1995b; Fetcher et al., 1996; Claessens et al., 2006; Shiels et al., 2008; Shiels and Walker, 2013), according to which the lower zone of the landslide (the foot) had higher concentrations of carbon, total organic nitrogen and exchangeable cations than the upper zone.

Based on floristic composition the NMDS shows a clear difference between landslide plots and surrounding areas. Plots in the landslide scarp are separated based on the dominance of species that are characteristic of ruderal and perturbed habitats (Fig. 5B and Table A3). The

dominant species in this group is *Ononis ramosissima* (species with wide distribution in Iberia and in parts of the Mediterranean ruderal areas, strongly disturbed habitats or even nitrophilous) and the second dominant species is *Brachypodium phoenicoides*. Due to its ability to colonize extreme environments (in relation to disturbance and nutrients) *Ononis ramosissima* is usually the dominant species on cut/fill slopes and is a major bioindicator of landslides due to its high dominance on the scarp and main body of the landslides (Table 3, A2 and A3). However, there are no landslides “specialists” in the sense of species exclusive to landslides (Walker and Shiels, 2013).

In the landslide main body the dominant species is *Genista tounefortii* and the second dominant is *Brachypodium phoenicoides*. The coverage of *Brachypodium phoenicoides* is greater in the landslide main body; however, the complex of microhabitats that characterized the landslide main body allows an abundance of medium-sized shrubs in contrast to the undisturbed area adjacent to landslide where we

Table 4  
Presence and Abundance of *Orchidaceae* in all plots.

	Landslide						Surrounding areas						
	Scarp			Main body			Foot	Perennial grassland			Heathland	Kerme oak	Oak forest
	Presence (*)	Presence %	Abundance	Presence (*)	Presence %	Abundance		Presence(*)	Presence %	Abundance			
<i>Orchis italica</i>	2	16.67	0.01	5	50	0.52	0	2	28.57	0.06	0	0	0
<i>Anacamptis pyramidalis</i>	1	8.33	0.03	5	50	0.41	0	3	42.86	0.06	0	0	0
<i>Ophrys scolopax</i>	2	16.67	0.01	5	50	0.07	0	4	57.14	0.16	0	0	0
<i>Ophrys lutea</i>	0	0.00	0.00	4	40	0.04	0	4	57.14	0.15	0	0	0
<i>Ophrys fusca</i>	0	0.00	0.00	2	20	0.02	0	2	28.57	0.16	0	0	0
<i>Ophrys bombyliflora</i>	0	0.00	0.00	3	30	0.04	0	4	57.14	0.00	0	0	0
<i>Aceras anthropophorum</i>	1	8.33	0.02	4	40	0.05	0	1	14.29	0.05	0	0	0

(\*) Number of times that the taxon occurs in all relevés.

can see a clearly spatial segregation between the heathlands (*Ulex* sp. and *Genista* sp.) and the grasslands (*Brachypodium*) that correspond to different successional stages. In the landslide main body heathlands and grasslands do not have a distinct spatial separation and occur together.

Finally, plots from the landslide foot are colonized by *Ulex densus* and *Ulex latebracteatus* as the first and second dominant species respectively and also a high dominance of vines and shrubs characteristic of the surroundings maquis. Fig. 5A shows that (out of all the landslide sectors) the records pertaining to the landslide foot are the ones closest to the corresponding groups in undisturbed area adjacent to landslides.

Despite the discussion about the relationship between disturbance regimes and species diversity and some criticism about Intermediate Disturbance Hypothesis (IDH) (Mackey and Currie, 2001; Hall et al., 2012; Fox, 2013) our work shows a tendency for peaked, unimodal diversity–disturbance relationships (DDRs) (Fig. 4) according to the model originally described by Connell (1978). Despite the meta-analysis of empirical disturbance studies conducted by Mackey and Currie (2001) according to which many different patterns of variation in community diversity across disturbance gradients can be observed in nature, (increasing, decreasing, and U-shaped DDRs (Mackey and Currie, 2001), Fig. 4 shows clearly that floristic richness rises from the landslide scarp to the landslide main body and falls to the landslide foot. It is true that the three landslide sectors were subject to a disturbance process; however, the intensity (from the vegetation point of view) is maximal on the landslide scarp and decreases to the base of the landslide. So the floristic diversity is minimal on the landslide scarp where the extreme conditions limit the competition. In the landslide foot a dense and high shrub community totally covers this sector and the floristic richness is low. In the landslide main body, the intermediate levels of disturbance (within the landslide) diversity is thus maximized because species that thrive at both early and late successional stages can coexist (Wilkinson, 1999; Kricher, 2011; Catford et al., 2012).

It is interesting to note that there is a significant difference in the variance values (obtained in the ANOVA analysis) between the three sectors of the landslides: i) scarp 23.8409; ii) main body 10.6222; iii) foot 4.1111. The plots in the landslide foot have similar floristic richness (all the values are low) while the landslide scarp has a high variance consistent with the diversity of situations found between the scarps. Depending on the magnitude of the landslide, among other factors, the landslide scarp may exhibit, or not, the mineral horizon on the surface and there is a set of situations between these two extremes.

### 5.3. The importance of landslides as biodiversity reservoirs

Orchids are documented as colonists of tropical landslides (Dalling, 1994; Myster and Sarmiento, 1998; Shiels et al., 2008; Walker et al., 2010). In the Mediterranean region and in calcicolous soils (neutrophilous to basophilous) within perturbed areas mostly due to abandoned cereals crops, orchids are abundant, justifying the high value for protection and conservation of these dry grasslands (Festuco-Brometalia). In some way the scarp and main body of landslides in calcicolous areas occupied by perennial grasslands are favorable to the successful establishment of orchids that subsist here in higher numbers than in adjacent perennial grasslands. The perennial grassland dominated by *Brachypodium phoenicoides* is a habitat of Natura 2000 Network (6210 Semi-natural dry grasslands and scrubland facies on calcareous substrates (Festuco-Brometalia) (\*important orchid sites) (EC, 2007; JNCC et al., 2007). The habitat is considered a priority type (6210\*), only if it is an important orchid site (EC, 2007) (Calaciura and Spinelli, 2008; Cruz and Espirito-Santo, 1999). In the case of the studied areas, the first condition to consider the orchids as typical of 6210\* is achieved as the test sites host a rich suite of orchid species (Table 4, EC, 2007). Therefore, we can state that the main body of the studied landslides (Mediterranean climate with soils derived

from limestones) colonized by perennial grasslands are included in the habitat 6210, priority protection subtype 6210\* due to the high richness in orchids. The perennial grasslands in surrounding areas (dominated by *Brachypodium phoenicoides*) belong to the same subtype (6210\*) although the orchid richness is higher in the landslide main body than in the perennial grassland of the undisturbed area adjacent to landslide. It should also be noted that due to the cyclic reactivation of some landslides north of Lisbon (Zêzere et al., 2015; Oliveira et al., 2015) the constant mobilization of the soil mass fosters the existence of a dynamic equilibrium between the landslide main body vegetation and the disturbance frequency, and consequently promotes the maintenance of the habitat conditions favorable to orchid colonization. On the contrary, in the undisturbed area adjacent to the landslide the *Brachypodium* grassland that are favorable to orchid colonization result from agricultural abandonment and undergo a successional process with the development of a low scrub stage followed by a high shrubby step and the orchids are not able to establish. The orchid species are supplanted by more vigorous plants at locations with plenty of water and nutrients (LIFE2002/NAT/D/8461). The abandonment of traditional agriculture and grazing in the Mediterranean region is creating unfavorable conditions for *Orchidaceae* (Crofts and Jefferson, 1999). This situation is forcing the authorities to draw up management plans to create habitats favorable to orchids in order to offset observed declines. A critical factor in the long-term maintenance of an orchid population is the maintenance of conditions conducive to germination and establishment (CFA, 2007; Pihl et al., 2001).

## 6. Conclusions

Our work demonstrates that there is a clear distinction between the landslide scarp, main body and foot concerning floristic composition, vegetation structure, floristic richness, functional types and seral stage in succession process. Despite the inexistence of a flora exclusive of landslides we demonstrated that there is a package of species that are characteristic of each landslide sector. Concerning the florist composition, we can conclude that for the same seral stage (in terms of structural and physiognomic characteristics) the floristic composition of the landslide plots is not the same as in the surrounding areas. This conclusion is especially valid for the landslide scarp and landslide main body and is due to the fact that the mass movement promotes significant modifications in soil structure (lasting for several decades) that does not occur in the surrounding areas. The successional process in the surrounding areas depends on the agricultural and grazing activities as well as on the frequency of wildland fires. We demonstrated that landslides in limestone's areas with a Mediterranean climate are an important reservoir of biodiversity mainly for *Orchidaceae* (priority habitat of Natura 2000 Network) and should be considered as protected areas. Simultaneously with management programs to create favorable habitats to the Mediterranean orchids, the protection of some landslides in limestone areas is a good and inexpensive alternative to the maintenance of these populations.

Supplementary data related to the communities of Portuguese oak forest series (*Arisaro clusi-Querceto broteroi sigmetum*) and related bioindicators that make up the regional natural vegetation of the studied territory is included in Table A1. The dominance or basal area of the taxa in the study area organized into the different landslides strata according to the selected sampling design can be found in Table A2. The indicator value (IndVal) analysis of the taxa present in the studied areas based on Table A1 is included in Table A3. Supplementary data associated with this article can be found in the online version, at <http://dx.doi.org/10.1016/j.scitotenv.2016.09.119>.

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