# Hydro-geomorphological consequences of the abandonment of agricultural terraces in the Mediterranean region: key controlling factors and landscape stability patterns

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**Abstract.** Traditional cultivation terraces are one of the most ancient and conspicuous agricultural landscapes in mountain and hilly regions of the Mediterranean basin. Spreading out from Asia, the first terraces in the Mediterranean region date from the Bronze Age and the classical Hellenic and Roman periods, reaching their greatest spatial extent during the eighteenth and nineteenth centuries. Under optimum management, these systems contribute to the conservation of soil and water resources by increasing infiltration and decreasing sediment yield. However, traditional management and cultivation ceased on many terraced landscapes of the northern-shore Mediterranean countries during the twentieth century, with variable results. An extensive bibliographic review and meta-analysis was carried out to explore the main effects of land abandonment of Mediterranean agricultural terraces on local hydrological and geomorphological processes. Our results point to the development of vegetation cover and degradation of terraced structures (e.g., walls, terrace risers, channels) as the main critical factors controlling the hydrological behaviour (i.e., runoff production and hydrological connectivity) of abandoned terrace systems. Severe geomorphological problems, in the form of intense surface erosion, aggressive piping and gullying, occurred under special climatic (semi-arid climate), lithologic (dispersive marls) and structural (high vertical hydraulic gradient) conditions. Dense colonization by vegetation proved to be of major importance for controlling surface erosion. Vegetation, however, showed a limited capacity to control the activity of mass movements in most cases. Mass movements in the form of small soil slips primarily affected long-abandoned terraces in hillslope concavities and valley bottom positions that concentrate (surface and subsurface) water fluxes and show recurrent soil saturation. In humid terraced landscapes characterized by high hillslope gradients and terrace risers, the most devastating effects of mass movements took place in the form of debris slips and terrace cascading landslides triggered by extreme rainfall. A variety of management options (non-intervention, stewardship of natural rewilding processes and active rehabilitation) can be applied, depending on vegetation development potential, site hydro-geomorphic vulnerability and local socio-economic interests. Effective conservation approaches will be required to preserve the environmental, socio-cultural and historical values of these ancient anthropogenic landscapes.

Keywords: Abandonment, Cultivation terraces, Erosion, Hydrological connectivity, Landscape stability, Mass movements, Mediterranean basin, Mitigation, Piping, Runoff.

## 1. Introduction

The interactions between a long history of land use, seasonally contrasted climate, rugged topography and variable lithology strongly condition landform structure and hydro-geomorphological processes throughout the Mediterranean basin. Agricultural areas in this region broadly display the effects of land management and the impact of human actions on physical settings, and provide environmental information on historical landscape transformations in response to demographic, cultural and socio-economic variations (Martínez-Casasnovas and Sánchez-Boch, 2000; Cots-Folch et al., 2006 García-Ruiz and Lana-Renault, 2011; Lasanta et al., 2017a). A paradigmatic example is provided by terraced agricultural landscapes, which induce deep hydrological and geomorphological alterations in the landscapes and are highly dependent on socio-economic processes such as agricultural transformation and land abandonment (Grove and Rackham, 2003; Tarolli et al., 2014; Arnáez et al., 2015).

Terracing is one of the most ancient agricultural practices in mountain landscapes, providing flat areas for cultivation in rugged terrain. For centuries, traditional cultivation terraces have been the most conspicuous features of agricultural landscapes in the mountain and hilly regions of the Mediterranean basin (Grove and Rackham, 2003). These systems are directly dug into the hillside and typically consist of a nearly flat platform (or terrace bed), which is cultivated, and an almost vertical riser protected by either a dry-stone wall or vegetation. The height of the riser usually varies between 1 and 2 m (reaching occasionally 4-6 m), depending mainly on general hillslope gradient and the size of the cultivation platforms (Jiménez-Olivencia, 1990; García-Ruiz and Lana-Renault, 2011; Arnáez et al., 2017). Traditional agricultural terraces in the Mediterranean region can take on several forms, depending on their distribution along contour lines and the valley axis: step terraces, which are parallel to the terrain contours; braided terraces, which zigzag up the hillslope; pocket terraces, which are crescent-shaped structures for individual trees; terraced fields, quadratic platforms surrounded by risers from adjacent fields; and check-dam terraces, usually built perpendicular to the thalweg of the valley axis (Grove and Rackham, 2003; Koulouri and Giourga, 2007; Bellin et al., 2009; Calsamiglia et al., 2018).

Spreading out from Asia, the first agricultural terraces in the eastern countries of the Mediterranean region (i.e., Israel, Jordan, Syria and Lebanon) date from the Bronze Age (Zurayk; 1994; Newson et al., 2007; Ore and Bruins, 2012; Gadot, 2015). In the Aegean Islands, the first cultivation terraces were probably built during the Hellenic period (*c*. 300 BC), whereas this mountain agricultural practice probably spread to the western regions of the Mediterranean basin during the Roman period (Bevan et al., 2003; Morel, 2006; Inbar and Zgaier, 2016). In the Middle Ages, traditional cultivation terraces started covering large parts of mountain regions in Greece, Italy, France and Spain, and also reached significant areas on the southern shores of the Mediterranean basin (Grove and Rackham, 2003; Petit et al., 2012). Traditional terrace construction reached its greatest expansion in the northern-shore countries of the Mediterranean basin during the eighteenth and nineteenth centuries, motivated by the growth of rural population and increased pressure on limited agricultural resources (Arnáez et al., 2011; Bevan and Conolly, 2011; Tarolli et al., 2014).

Terrace cultivation and maintenance, however, have ceased in many mountain landscapes of the Mediterranean region. Initially affecting areas of France in the nineteenth century, terrace abandonment progressed rapidly in marginal mountain areas of Greece, Italy, Portugal and Spain during the twentieth century (Debussche et al., 1999; Lasanta et al., 2001; Petanidou et al., 2008; Kizos and Koulouri, 2006; Agnoletti, 2011; Lourenço et al., 2014). Land abandonment in these countries is linked to a variety of socio-economic, technological and political changes encompassing, among others, the migration of rural populations to industrialized cities, the loss of the economic value of labour-intensive subsistence agriculture in marginal areas, difficulties in the use of heavy machinery in rugged terrain, fragmentation of land property, concentration of crop production in intensely cultivated lowland fields, the relegation of the primary sector in national economies and, more recently, the application of European Union (EU) set-aside policies to control agricultural production (Ramos and Martínez-Casasnovas, 2007; Cyffka and Bock, 2008; García-Ruiz and Lana-Renault, 2011; Stanchi et al., 2012; Lasanta et al., 2017b; Modica et al., 2017). At present, cultivation of traditional terrace systems in the northern-shore Mediterranean countries is sustained only in limited examples where highly profitable crops (e.g., protected denomination-of-origin vineyards and olive/citrus orchards; Fig. 1a) or subsidized farming can justify major manpower investments for terrace maintenance (García-Ruiz and Lana-Renault, 2011; Tarolli et al., 2014). However, traditional farming terraces are still widely cultivated in mountain and hilly areas of southern-shore Mediterranean countries (e.g., Morocco, Tunisia and Algeria), where the persistence of subsistence agriculture systems

(Fig. 1b) and the implementation of DRS (*Défense et Restauration des Sols*) campaigns for soil conservation since 1950 have contributed to the preservation of these traditional structures (Heusch, 1986; Barow and Hicham, 2000; Montanari, 2013).

Traditional agricultural terraces have important effects on the hydrology and geomorphology of Mediterranean landscapes, as they alter the distributions of soil depth and both slope gradient and length (Gallart et al., 2002; García-Ruiz and Lana-Renault, 2011; Tarolli et al., 2014) and frequently include artificial drainage channels and irrigation ditches that modify surface flow patterns (Gallart et al., 1994; Cammeraat, 2004; Latron and Gallart, 2008; Nunes et al., 2016). Under optimum management, these human-made systems promote the regulation of the water cycle and the conservation of soil resources, with positive results on crop production. For example, terracing increases water infiltration and soil-water storage capacity by reducing the general slope, which also contributes to reduced runoff velocity and soil erosion (Sandor, 1998; Nasri et al., 2004; Hammad et al., 2006; Stanchi et al., 2012; Perlotto and D'Agostino, 2016). However, terrace abandonment in Mediterranean landscapes can lead to a variety of results in terms of hydro-geomorphological behaviour and stability (Fig. 2). Abandoned terraces may remain relatively stable where dense vegetation (herbaceous, shrub or tree) has colonized these structures (Figs. 2a and b) after the cessation of terrace cultivation and maintenance (Llorens et al., 1992, 1997a; Ruecker et al., 1998; Pardini and Gispert, 2012). Arnáez et al. (2015), in a recent worldwide review of runoff and soil erosion studies of terraced landscapes, indicated that abandoned traditional terraces under these fairly stable conditions experience markedly low erosion rates, typically less than 3 t $ha^{-1}$ $yr^{-1}$. In other cases, the collapse of terrace walls and surface draining channels, sometimes accompanied by the development of mass movements, aggressive piping and/or gullying phenomena, can induce sharp hydro-geomorphic responses to terrace abandonment (Figs. 2c and d) that encourage the re-establishment of natural drainage pathways in the landscape (Leeschen et al., 2008; Meerkerk et al., 2009; Arnáez et al., 2017) or the formation of highly erosive landforms (Calvo-Cases et al., 2011; Romero-Diaz et al., 2011; Moreno-de-las-Heras and Gallart, 2018).

A wide variety of factors and local conditions (e.g., climate, land cover, soil and terrace characteristics) can play an active role in determining the way traditional terrace cultivation landscapes change after their abandonment (Lesschen et al., 2007; García-Ruiz and Lana-Renault, 2011; Romero-Diaz et al., 2017). However, the wide diversity of age, type and preservation status that characterizes traditional Mediterranean terraces, and the large variability of hydrological and geomorphological processes that dominate these abandoned agricultural landscapes, complicate the understanding of the effects of land abandonment in these human-made settings (Grove and Rackham, 2003; García-Ruiz and Lana-Renault, 2011; Tarolli et al., 2014; Arnáez et al., 2015). In addition, the inherent complexity of the Mediterranean climate (that alternates arid and more humid conditions at both the seasonal and inter-annual time scales, and rapidly transitions towards oceanic, continental and sub-desert influence along different areas of the Mediterranean basin) compromises considerably the depiction of the climatic imprint of the mechanisms that control soil erosion and landscape evolution in the region (Tricart and Cailleux, 1965; Thornes and Wainwright, 2003; García-Ruiz et al., 2013).

This study aims to explore the hydro-geomorphological consequences of the abandonment of traditional agricultural terraces in the Mediterranean region. Our analysis is based on a systematic review and meta-analysis of observational, experimental and modelling studies published over the last four decades, containing hydrological and erosional information of landscapes affected by the abandonment of traditional cultivation terraces throughout the Mediterranean basin. First, we identified key controlling factors that affect the hydrological response and erosional behaviour of abandoned terraces. Second, we studied the influence of relevant local conditions (i.e., climate, extent of vegetation development, lithology and hillslope characteristics) on the emergence of environmental patterns of terrace stability after land abandonment. Feasible management measures to mitigate the negative consequences of terrace abandonment are also discussed.

## 2. Review data search criteria and meta-analysis methods

A dataset of abandoned terraced sites in the Mediterranean basin was collected from scientific studies published during the last four decades. We applied two widely used bibliographic data-search engines (Scopus and Google Scholar) to identify relevant articles, conference papers and book chapters. A broad combination of keywords was applied in the data search, including: *abandoned* (OR *abandonment*) AND *Mediterranean* AND *terrace* (OR *terracing*) AND *erosion* (OR *collapse* OR *connectivity* OR *failure* OR *gully* OR *gullying* OR *hydrology* OR *infiltration* OR *landslide* OR *mass movements* OR *piping* OR *runoff* OR *vegetation*). All the data-search entries and their corresponding internal references were explored to identify observational, experimental and modelling studies directly or indirectly dealing with the analysis of the hydrological and geomorphological behaviour of Mediterranean sites affected by the abandonment of traditional cultivation terraces.

The name/location (region, country, coordinates and elevation) of the study sites described in the scientific literature was recorded and used to organize a dataset. We gathered from the reviewed studies the following general information for each abandoned terrace site (if available): (i) climate data comprising mean annual precipitation (MAP, mm), potential evapotranspiration (PET, mm) and climate type (following the UNEP aridity classification; UNEP, 1992); (ii) landscape and terrace structural characteristics, including hillslope gradient (%), local lithology as well as the presence of dry-stone walls; (iii) terrace status, encompassing time since abandonment (years), vegetation development (% cover), soil erosion rate (t ha$^{-1}$ yr$^{-1}$) and the incidence of active gullying, piping/tunnelling and mass movements (i.e., wall failures, small soil slips and larger landslides); and finally (iv) study approach (field surveying, experimental observations, GIS and imagery, and modelling) and scale of analysis (plot, catchment or regional scales). For those sites lacking complete climate information, MAP, PET and climate type values were obtained from the Global Aridity dataset developed by the CGIAR Consortium for Spatial Information (Trabucco and Zomer, 2009).

We explored in detail the identified literature to reveal the main key factors (i.e., field attributes and processes) controlling the hydro-geomorphological consequences of terrace abandonment. For each individual site in the data base, we identified the field attributes and processes that were specified in the literature as showing a significant role in determining the landscape's hydrological and/or geomorphological behaviour. All identified key controlling factors were arranged according to a series of relevant hydrological (runoff/infiltration and hydrological connectivity) and geomorphological (surface wash erosion, gullying, piping/tunnelling and mass movements) research topics. Then, for each key factor and research topic, we calculated the relative frequency of citation (i.e., % of sites indicating in their corresponding studies a particular key controlling factor as a determining feature for a specific hydrological or geomorphological research topic). We applied the relative frequencies of citation obtained as a general overview marker for evaluating the importance of the key factors. For analysis, the key factors were grouped into positive and negative influencing attributes/processes according to their impact on the hydrological and geomorphological behaviour of the sites. Regarding hydrological behaviour, a positive (or negative) influence was assigned to those key factors contributing to the reduction (or increase) of local runoff production and/or landscape hydrological connectivity (i.e., the spatial connection of runoff fluxes at the broad landscape/catchment scales). For the geomorphological behaviour of the explored terraced landscapes, positive (or negative) influences were ascribed to those key factors contributing to the control (or increase) of the activity of surface and/or subsurface erosion processes, and the incidence of mass movement phenomena.

We used the reviewed hydro-geomorphological information (e.g., erosion rates, occurrence of rilling, gullying, piping/tunnelling and mass movements) to evaluate the erosional behaviour of all the individual sites recorded in our data base. Those sites showing limited surface erosion (e.g., no signs of intense surface wash or rill incision) and no general terrace collapses caused by mass movements and/or piping phenomena were flagged as stable (non-erosive) landscapes. On the contrary, recorded sites affected by aggressive piping, generalized mass movements and/or intense surface wash erosion phenomena were classified as behaving as unstable (erosive) landscapes. An additional landscape behaviour category, ‘inconclusive’, was used for those sites lacking definitive information in the bibliography. The obtained site evaluation of terrace behaviour (i.e., classified as stable, unstable or inconclusive behaviour) was further used to assess the influence of local conditions (i.e., climate type, vegetation cover, local lithology and general hillslope gradient) on the emergence of environmental patterns of terrace stability after land abandonment. Local condition variables were categorized for analysis and the relative frequency (%) of sites showing stable, unstable and inconclusive behaviour was calculated for each categorized level. We applied three categorical levels of increased aridity for climate type (arid and semi-arid, dry-subhumid, and subhumid and humid climate); three levels of increased plant development for vegetation cover (under 33%, 33%-66% and over 66% cover); three different levels for lithology (fine-grained sedimentary materials, massive limestone and sandstone formations, and igneous and metamorphic materials); and finally, four increasing slope gradient levels for hillslope topography (<15%, 15%-25%, 25%-35% and >35% slope gradient). Further analysis was applied to reveal the environmental conditions that predispose abandoned terrace landscapes to the strong destructive potential of piping/tunnelling and mass movements. The absolute frequencies (number of sites) of landscapes affected by aggressive piping phenomena and terrace sliding failures were assessed individually against the local condition variables (i.e., climate type, vegetation cover, lithology type and hillslope gradient).

## 3. Terrace systems explored: site distribution and characteristics

We identified a total of 90 studies containing hydrological and geomorphological information about 59 sites affected by the abandonment of traditional cultivation terraces in the Mediterranean region (Fig. 3a; a complete list of sites, reviewed studies and specific research topics can be found in Supplementary Appendix A). About two-thirds of the sites (40 abandoned terrace landscapes) were located in Spain; 12 study sites (about 20% of the total) were in Italy and Greece; and the remaining 7 (~12%) were in other Mediterranean countries (Portugal, France, Malta, Israel and Jordan).

All the study sites were located in mountain and hilly regions at elevations ranging from near sea level to 1600 masl (Supplementary Appendix A). Nearly 45% of the sites were in arid and semi-arid areas (MAP to PET ratio <0.50), with a large number in the southeastern regions of the Iberian Peninsula (Fig. 3a). Terraced landscapes under dry-subhumid climate conditions (0.50-0.65 MAP to PET ratio) accounted for 21% of the study sites, while 34% of the sites were located in subhumid and humid (MAP to PET ratio >0.65) mountain environments, particularly in the Pyrenees and in the coastal and inland mountain regions of Italy (e.g., Liguria, Toscana, Calabria).

Time since abandonment varied from one to over 100 yr (Supplementary Appendix A). About one-third of the study sites showed extensive development of vegetation (>66% cover; Fig. 3b), frequently in the form of Mediterranean grasslands, scrub formations or pine forest cover. Most of the sites were located in areas with moderate to very high hillslope gradients (Fig. 3c), although some sites were also found in low-gradient (<15% slope) landscapes, specifically check-dam terraces or cascading earth embankments, which typically develop along valley bottoms and dry watercourses (e.g., *wadies*, *ramblas* and *barrancos*) in arid and semi-arid regions. Fine-grained sedimentary materials, encompassing marls, mudstones, clays, turbidites and other formations alternating soft and hard materials, accounted for the most pervasive lithology group in the reviewed terrace systems, followed by massive limestone/sandstone formations, and both igneous and metamorphic materials (38%, 25% and 14%, respectively; Fig. 3d). About 70% of the reviewed landscapes had dry-stone wall terraces (Fig. 3e). The remaining 30% of sites were structured in the form of earth-banked terraces, frequently built in areas dominated by thick units of fine-grained soft lithology (e.g., marls, clays) lacking stone boulders for the construction of dry-stone masonry.

The most common research subjects covered at the study sites were surface wash erosion and runoff/infiltration (covering 60%-65% of the sites; Fig. 3f). Mass movements and gully occurrence took second place (30%-40% of sites), followed by piping/tunnelling and hydrological connectivity (15% of sites). Plot-scale field surveying (of vegetation, soil characteristics and erosion features) was the most prevalent research approach, covering nearly 90% of the sites (Fig. 3g). Half the sites were also explored through experimental observations, primarily at the plot scale (e.g., infiltrometer and rainfall simulation tests, Gerlach trough monitoring of runoff/erosion), but in some cases encompassing also the larger, catchment scale (e.g., gauging station monitoring of runoff/sediment fluxes). About a quarter of the identified terraced sites were studied at the broad catchment and/or regional scales by GIS/remote sensing and/or data modelling (Fig. 3g).

## 4. Key factors determining the hydro-geomorphological consequences of terrace abandonment

### *4.1. Hydrological behaviour: infiltration, runoff and hydrological connectivity*

Traditional agricultural terraces — and the complementary drainage/irrigation structures (e.g., artificial channels, trenches and ditches) that often accompany these cultivation systems — strongly influence the regulation of hydrological processes (Nasri et al., 2004; Hammad et al., 2006; Nunes et al., 2016; Rogger et al., 2017). After the cessation of cultivation and active management, traditional terraces may lose, at least in part, their water-conservation and/or flow-regulation efficiency (Arnáez et al., 2015). A wide range of factors affecting the hydrological behaviour of abandoned terrace systems were identified within the reviewed bibliography, with some key field attributes and processes appearing more frequently than others (Fig. 4). The following two subsections provide broad discussion of these key factors regulating terrace hydrological behaviour at the local and the wider (landscape/catchment) scales, respectively.

### *4.1.1. Key factors controlling local-scale infiltration and runoff dynamics*

Vegetation cover was identified as the most recursively quoted controlling factor for the local dynamics of infiltration and runoff after the abandonment of traditional terrace systems (Fig. 4a), frequently cited in combination with the content of soil organic matter and time since abandonment (Rodríguez-Aizpeloa et al., 1991; Cerdà, 1994; Robledano-Aymerich et al., 2014; Romero-Díaz et al., 2016). In fact, successful establishment of vegetation and development of soil organic matter pools contribute strongly to the improvement of soil hydrological conditions after terrace abandonment through increased soil macro-porosity and aggregate stability. An example of these effects is provided by Romero-Díaz et al. (2017), who studied the interactions between terrace abandonment, vegetation cover, soil organic matter and soil infiltration capacity over a 100-yr chronosequence of abandoned olive orchards in eastern Spain (Vallada, Valencia). Their results — using cylinder infiltrometer tests — indicated that, after an initial drop in infiltration capacity for recently abandoned terraces, vegetation development and soil organic matter steadily increased, resulting in a three-fold rise in infiltration capacity along the chronosequence. Similarly, Koulouri and Giorgia (2007) found in terraced fields of Lesvos (Greece) a 35% reduction in runoff production between recently abandoned, barely-covered sites and long-term (over 15 yr) abandoned terraces colonized by Mediterranean shrubs.

Other local soil attributes, such as stoniness (i.e., mm to dm-size rock clasts and gravels remaining in the terraced soils after traditional backfill boulder/cobble removal) and soil thickness, were identified as having a relevant positive influence on the local dynamics of soil infiltration and runoff generation (Fig. 4a). In particular, abandoned terraces containing high densities of stone clasts and gravels in the soil profiles, such as terrace systems developed on rocky metamorphic lithology and limestone, frequently show high infiltration capacity, in general characterized by the formation of deep infiltration fronts and low runoff production rates (Solé-Benet et al., 2010; Al Qudah et al., 2016; Romero-Díaz et al., 2016; Martínez-Hernández et al., 2017). Similarly, soil thickness shows a strong positive influence on the hydrological behaviour of abandoned terraces. Deep terraced soils can absorb and store very important amounts of rainfall (Llorens et al., 1992). However, the unequal distribution of soil depths within the terrace systems also favours hydromorphic behaviour (i.e., saturation of some terrace sectors during prolonged periods), particularly in wet environments. For example, hydrological research in humid and subhumid Pyrenean landscapes commonly highlights the emergence of scattered saturation affecting old abandoned terraces for long periods during the autumn and winter seasons (Gallart et al., 1994; Latron and Gallart, 2007; Seeger and Ries, 2008; Molina et al., 2014). As a general rule, these patterns are initiated in the inner parts of the terraces, where soils tend to be shallower (Fig. 4b).

Surface crusting (commonly associated with fine-grained marly soils) and vegetation disturbance (by the effects of livestock grazing and wildfires) were identified as the most commonly cited negative factors affecting runoff and soil infiltration at the local (terrace) scale (Fig. 4a). Surface sealing and crust formation, frequently affecting recently abandoned systems, hinders soil infiltration in bare and barely covered terraces over a variety of climate and lithology conditions (Romero-Díaz et al., 2016). Their effects are, however, more pronounced in abandoned terraces in semi-arid climates constructed on fine-grained sedimentary materials lacking well-developed soil structure (Francis, 1990; Lesschen et al., 2007; Solé-Benet et al., 2010; Calvo-Cases et al., 2011; Martínez-Hernández et al., 2017). Livestock grazing reduces vegetation cover and increases soil compaction, contributing to both reduced infiltration capacity and increased runoff. Rainfall simulation studies carried out in terraced landscapes of the Iberian Range (Camero Viejo, northern Spain) demonstrated that the introduction of heavy grazing (up to 70 heads of livestock per km$^{-2}$) can double the production of runoff in old abandoned systems (Lasanta et al., 2001; Arnáez et al., 2015). Similarly, experimental studies of abandoned terrace systems affected by wildfires indicated that fire occurrence causes ample alterations at the soil surface (e.g., removal of soil surface protection by vegetation and litter, near-surface destruction of soil organic matter and reduction of soil porosity), inducing sharp increases in runoff production, particularly during the first year after fire occurrence (Rodríguez-Aizpeloa et al., 1991; Lourenço et al., 2014; Pardini et al., 2017).

### *4.1.2. Key factors controlling wider-scale hydrological connectivity*

Traditional cultivation terraces act as water sinks that reduce surface hydrological connectivity and break up the continuity of subsurface water flows, imposing large rainfall thresholds on catchment-scale runoff production (Cammeraat, 2004). For example, Lesschen et al. (2009) modelled in a 500 ha terraced catchment of SE Spain (Cárcavo basin, Murcia) a 4-fold reduction in catchment runoff production during a large event (~160 mm rainfall in six days) for a fully functional terrace scenario (5.2% runoff coefficient), compared with an alternative scenario lacking cultivation terraces (25.9% runoff coefficient). In addition, Bellin et al. (2009) indicated for the same semi-arid basin that the presence of cultivation terraces strongly reduces the likelihood of runoff reaching the river system for heavy storms with return periods of up to 8-10 yr. Both soil thickness and antecedent rainfall conditions emerged in the studies reviewed and sites analysed as significant factors mediating the arrangement and connectivity of runoff fluxes at the large catchment scale (Fig. 4c). The presence of thick soils is generally perceived as one of the most characteristic determinants for the sink behaviour of traditional cultivation terraces and, at the catchment scale, is frequently linked to the formation of slow runoff responses with small to moderate peak flows and long recession limbs (Llorens et al., 1992; Latron and Gallart, 2008; Lana-Renault et al., 2018). Unlike soil thickness, antecedent rainfall (or soil moisture) conditions negatively affect sink behaviour and favour large-scale runoff connections of terraced landscapes. These effects may be particularly significant in subhumid and humid environments, where water table rise and perched saturation usually cause the progressive expansion of saturated areas during wet periods, enhancing saturation excess runoff and, therefore, facilitating the formation of well-connected flows between local runoff sources and catchment streams (Gallart et al., 1994, 2002; Latron and Gallart, 2008; Lana-Renault et al., 2014; Calsamiglia et al., 2016; Nadal-Romero et al., 2016).

Our key-factor meta-analysis identified the degradation of unmaintained terrace structures and the long-term development of vegetation as the most relevant processes affecting the hydrological connectivity of terraced landscapes after land abandonment (Fig. 4c). Progressive collapse of terrace walls and risers, frequently accompanied by the clogging of artificial drainage channels and the development of gullies, contribute to the reactivation of old (natural) water pathways (Fig. 4d), increasing both surface and subsurface water flow connections between the hillslopes and the channel network (Gallart et al., 1994; Lesschen et al., 2009; López-Vicente et al., 2013, 2017; Calsamiglia et al., 2018). For example, Meerkerk et al. (2009) reported for the above-mentioned Cárcavo basin (SE Spain) a 3-fold increase in the contributing area of concentrated flow to the river system as a consequence of the collapse of 60% of the cultivation terraces between 1956 and 2006. However, the development of vegetation, particularly forest cover, induces long-term reductions in the hydrological connectivity of terraced landscapes, also attenuating the negative effects caused by terrace collapse on catchment-scale flow arrangement and flooding (Lesschen et al., 2009; López-Vicente et al., 2013; Lana-Renault et al., 2018). López-Vicente et al. (2017) illustrated the positive effects of forest cover development on hydrological connectivity when studying the long-term (70-yr) evolution of surface flow patterns for the Araguás afforested catchment (central Pyrenees, Spain). Hydrological connectivity (measured using the distribution of flowpath lengths) in this terraced landscape increased by 25% between 1945 and 1973 as a consequence of the decay of 50% of the agricultural terraces. The amount of intact terraces had decreased by an additional 30% in 2012, although widespread development of forest cover by active afforestation buffered the negative effects of terrace degradation during this period, resulting in a ~10% reduction of mean flowpath length. In fact, hydrology research in old abandoned terraces that were naturally colonized by tree species or actively afforested indicates that forest cover can intercept up to 25% of the annual rainfall (Llorens et al., 1997b, 2018) and significantly reduce soil moisture content (Gallart et al., 2002; Garcia-Estringana et al., 2013), which may also reduce flooding frequency and peak discharge at the catchment level (Nadal-Romero et al., 2016).

### *4.2. Geomorphological behaviour: sheet wash, gullying, mass movements and piping*

Traditional cultivation terraces are generally considered effective soil conservation structures that under optimal management control the geomorphological activity of agricultural fields (Stanchi et al., 2012; Arnáez et al., 2015). For example, Hammad et al. (2006) experimentally quantified the efficiency of traditional cultivation terraces for soil conservation in semi-arid cereal crops of the Ramallah District (West Bank, Palestinian Autonomous Areas), obtaining a ~70% cumulative reduction in soil erosion for a set of 31 erosive events. Similarly, Bevan and Connelly (2011), using RUSLE3D simulations, indicated that the presence of traditional cultivation terraces locally decreased soil erosion by up to 50% in the agricultural landscapes of Antikythera Island (Greece). However, soil erosion activity is not always effectively reduced on abandoned traditional terraces (García-Ruiz and Lana-Renault, 2011; Arnáez et al., 2015; Romero-Díaz et al., 2016). In fact, general exploration of annual soil loss data for the abandoned terrace systems reviewed in this study revealed that soil erosion has a broad range of forms and intensities (Fig. 5). Where surface wash dominated erosive activity, soil loss remained in many cases below or within the sustainable erosion limits imposed by the typical rates of natural soil formation for the European region (0.3-1.4 t ha$^{-1}$ yr$^{-1}$; Verheijen et al., 2009). However, in particular cases (e.g., recently abandoned systems and partially dismantled terraces showing limited vegetation colonization), soil loss by surface wash exceeded these tolerable limits, reaching soil erosion intensities at the plot scale near to and over 10 t ha$^{-1}$ yr$^{-1}$ (Bazzoffi and Gardin, 2011; López-Vicente et al., 2013). Up to an order of magnitude above the identified top surface wash erosion levels, the highest erosion rates in the explored abandoned fields (40-400 t ha$^{-1}$ yr$^{-1}$; Fig. 5) were reported at the plot and terrace-unit scale in systems affected by mass movements, piping and gullying (Lehmann, 1993; Lesschen et al., 2008; Calvo-Cases et al., 2011; Romero-Díaz et al., 2011; López-Vicente et al., 2013).

Our bibliographic exploration and key-factor meta-analysis revealed a broad range of field attributes and processes controlling the geomorphological behaviour of abandoned terrace systems, including a variety of land cover factors, mediating landscape processes, terrace and hillslope structural characteristics and key local soil physico-chemical traits (Figs. 6-8). The following four sub-sections discuss the influence of these controlling field attributes and processes on the regulation of terrace geomorphological activity after field abandonment, in the light of surface wash, gullying, mass wasting and piping/tunnelling dynamics.

### *4.2.2. Key factors controlling surface wash erosion dynamics*

Vegetation cover, usually associated with time since abandonment, was identified as the main key field attribute exerting positive control on the dynamics of surface wash erosion in the abandoned terrace sites (Fig. 6a). Widespread development of (grass, scrub and forest) vegetation cover after terrace abandonment improves soil conditions (e.g., soil erodibility, infiltration capacity) and provides surface protection against raindrop impact, sheet erosion and rill incision (Francis, 1990; Rodríguez-Aizpeloa et al., 1991; Cerdà, 1994; Lesschen et al., 2009; Romero-Díaz et al., 2017). For example, Ruecker et al. (1998) reported for a set of abandoned agricultural terraces in dry-subhumid Spain that annual soil loss decreased from 2.2 t $ha^{-1}$ $yr^{-1}$ in the first fallow years to about 0.6 t $ha^{-1}$ $yr^{-1}$after widespread establishment of vegetation (over 70% scrub cover) within 10-30 yr. Similarly, López-Vicente et al. (2013), using a physically-based soil erosion and sediment routing model, concluded for a 74-ha terraced catchment in the Ebro basin (Estanque de Arriba, NE Spain) that the long-term development of vegetation in abandoned cropping terraces and agricultural fields can produce up to a 90% reduction in annual soil loss. Our key factor meta-analysis detected, however, that vegetation development after terrace abandonment may show in some particular cases complex conflicting interactions with surface erosion dynamics, principally at the shrub colonization stage (Fig. 6a). In fact, Koulouri and Giorgia (2007) found in 5- to 20-yr abandoned terraces on Lesvos (Greece) that the formation of large vegetation gaps during the shrub colonization phase resulted in increased surface wash erosion with abandonment age. Beyond vegetation development, long-term surface armouring by rock fragment cover may also contribute to controlling surface erosion in old abandoned terrace systems (Seeger and Ries, 2008; Ries, 2010; Solé-Benet et al., 2010; Fig. 6a). The stabilizing effects of rock fragment sieving crusts may be particularly important for gravely terraced soils developed over stone-rich (metamorphic and limestone) lithologies (Romero-Díaz et al., 2016). These effects have significant implications for the stability of terraces in dry environments, where climate conditions impose large constraints on vegetation development after terrace abandonment (Solé-Benet et al., 2010).

Bare soil cover — usually associated with recently abandoned terraces and marl lithology — and the effects of both grazing and wildfires were the most frequently cited negative factors affecting surface erosion dynamics after land abandonment (Fig. 6a). Widespread bare soil is broadly recognised as the main cause promoting surface wash erosion during the first fallow years of abandoned terraces (Francis, 1990; Rodríguez-Aizpeloa et al., 1991). On marl lithology, the soil surface may remain largely uncovered due to strong soil physical constraints (e.g., massive soil structure, low infiltration and plant-available water retention capacity, significant salt contents) that prevent extensive vegetation development even for old abandoned terraces, favouring the activity of soil erosion processes (Robledano-Aymerich et al., 2014; Romero-Díaz et al., 2017). Indirectly related to surface cover and soil conditions, both fire occurrence and over-grazing greatly increase the activity of surface wash processes in abandoned terrace systems (Lehmann, 1993; Calsamiglia et al., 2016). Plot-scale erosion studies in old abandoned terraces disturbed by wildfires highlighted that enhanced runoff production and soil erodibility after fire occurrence can increase soil loss by one order of magnitude (Rodríguez-Aizpeloa et al., 1991; Lourenço et al., 2014; Pardini et al., 2017). Similarly, small-scale rainfall simulation studies in abandoned terraces affected by different levels of livestock grazing revealed that soil loss in heavily grazed terraces can be 2-4 times greater than in old abandoned systems that are only occasionally grazed (Lasanta et al., 2001; Arnáez et al., 2011).

Although less frequently cited, the dip of the terraced surface was also identified within the reviewed sites and studies as a significant key factor enhancing surface wash erosion (Fig. 6a). Notwithstanding that terraces are generally built to attain nearly flat surfaces, the terrace bed in some occasions may show significant dip angles (up to 15-20º), which may favour the action of surface wash erosion, particularly after the abandonment of active management (García-Ruiz et al., 1988; Koulori and Giorgia, 2007). In addition, long-term dismantling of terrace risers by mass movements can induce progressive increases in dip angle and length of the terrace surfaces in old abandoned systems, also increasing the risk of surface wash erosion (Lehmann, 1993; Bazzoffi and Gardin, 2011).

### *4.2.3. Key factors controlling gully occurrence*

Traditional cultivation terraces after the cessation of active structural maintenance are vulnerable to the damaging effects of gully erosion, which can cause intense soil loss rates up to and over 30-100 t $ha^{-1}$ $yr^{-1}$ (Lehmann, 1993; Lesschen et al., 2008; López-Vicente et al., 2013; Romero-Díaz et al., 2016). The degradation of terrace structures (e.g., sliding of stone walls and risers, breakdown of artificial channels) and collapse of subsurface (pipe and tunnel) erosive outfalls, frequently in combination with the effects of extreme rainfall and the establishment of livestock routes across terraces, were identified as the most relevant factors controlling gully occurrence in abandoned terraced fields (Fig. 6b). Gully development after terrace abandonment occurs: (i) because of the incision of unmaintained drainage channels and irrigation ditches

(Llorens et al., 1997a; Gallart, 2009; López-Vicente et al., 2013); (ii) as a result of runoff concentration in damaged terrace risers (Fig. 6c) frequently causing incision and regressive erosion on scars and soil slips originated by previous mass movements (Marco-Molina et al., 1996; Cyffka and Bock, 2008; Ries, 2010; López-Vicente et al., 2013); or (iii) as a consequence of channel expansion across pipes and tunnels induced by subsurface erosion (López-Bermúdez and Torcal-Sáinz, 1986; Lesschen et al., 2008; Romero-Díaz et al., 2009; Calvo-Cases et al., 2011); all three initiation processes favoured by extreme rainfall. Interestingly, the overall results of these studies suggest that gully development may be initiated more frequently as a secondary effect of mass movements and subsurface erosion than as the direct effect of surface wash erosion. Walking livestock, which typically move through contiguous terraces using spots damaged by soil slips and dry-stone wall collapses, also facilitate the expansion of gullies in abandoned landscapes (Jiménez-Olivencia, 1990; Lehmann, 1993).

Vegetation cover emerged as a relevant factor controlling gully occurrence in abandoned terraced landscapes (Fig. 6b). In fact, vegetation development may control gully incision in terrace wall spots affected by mass movements (Marco-Molina et al., 1996; Lesschen et al., 2008; Arnáez et al., 2017). These effects may be particularly strong in subhumid and humid landscapes with high vegetation development potential (Fig. 6d), where rapid grass colonization of terrace edge scars caused by fallen dry-stone walls and slides may effectively prevent gully development on damaged terrace risers (Llorens et al., 1997a).

### *4.2.4. Key factors controlling the dynamics of mass movements*

Agricultural terraces and their associated drainage structures induce fragmentation of the groundwater table and important subsurface flow discontinuities, which can result in increased hillslope stability against large-scale mass wasting processes (Gallart et al., 1994). After the cessation of active management, however, the risers and walls of abandoned agricultural terraces can become increasingly affected by the dismantling activity of mass movements. Such terrace collapses generally occur in the form of small soil slips and simple falls of dry-stone walls, but may also take the form of larger terrace-cascading landslides (Arnáez et al., 2015). Small soil slips affecting the risers of old abandoned terraces can mobilize rather important amounts of soils. For example, Arnáez et al. (2017) estimated soil loss volumes of as much as 16 $m^3$ per slide and 156 $m^3$ per 100 m of terrace wall in old (up to 60 yr) abandoned terraces of the Iberian Range (Camero Viejo, northern Spain). The mobilized soils are, in general, deposited immediately below the affected risers and walls (Fig. 7a), inducing a progressive recovery of natural gradients (Jiménez-Olivencia, 1990; Lehmann, 1993; Marco-Molina and Morales-Gil, 1995; Lasanta et al., 2001; Bazzoffi and Gardin, 2011). Although localized in space, the effects of these small soil slips may propagate downward by promoting surface flow concentration along preferential pathways that, in the long term, can destabilize vulnerable downslope wall sections (Zurayk, 1994; Calsamiglia et al., 2018). Of greater impact, large-scale terrace-cascading landslides usually associated with debris flow formation during extreme rainfall (Fig. 7b) can cause rapid re-establishment of the original (un-terraced) hillslope profile (Crosta et al., 2003; Cevasco et al., 2013; Savo et al., 2014; Brandolini et al., 2018).

Our meta-analysis of key factors highlighted extreme rainfall, drainage dysfunction (i.e., soil saturation, clogging of drainage channels), local topography (hillslope gradient and position, terrace riser height) and disturbance of walls (animals/root growth) as the most commonly cited determinants controlling the dynamics of mass movements in abandoned cultivation terraces (Fig. 7c). Extreme rainfall may result in soil saturation and surface overflow of terrace walls, promoting terrace sliding failure (Gallart and Clotet-Perarnau, 1988; Jiménez-Olivencia, 1990; Marco-Molina and Morales-Gil, 1995; Brandolini et al., 2008; Lourenço et al., 2014; Savo et al., 2014; Paliaga et al., 2016). Saturation reduces soil cohesion and increases the weight of retained soil materials, contributing to reducing the stability of terraces against mass movements, particularly during and after heavy or prolonged rainfall (Lasanta et al., 2001; Crosta et al., 2003; Zgaier and Inbar, 2005; Arnáez et al., 2011; Cevasco et al., 2014). Terrace failure may also be initiated without the concurrence of soil saturation. Rapid lateral subsurface flow favoured by soil cracks, micro-pipes and the presence of low-permeability subsoil layers can induce the accumulation of water in cavities at the backfill-wall interface, building a water column that develops hydrostatic pressure, and causes dry-stone wall instability (Arnáez et al., 2015; Preti et al., 2017). In these cases, the fall of affected dry-stone wall sections may take place without mobilizing directly significant amounts of the retained backfill soil (Preti et al., 2018). Although wall failure and terrace sliding are frequently linked to extreme rainfall, field observations suggest that horizontal earth pressure induced by soil infiltration in non-exceptional rainfall events may also cause gradual movement and bulge deformation of terrace walls, which prepares these abandoned structures for terrace failure (Jiménez-Olivencia, 1990; Pallarès-Bou and Calvo-Cases, 1994; Inbar and Zgaier, 2016; Preti et al., 2018). Overall, the activity of these multiple terrace failure mechanisms is strongly favoured by the degradation and clogging of artificial channels that maintain drainage functionality in traditional terraced landscapes (Crosta et al., 2003; Brandolini et al., 2008; Bazzoffi and Gardin, 2011; Cevasco et al., 2014; Lourenço et al., 2014).

Hillslope gradient and terrace height, commonly well-correlated factors, and hillslope position are important field attributes that predispose terraced landscapes to the dismantling effects of mass movements (García-Ruiz and Lana-Renault, 2011). Hillslope gradient and terrace height provide abandoned terraced landscapes with relief vigour for the gravitational action of mass wasting processes (Jiménez-Olivencia, 1990; Ferre et al., 1994; Morel, 2006). Differently, hillslope concavities — in some cases hidden under the terraces in the form of buried hollows or depressions — and bottom hillslope positions promote the convergence of both surface and subsurface water on vulnerable sections of terrace risers and walls, also favouring terrace sliding failure (Crosta et al., 2003; Lesschen et al., 2008; Arnáez et al., 2015; Calsamiglia et al., 2018). Good examples of the influence of these topographical factors on terrace stability are provided by detailed geomorphological explorations of abandoned terraced landscapes in the upper valleys of the Leza, Jubera and Cidacos rivers (Iberian Range, NE Spain), where García-Ruiz et al. (1988) found a positive relationship between the frequency of terrace failure and hillslope gradient. Further, Arnáez et al. (2017) indicated that the volume of soil mobilized per terrace unit in the form of small soil slips correlated closely with the height of the terrace risers for this region. In addition, high likelihood of terrace failure in concave and hillslope-foot positions was revealed, mostly affecting abandoned terraces that showed recurrent saturation during the wet (autumn and winter) seasons (Lasanta et al., 2001; Arnáez et al., 2011, 2017).

Physical disturbance of dry-stone masonry also increases the instability of terrace walls by facilitating the action of mass movements in abandoned terraces. For example, sheep and goat hoofs can severely damage dry-stone walls (Lehmann, 1993; Marco-Molina and Morales-Gil, 1995). Similarly, the growth of shrub roots in gaps between the boulders of dry-stone walls was suggested in several studies as a significant destabilising factor that may contribute to the decay of terrace walls, due to increased physical pressure and chemical reactions on the stone surfaces (Morel, 2006; Lesschen et al., 2008; Savo et al., 2014; Calsamiglia et al., 2018). Other, less commonly cited field attributes and processes, such as impermeable bedrock or wildfire, were also identified as relevant factors influencing the risk of terrace sliding failure (Fig. 7c). The presence of impermeable bedrock or subsoil may promote the destructive action of mass movements on abandoned cultivation terraces, by favouring the formation of slip planes at the contact between terraced soils and deeper bedrock/subsoil materials (Crosta et al., 2003; Cammeraat et al., 2005; Brandolini et al., 2008; Cevasco et al., 2014). Differently, wildfires may destabilize terrace walls indirectly, by favouring runoff production and flow concentration in localized pathways that might lead to the formation of high-pressure points on the walls (Lourenço et al., 2014; Savo et al., 2014; Calsamiglia et al., 2018).

#### *4.2.5. Key factors controlling piping and tunnelling dynamics*

Under particular conditions, subsurface erosion can dominate the hydro-geomorphological dynamics of terraced landscapes. In the most severe cases, aggressive piping and tunnelling cause the formation of large holes and gullies on abandoned soil embankments and terraces, inducing intense soil loss and chaotic dismantling of the terraced morphology (Fig. 8a). Romero-Díaz et al. (2011), in a detailed morphometric exploration of a hundred abandoned terraces affected by aggressive piping phenomena in the Mula basin (Campos del Rio, Murcia, SE Spain), estimated that approximately 35% of the studied plots showed soil-loss rates above 100 t $ha^{-1}$ $yr^{-1}$, with some extreme cases reaching over 500 t $ha^{-1}$ $yr^{-1}$ soil erosion and 3-8 m maximum gully depth. These destructive erosion phenomena can progress very rapidly on abandoned systems. For example, volumetric soil-loss estimations for an abandoned terrace system affected by aggressive piping in Petrer (Alicante, SE Spain) reflected rapid gully development (accounting for 374 t $ha^{-1}$ $yr^{-1}$ erosion) during the first decade after the cessation of active management, followed by slower gully retreat (190 t $ha^{-1}$ $yr^{-1}$ soil loss) by lateral tunnel expansion during a 12-yr follow-up period (Calvo-Cases et al., 2011). Although pipe/tunnel development on terraced landscapes is generally perceived as a consequence of land abandonment in piping-prone settings, pipe formation may precede the cessation of terrace cultivation, bringing about land abandonment due to high maintenance cost because of subsurface soil erosion (Watts, 1991; Faulkner et al., 2003; Romero-Díaz et al., 2007).

The presence of high hydraulic gradients between terraces and particular physical and chemical soil traits emerged as the main controlling factors determining the activity of subsurface erosion phenomena across the explored studies and sites (Fig. 8b). Aggressive piping in these traditional cultivation systems is generally linked to the presence of high hydraulic gradients between adjacent terrace beds, particularly on reworked agricultural soils of a dispersive character (Romero-Díaz et al., 2007, 2009, 2016; Solé-Benet et al., 2010; Calvo-Cases et al., 2011). While the flat topography of the cultivation platforms facilitates surface ponding and infiltration, the terrace risers provide infiltrating water with steep hydraulic gradients for macro-pore enlargement and pipe formation (Faulkner et al., 2003). These hydraulic gradients also condition the maximum depth that pipes can reach (Romero-Díaz et al., 2007, 2011). In some cases, pipes and gullies may even locally exceed the elevation of terrace risers, reaching the base level of adjacent terraces or the river bed (Fig. 8c).Topographically, the most severe impact of subsurface erosion typically takes place at medium and lower positions of streambed cascading terraces and earth embankments, on systems with risers over 1 m in height and longer plot length than terrace width (Romero-Díaz et al., 2011, 2016).

Some particular soil properties play a decisive role in promoting pipe initiation and development in abandoned cultivation terraces. Fine-grained soils showing significant texture and structural variations with soil depth favour pipe formation. For example, broad regional exploration of soil properties in abandoned terraces affected by intense subsurface erosion phenomena in the region of Murcia (SE Spain) revealed that the soils of these severely eroded systems are characterised by weak structure and silty-loam texture at the surface, while they have more impermeable clayey granulometry and massive structure in deep soil layers (López-Bermúdez and Torcal-Sáinz, 1986; López-Bermúdez and Romero-Díaz, 1989). These conditions strongly facilitate lateral expansion of pipes and tunnel initiation above the impermeable soil horizons (Romero-Díaz et al., 2016). Similarly, the presence of significant amounts of swelling clay (e.g., smectite) may also contribute to pipe initiation through the formation of deep soil cracks and enhanced macro-pore flow (Romero-Díaz et al., 2007; Calvo-Cases et al., 2011). As for the chemical properties of the soils, high soil pH (indicating base saturation), the presence of highly soluble salt contents and excess of exchangeable sodium provide abandoned cultivation terraces with optimal conditions for the development of aggressive piping (Romero-Diaz et al., 2016). Particularly relevant is high sodium content saturating part of the exchange complex of clays, which causes deflocculation and rapid soil dispersion, rendering soil materials highly susceptible to subsurface erosion in the presence of steep hydraulic gradients (Faulkner, 2013). Calvo-Cases et al. (2011) found that, for alkaline soils and bedrock regoliths of the Barranco del Pi basin in Petrer (Alicante, SE Spain), dispersive behaviour may develop above threshold values of 1 mS cm$^{-1}$ electrical conductivity and 1.5 sodium adsorption ratio, favouring the formation of pipes, tunnels and gullies on abandoned streambed terraces and surrounding badland areas. Similarly, Romero-Díaz et al. (2007, 2009, 2016) identified the presence of high levels of exchangeable sodium at subsurface levels of terraced soils as a critical factor favouring soil dispersion and pipe initiation for a broad range of abandoned agricultural systems in SE Spain.

## 5. Patterns of landscape stability and management considerations

### *5.1. Environmental patterns of terrace stability after land abandonment*

Evaluation of terrace stability, based on the explored sites and the bibliography reviewed in this study, pointed to the great frequency of unstable, erosive landscapes (i.e., sites with signs of intense surface wash erosion and/or terrace degradation due to the effects of aggressive piping, gullying or generalized mass movements) in arid and semi-arid environments and, more strikingly, abandoned terraces with no or little vegetation development (Fig. 9). Scarce and irregular precipitation in combination with high temperatures and long dry periods are major limitations on the development of vegetation cover and soil erosion protection in abandoned agricultural landscapes (García-Ruiz and Lana-Renault, 2011; Romero-Díaz et al., 2017). For example, Lesschen et al. (2008) stated slow vegetation recovery after cessation of terrace cultivation for a semi-arid environment with scarce (~300 mm) annual precipitation. Two decades after land abandonment, vegetation cover on the field was still low (30%-40%), which led to crusting and increased runoff concentration, favouring sheet wash erosion and gully incision. In humid and subhumid environments, recolonization of vegetation is usually faster due to higher water availability. Cammeraat et al. (2005) in subhumid abandoned terraces with annual precipitation in the 500-1000 mm range reported full-cover establishment by grasses and annual herbs within the first few years of abandonment, which prevented sheet wash and rill incision. More recently, hydro-geomorphological research in abandoned terrace systems distributed along a broad gradient of annual rainfall in NE Spain (from about 300 mm in the Central Ebro basin to over 900 mm in the Pyrenees) indicated that ample vegetation development under subhumid and humid conditions exerted effective control on surface erosion processes, while the driest areas showed ongoing degradation, with high erosion rates (Seeger and Ries, 2008; Ries, 2010). Our meta-analysis results revealed that the frequency of sites showing erosive terrace behaviour declined with increased vegetation development, particularly above 66% cover (Fig. 9). Accordingly, experimental observations in natural and disturbed Mediterranean soils have highlighted minimum 30%-50% vegetation cover development as an important threshold for the control of runoff production and surface erosion processes (Francis and Thornes, 1990; Gimeno-García et al., 2007; Moreno-de-las-Heras et al., 2009). Ries (2010) indicated that significant control of surface erosion processes in long-term overexploited agricultural soils with exhausted organic matter and weakened soil structure may require development of at least 60% vegetation cover.

Concerning local lithology, erosion issues in the form of intense surface wash, gullying and, in some cases, piping were concentrated in abandoned terrace systems developed over fine-grained, sedimentary bedrock: 61% of sites on marls, clays and turbidites showed erosive behaviour against 25% of stable, non-erosive landscapes for this lithology group (Fig. 9). In particular, the cessation of cultivation and active terrace management can show very negative effects on marl lithology, with limited vegetation development, rapid deterioration of soil characteristics (e.g., soil structure, infiltration capacity) and increased soil erosion after land abandonment (Romero-Díaz et al., 2017). Both high soil erodibility and inherent restrictions for vegetation colonization enhance surface erosion processes for abandoned terrace systems on marl lithology (Cerdà, 1994; Ries, 2010; Robledano-Aymerich et al., 2014; Romero-Díaz et al., 2016). In contrast, large-scale regional studies of old traditional terraces and agricultural fields in Mediterranean mountain settings revealed that metamorphic phyllite and schists as well as limestone lithology show, in general, more balanced responses to land abandonment, with increased recovery of vegetation, better soil quality and improved hydrological properties after the cessation of agricultural use (Robledano-Aymerich et al., 2014; Romero-Díaz et al., 2016, 2017).

In agreement with the general patterns of terrace stability described above, individual analysis of the frequency of piping/tunnelling phenomena indicated that dry (arid and semi-arid) terraced landscapes on fine-grained (marl and mudstone) sedimentary lithology show great vulnerability to the effects of aggressive subsurface erosion (Fig. 10a). More precisely, a large number of landscapes affected by aggressive piping were found in studies describing abandoned cultivation terraces developed on saline marl materials — frequently of marine origin — in semi-arid SE Spain, which generally had little vegetation development (López-Bermudez and Torcal-Sáinz, 1986; López-Bermúdez and Romero-Díaz, 1989; Romero-Díaz et al., 2007, 2009, 2011, 2016; Calvo-Cases et al., 2011). Unlike in humid and subhumid climates, salts in arid and semi-arid Mediterranean environments are barely leached from the soil and bedrock materials, since evapotranspiration largely exceeds precipitation during long periods of the year. Consequently, sodium remains largely active within the soil profile, providing fine-grained soil materials with dispersive behaviour and pipe-forming predisposition (Faulkner, 2018). In addition, concentration of scarce precipitation in high-intensity rainfall and soil surface cracking by high summer temperatures may also contribute to pipe development in dry abandoned terraces under arid and semi-arid Mediterranean conditions (Romero-Díaz et al., 2007).

Although we found bibliographic evidence for the activity of aggressive piping in semi-arid terraces with dispersive fine-grained materials under a broad range of hillslope gradient conditions (from <15% to >35% hillslope gradient), most subsurface erosion studies focussed in abandoned terraces located in low and moderate gradient landscapes (Fig. 10a). In particular, the analysis of piping/tunnelling phenomena was very noticeable in published studies on check-dam terraces and cascading-earth embankments located along valley bottoms and dry stream beds, which constitutes a common agricultural practice for cereal and almond/olive tree crop production in semi-arid SE Spain (López-Bermudez and Romero-Díaz et al., 1989; Romero-Díaz et al., 2007; Lesschen et al., 2008; Calvo-Cases et al., 2011). In these cases, large gullies and macro-pipes often develop in the centre of abandoned cultivation terraces, inducing a sharp recovery of the natural drainage pattern imposed by the original (non-terraced) stream beds (Romero-Díaz et al., 2011, 2016).

Analysis of the absolute frequency of sliding failure phenomena for the sites explored in this study showed that mass movements are critically concentrated in high-gradient landscapes (>25% slope; Fig. 10b), markedly reducing the relative frequency of landscapes with stable (non-erosive) terrace behaviour in steep systems (Fig. 9). In fact, mass movements constitute major destabilizing phenomena for abandoned terraced sites on high-gradient hillslope landscapes. Jiménez-Olivencia (1990), for instance, in a catchment-scale study of old (about 30 yr) abandoned terraces on a steep (20%-80% gradient) mountain landscape near Sierra Nevada (Acequia de Cachariche, southern Spain), reported that terrace collapses massively affected extremely steep (>50% slope) hillslope sections, while abandoned systems located on moderately steep (<30% gradient) areas retained, at least partially, the terraced morphology. Beyond hillslope gradient, our terrace stability meta-analysis revealed that the amount of reported terrace sliding failure issues in the reviewed sites and studies is homogeneously distributed between all lithology groups under consideration, suggesting that mass movements can affect vulnerable terrace systems (e.g., high wall terraces on high-gradient landscapes and hillslope concavities) in a wide variety of soil conditions.

Although terrace sliding failure peaked for subhumid and humid terraced sites, the bibliography reviewed in this study also frequently reported terrace collapse due to mass movements in abandoned sites under drier climate conditions (Fig. 10a). This may be explained by the incidence of extreme (heavy and/or prolonged) rainfall, previously revealed as a significant mass movement trigger in our key-factor meta-analysis (Fig. 7c), which may induce the collapse of abandoned terraces in humid and subhumid landscapes (Cevasco et al., 2013; Lourenço et al., 2014), but also in dry-subhumid and semi-arid Mediterranean environments (e.g., Jiménez-Olivencia, 1990; Marco-Molina and Morales-Gil, 1995). In fact, regardless of local climate aridity, broad-range rainfall conditions for the Mediterranean basin are characterized by the relevance of extreme events that concentrate large amounts of precipitation in heavy and/or prolonged rainfall (Mariani and Parisi, 2014). Extreme events showed the most devastating effects on traditional terraces located in very high-gradient (frequently >50% slope) landscapes under subhumid and humid conditions, where perched groundwater table formation and terrace saturation by heavy and/or prolonged rainfall cause debris slips and avalanches with catastrophic consequences for people, buildings and infrastructures (Cevasco et al., 2013; Savo et al., 2014; Paliaga et al., 2016). For example, a centennial return-period event hit an extensive, humid area of NW Italy between eastern Liguria and northern Tuscany on 25 October 2011, recording cumulative precipitation of 330-540 mm in 24 h and a peak rainfall discharge of 90-150 mm/h. In the small (5.7 km$^2$) coastal basin of Vernazza (Cinque Terre region, eastern Liguria), this extreme event triggered over 500 shallow landslides, mostly on steep (>45% slope) terraced hillslopes over impermeable and semi-permeable (claystone/siltstone) bedrock, which contributed to the formation downstream of a catastrophic debris flood affecting the village of Vernazza (Cevasco et al., 2013, 2014). Landslides and floods in the basin caused three casualties and nearly €130 million damage to buildings and infrastructure. Debris slides and terrace-cascading avalanches severely affected abandoned terraces during this event (Fig. 7b), mobilizing over 33,000 $m^3$ $km^{-2}$ of eroded soil (Brandolini et al., 2008). Similar effects were reported for a montane Mediterranean area in the Catalan Pyrenees (upper Llobregat basin, NE Spain), where a ~100-yr return-period event in November 1982 accumulated up to 350 mm rainfall in 48 h, causing 616 shallow slips and landslides in old abandoned, steep terraced hillslopes over a surveyed terrain extension of 200 $km^2$ (Gallart and Clotet-Perarnau, 1988).

Interestingly, we found a high frequency of terraced landscapes affected by the action of mass movements at sites showing moderate to extensive vegetation cover (Fig. 10b). In most cases, short- to decadal-term scrub vegetation development showed little capacity to reduce the occurrence of mass movements (Lehmann, 1993; Cammeraat et al., 2005; Morel, 2006; Koulori and Giorgia, 2007; Paliaga et al., 2016). For example, landslide mapping and analysis for the Vernazza basin after the 25 October 2011 heavy rainfall indicated that the highest percentage of landslide scars in the area were found in well-vegetated, abandoned terraces (Cevasco et al., 2014). Similarly, Koulouri and Giourgia (2007) in (up to 20 yr) abandoned cultivation terraces of Lesvos (Greece) indicated that, despite widespread development of shrub vegetation (in some cases over 60% cover), the abundance of terraces with ruined structures largely increased with abandonment time. Overall, these studies are consistent with the results obtained by Cammeraat et al. (2005) for abandoned landscapes in the Alcoy valley (Alicante, SE

Spain), where the activity of mass movements strongly increased over time on cultivation terraces abandoned for up to 30 yr. Dense grass/shrub vegetation development in these old systems provided soil reinforcement by roots up to 40 cm deep. However, roots did not extend deep enough into the soil to prevent shallow mass wasting processes, which developed on deeper (~1 m) slip planes at the contact between the soil profile and less permeable bedrock materials underneath. Eventually, a stabilization or decline in the activity of mass movements was observed after 40 yr of abandonment in old terraces extensively colonized by pine trees that may have facilitated deep root anchoring. Similarly, Brandolini et al. (2018) found in Cinque Terre abandoned landscapes in the Vernazza basin that the activity of surface soil slips and shallow landslides peaked for terraces ranging between 10 and 30 yr of abandonment, then decreasing for older systems showing full recovery of natural woodland vegetation.

### *5.2. Land management considerations for Mediterranean landscapes affected by the abandonment of traditional agricultural terraces*

Traditional cultivation terraces constitute a delicate equilibrium state between local hydro-geomorphological settings and anthropogenic use (Tarolli et al., 2014). After the cessation of active agricultural management, this delicate equilibrium can be lost rapidly. In fact, these traditional structures require constant work for their conservation (Lasanta et al., 2013). Abandoned terrace systems create good conditions for geomorphic processes (i.e., surface and subsurface erosion, mass wasting) that seek to re-establish the natural flowpaths of the landscapes and return the altered gradients of the levelled surfaces to their natural hillslope equilibrium (Gallart et al., 1994;

Brandolini et al., 2008; García-Ruiz and Lana-Renault, 2011; Romero-Díaz et al., 2016).

A range of options can be considered for the management of Mediterranean landscapes affected by the abandonment of traditional agricultural terraces, including non-intervention, stewardship of rewilding processes and active maintenance and/or rehabilitation of terrace structures (Lasanta et al., 2013; Robledano-Aymerich et al., 2014). Vegetation development potential, structural hydro-geomorphic vulnerability of the abandoned landscapes and local socio-economic interests largely condition the feasibility of the different landscape management choices in each particular case and territory. Natural rewilding can provide in some cases a practical way to stabilize abandoned terraced landscapes in the long term, particularly in low to moderately steep Mediterranean old fields under dry-subhumid and wetter, humid climate conditions. In the most positive situations, where dense grass and/or forest cover development takes place, terrace morphology can remain largely stable for decades after the cessation of agricultural activities (Llorens et al., 1997a). Natural rewilding may also provide a feasible option in semi-arid abandoned landscapes on metamorphic and limestone lithology, where favourable soil conditions for infiltration (e.g., high stoniness and/or balanced soil texture) limit both runoff production and soil erosion, also promoting the recovery of vegetation (Robledano-Aymerich et al., 2014; Romero-Díaz et al., 2017). Dense brush development by natural rewilding processes, however, can facilitate wildfire occurrence, with negative repercussions for the stability of abandoned terraces (Rodríguez-Aizpeloa et al., 1991; Lourenço et al., 2014; Pardini et al., 2017; Calsamiglia et al., 2018). In old abandoned landscapes under dry-subhumid Mediterranean conditions, where convergence of high brush development potential and strong summer droughts increase fire risk very decisively, extensive livestock grazing may provide an effective control for scrub propagation and wildfire prevention (Vicente-Serrano et al., 2000; Lasanta et al., 2018). In these cases, management actions should be directed toward regulating grazing pressure, since heavy grazing can also promote surface erosion and wall deterioration in abandoned terraced landscapes (Marco-Molina and Morales-Gil, 1995; Lasanta et al., 2001; Arnáez et al., 2015).

Active management may be required to control soil erosion, facilitate vegetation development and improve soil conditions (particularly organic matter contents) in semi-arid abandoned terraced landscapes on fine-grained, marl lithology. Landscape management in these areas should include specific, within-field mitigation measures (e.g., localized revegetation with local species) rather than widespread afforestation actions that may severely transform the steppe physiognomy and ecological uniqueness that frequently characterize marly fields (Hooke and Sandercock, 2012; Robledano-Aymerich et al., 2014; Romero-Díaz et al., 2017). Where marl lithology shows dispersive soil behaviour (typically on sodic, marine-sourced materials), terrace rehabilitation operations such as pipe/gully filling or surface pipe obliteration by ploughing are markedly inefficient, since subsurface erosion rapidly re-establishes pipe connections after high-intensity rainfall (Romero-Díaz et al., 2016). Faulkner et al. (2003) illustrated a variety of management strategies for pipe-prone soil materials. The use of gypsum amendments is a common remediation measure for shallow-piped dispersive soils; replacement of sodium by calcium in the soil exchange complex contributes to reducing the dispersive character of the amended soils. More interestingly, revegetation can also induce significant reductions in exchangeable sodium, helping to stabilize dispersive soil materials. However, the influence of subsurface soil layers containing high levels of exchangeable sodium and high hydraulic gradients imposed by the terrace morphology may strongly constrain the stabilizing effect of the described surface mitigation measures for abandoned terraces that are affected by deep vertical pipe development, where slope-channel coupling can be to a large extent reinstated (Faulkner, 2013, 2018). Chaotic landform readjustment by aggressive piping is unlikely to be effectively controlled by mitigation measures in these extreme conditions.

The most common hazard compromising the long-term stability of old abandoned terraces is the activity of small soil slips and shallow landslides, which largely affect terrace ridges, dry-stone walls and the conservation of terrace backfill soils. Lesschen et al. (2008) recommended local revegetation with native grass species in terrace wall scars and areas with concentrated water flow as an effective practical measure for the control of gully incision and/or expansion. To optimize management efforts, these operations should be specifically targeted to hotspot sites where, if improperly managed, wall collapse and further gully incision may cause significant erosive problems (e.g., hillslope concavities and valley bottom positions with concentrated surface and subsurface water flows). Hotspot identification for prioritizing mitigation actions can be assisted by spatial modelling of flowpath distribution using high-resolution LiDAR elevation data, which has been identified as an effective semi-automated strategy for revealing damaged areas and vulnerable wall sections in terraced landscapes (Tarolli et al., 2015; Hooke et al., 2017; Calsamiglia et al., 2018).

Active maintenance and rehabilitation of terrace structures is probably the most effective approach for controlling the negative hydro-geomorphological repercussions caused by the abandonment of agricultural practices in traditional Mediterranean terraces. Importantly, terrace reconstruction in these traditional systems requires effective rehabilitation of their drainage regulation capabilities. Non-traditional measures reducing drainage efficiency (e.g., wall reinforcement using mortar or behindwall brickwork) can encourage terrace saturation and thus increase wall instability (Tarolli et al., 2014). Therefore, terrace rehabilitation must make use of more traditional techniques and measures. These include re-establishing the foundations of broken dry-stone wall sections, replacing loose or dislodged stones, cleaning or reconstructing drainage channels, as well as pruning plant roots and/or removing shrubs from walls. The very high costs of these labour-intensive measures, however, makes terrace rehabilitation impracticable in most cases. Zurayk (1994) calculated that full rehabilitation of ruined 5-m-wide bench terrace structures in mountain areas of Lebanon required over 350 person-days of labour input per ha. For Italian mountain landscapes, dry-stone wall rebuilding costs can reach up to €190 per $m^2$ of terrace wall (Lodatti, 2012). Therefore, basic cost-benefit analysis is required for the implementation of terrace rehabilitation practices. In steep, humid mountain landscapes of the Mediterranean region, where mass movements affecting unmaintained terraces can take the form of devastating debris slips and avalanches, terrace rehabilitation can in some cases be justified in view of the large damage costs and casualties produced by these catastrophic dynamics in inhabited villages and densely populated locations (Crosta et al., 2003; Cevasco et al., 2014). For other vulnerable landscapes where terrace rehabilitation costs cannot be assumed, afforestation with deep rooted tree species may facilitate root anchoring of abandoned terrace systems. Increased rainfall interception and evapotranspiration by tree cover development may further reduce the frequency and intensity of saturation phenomena in afforested terrace systems, whilst also helping to reduce landslide risk.

Beyond the environmental importance of traditional terraces in mountain and hilly Mediterranean landscapes, these ancient agricultural systems also provide priceless history, cultural legacy and collective memory over many generations for entire territories and societies (Grove and Rackham, 2003; Brandolini et al., 2008; Lasanta et al., 2013; Tarolli et al., 2014). Preserving traditional terrace systems, therefore, deserves particular land planning and governance attention. Land-use forecast analysis for the next 20-30 yr indicates that rural abandonment will continue affecting extensive areas of hilly and mountain zones in northern-shore regions of the Mediterranean basin, including the Pyrenees, Massif Central, Alps, Apennines and the Carpathians (Keenleyside and Tucker, 2010). Although diminishing the effects of rural desertion on the maintenance of traditional terraces can be largely unfeasible in most cases, positive appraisal of the productive, cultural, environmental and aesthetic functions of these traditional agricultural landscapes may facilitate their conservation (Lasanta et al., 2013).

Global awareness of the cultural and environmental importance of traditional terraced landscapes has increased since the early 1990s, when UNESCO recognized the historic, socio-cultural and agronomic World Heritage value of the mountain rice terraces of Ifugao, in the Philippine Cordilleras. Since then, several traditional terraced landscapes have been declared World Heritage sites in Mediterranean countries, including the Cinque Terre and Amalfi coasts (1997) of Italy, Ouadi Qadishe (1998) in Lebanon, the Alto Douro wine region (2001) in Portugal, Cévennes (2011) in France, the Serra de Tramuntana (2011) in Spain, and Battir (2014) in the Palestinian Autonomous Areas. In EU-member Mediterranean countries, agricultural terraces can also benefit from the EU's harmonizing agricultural and rural development policies, which directly or indirectly recognise the environmental and socio-economic values of these traditional landscapes. For example, the Common Agricultural Policy (CAP) sustained non-productive investments and actions that benefit terraced landscapes within the so-called Less Favoured Areas until 2014 and, more recently, under the "steep gradient" (>15% slope) demarcation criteria in support of agricultural production for Areas Facing Natural Constraints. In addition, agricultural terraced landscapes are included as eligible preservation elements within the greening measures (i.e., Ecological Focus Areas) of the present (2014-2020) Rural Development Plan for some EU-member Mediterranean states (Italy, Bulgaria and Romania). However, the high land-property fragmentation that characterizes terraced landscapes in the Mediterranean region (in most cases failing to reach the minimum 2-3 ha limit imposed by the CAP eligibility criteria) and the large morphological landscape diversity of these agricultural structures (also common in <15% gradient terrain) strongly limit the impact of these large-scale EU harmonizing policies on the maintenance of traditional terrace systems (Asins-Velis et al., 2016).

Effective protection of traditional agricultural terraces requires creative management of the delicate socio-economic and environmental aspects that govern the complex relationships between landscape, tourism, agriculture and rural development. Bottom-up local action programmes involving collective field-based terrace maintenance activities in visible and easily accessible areas have shown positive results in building the self-confidence of sceptical local actors and reconnecting young participants with traditional terrace-building knowledge (Zoumides et al., 2017). Similarly, the implementation of public terrace-adoption initiatives, based on the establishment of free temporal loans for people interested in reusing abandoned landscapes for leisure and food production, has shown positive returns in revitalizing traditional terrace systems in peri-urban mountain landscapes that still remain significantly populated (Varotto and Lodatti, 2014). The success of these initiatives requires provision in the long run of socio-economic and environmental gains for the local communities. Differentiation of local products based on traditional production in small-scale commercial agriculture, close collaboration with the agro-tourism industry and promotion of environmental education or green-care leisure activities may contribute to creating long-term benefits for conservation initiatives in traditional terraced landscapes of the Mediterranean region (Tarolli et al., 2014; Paliaga et al., 2016; Zoumides et al., 2017).

## 6. Final remarks and conclusions

Extensive literature review and meta-analysis of observational, experimental and modelling studies published during the last four decades provides in this article critical information on the hydro-geomorphological behaviour, key controlling factors and environmental patterns of landscape stability of abandoned agricultural terraces in the Mediterranean region:

(i) Traditional terraces reduce hillslope gradient and length, contributing to an increase in infiltration rates and a reduction of runoff production and surface flow velocity at the local scale. Once these traditional systems are abandoned, their hydrological behaviour can change in relation to the crusting of bare surfaces — particularly on marly soils and/or recently abandoned systems — and the development of vegetation cover and soil organic matter pools.

(ii) Terraced systems break up the spatial continuity of both surface and subsurface water flows, reducing hillslope-channel flow connections. After the abandonment of these traditional systems, progressive collapse of terraced structures (i.e., walls, risers, channels) contributes to reinstating large-scale flow connections, which may increase peak-flow discharge in catchment streams. Long-term development of forest cover attenuates the effects of terrace collapse on large-scale flow connections and flooding, by increasing rainfall interception and evapotranspiration.

(iii) After the cessation of active maintenance, agricultural terraces may lose to a variable extent their soil-conservation functions. Analysis of available erosion data revealed that abandoned terraces can develop intense soil loss in a variety of forms: active surface wash, gullying, mass movements and piping. Dense colonization by vegetation in these abandoned systems was shown to be of major importance for controlling surface erosion, which typically showed a more intense activity on fine-grained sedimentary lithology (e.g., marls, clays, mudstones). In arid and semi-arid abandoned terraces with difficulties for vegetation development, surface armouring by rock fragment cover may play a significant role in reducing surface erosion.

(iv) The most common hazard affecting the stability of old abandoned terraces is the activity of mass movements, generally taking place in the form of simple falls of dry-stone walls, small soil slips and shallow landslides. In many cases, the ability of vegetation to prevent the risk of terrace degradation by mass movements was limited. Terrace backfill soil saturation after long and/or intense rainfall (principally in hillslope concavities and valley bottom positions showing concentration of surface and subsurface flows), hillslope gradient and terrace height facilitate the action of mass movements in abandoned terraces. In the most extreme cases, these phenomena took the form of devastating debris slips and cascading landslides triggered by extreme rainfall in humid abandoned terrace landscapes characterized by steep hillslope gradients and high terrace walls.

(v) Convergence of climate limitations for vegetation development in semi-arid areas with the presence of unfavourable marl lithology can result in sharp geomorphic readjustments of agricultural terraces, typically in the form of intense surface wash erosion, gully development and piping. As reflected by the distribution of sites identified in our review and meta-analysis, these phenomena have inspired intensive geomorphological research during recent decades in the southeastern regions of Spain, where local semi-arid conditions overlap with extensive areas of (chiefly marine-sourced) marl lithology. In these systems, the collapse of pipes and tunnels formed by subsurface erosion can lead to the development of deep gully incisions accompanied by very intense soil loss and chaotic dismantling of terrace morphology. The presence of high hydraulic gradients between terraces and particular physico-chemical characteristics of the soil materials (e.g., high salinity and exchangeable sodium contents, abundance of fines, lack of soil structure, presence of swelling clays) are recognised as the main factors controlling the activity of aggressive piping in these terraced landscapes.

In summary, our review and meta-analysis reflected a wide variety of factors (for example, climate aridity, local lithology/soil properties, terrace characteristics and the action of extreme rainfall events) that play a significant role determining the hydro-geomorphological behaviour and long-term stability of abandoned terrace systems in the Mediterranean region. A variety of management options can be targeted to these landscapes, depending on vegetation development potential, site hydro-geomorphic vulnerability and local socio-economic interests. Non-intervention, allowing natural rewilding of abandoned systems, can favour the stabilization of unmaintained agricultural terraces in low to moderately steep landscapes under humid and subhumid climate conditions, as well as in semi-arid environments with favourable metamorphic and limestone lithology. More active management, including reforestation, restoration of stone walls or the rehabilitation of drainage structures, is required to control erosion activity in arid and semi-arid areas with unfavourable marl lithology or in high-gradient, humid landscapes susceptible to the formation of large-scale terrace-cascading landslides. The high cost of these measures, however, greatly limits the feasibility of terrace rehabilitation and mitigation actions. Future creative conservation approaches recognizing the complex aspects that rule the relationships between landscape, tourism, agriculture and rural development will be required to preserve the environmental, socio-cultural and historical values represented by traditional terraces in the Mediterranean region.

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## References

Agnoletti, M., Cargnello, G., Gardin, L., Santoro, A., Bazzoffi, P., Sansone, L., Pezza, L., Belfiore, N., 2011. Traditional landscape and rural development: comparative study in three terraced areas in northern, central and southern Italy to evaluate the efficacy of GAEC standard 4.4 of cross compliance. Italian Journal of Agronomy 6 (s1:e16), 121-138.

Al Qudah, K., Abdelal, Q., Hamarneh, C., Abu-Jaber, N., 2016. Taming the torrents: the hydrological impacts of ancient terracing practices in Jordan. Journal of Hydrology 542, 913–922.

Alatorre, L.C., Beguería, S., Lana-Renault, N., Navas, A., García-Ruiz, J.M., 2012. Soil erosion and sediment delivery in a mountain catchment under scenarios of land use change using a spatially distributed numerical model. Hydrology and Earth System Sciences 16, 1321-1334.

Arnáez, J., Lasanta, T., Errea, M., P., Ortigosa, L., 2011. Land abandonment, landscape evolution, and soil erosion in a Spanish Mediterranean mountain region: the case of Camero Viejo. Land Degradation and Development 22, 537–550.

Arnáez, J., Lana-Renault, N., Lasanta, T., Ruiz-Flaño, P., Castroviejo, J., 2015. Effects of farming terraces on hydrological and geomorphological processes. A review. Catena 128, 122-134.

Arnáez, J., Lana-Renault, N., Ruiz-Flaño, P., Pascual, N., Lasanta, T., 2017. Mass soil movement on terraced landscapes of the Mediterranean mountain areas: a case study in the Iberian Range. Cuadernos de Investigación Geográfica 43, 83-100.

Asins-Velis, S., Arnau-Rosalén, E., Romero-González, J., Calvo-Cases, A., 2016. Analysis of the consequences of the European Union criteria on slope gradient for the delimitation of “Areas Facing Natural Constraints” with agricultural terraces. Annales, Series Historia et Sociologia 26, 433-448.

Bazzoffi, P., Gardin, L., 2011. Effectiveness of the GAEC standard of cross compliance retain terraces on soil erosion control. Italian Journal of Agronomy 6 (s1:e6), 43-51.

Barrow, C.J., Hicham, H., 2000. Two complementary and integrated land uses of the western High Atlas Mountains, Morocco: the potential for sustainable rural development. Applied Geography 22, 369-394.

Bellin, N., van Wesemael, B., Meerkerk, A., Vanacker, V., Barbera, G.G., 2009. Abandonment of soil and water conservation structures in Mediterranean ecosystems. A case study from south east Spain. Catena 76, 114–121.

Bevan, A., Conolly, J., 2011. Terraced fields and Mediterranean landscape structure: an analytical case study from Antikythera, Greece. Ecological Modeling 222, 1303–1314.

Bevan, A., Frederick, C., Krahtopoulou, A., 2003. A Digital Mediterranean Countryside: GIS approaches to the spatial structure of the post-medieval landscape on Kythera (Greece). Archeologia e Calcolatori 14, 217-236.

Brandolini, P., Faccini, F., Pescetto, C., 2008. I paesaggi terrazzati d'Italia. I terrazzamenti della Liguria: un bene culturale e del paesaggio a rischio. L'Universo 88(2), 206-221 (in Italian).

Brandolini, P., Cevasco, A., Capolongo, D., Pepe, G., Lovergine, F., del Monte, M., 2018. Response of terraced slopes to a very intense rainfall event and relationships with land abandonment: a case study from Cinque Terre (Italy). Land Degradation and Development 29, 630-642.

Calsamiglia, A., Fortesa, J., García-Comendador, J., Estrany, J., 2016. Respuesta hidro-sedimentaria en dos cuencas mediterráneas representativas afectadas por el cambio global. Cuaternario y Geomorfología 30, 87-103 (in Spanish).

Calsamiglia, A., Fortesa, J., García-Comendador, J., Lucas-Borja, M.E., Calvo-Cases, A., J., Estrany, J., 2018. Spatial patterns of sediment connectivity in terraced lands:

anthropogenic controls of catchment sensitivity. Land Degradation and Development 29, 1198-1210.

Calvo-Cases, A., Boix-Fayos, C., Arnau-Rosalen, E., Roxo, M.J., 2011. Cárcavas y regueros generados en suelos sódicos. Petrer (Alicante, España). Cuadernos de Investigación Geográfica 37, 25-40 (in Spanish).

Cammeraat, L.H., 2004. Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in southeast Spain. Agriculture, Ecosystems and Environment 104, 317–332.

Cammeraat, E., van Beek, R., Kooijman, A., 2005. Vegetation succession and its consequences for slope stability in SE Spain. Plant and Soil 278, 135–147.

Cerdà, A., 1994. Arroyada superficial en terrazas de cultivo abandonadas. El caso del País Valenciano. Cuadernos de Geografía 56, 136-154 (in Spanish).

Cevasco, A., Brandolini, P., Scopesi, C., Rellini, I., 2013. Relationships between geo-hydrological processes induced by heavy rainfall and land-use: the case of 25 October 2011 in the Vernazza catchment (Cinque Terre, NW Italy). Journal of Maps 9, 289-298.

Cevasco, A., Pepe, G., Brandolini, P., 2014. The influences of geological and land use settings on shallow landslides triggered by an intense rainfall event in a coastal terraced environment. Bulletin of Engineering Geology and the Environment 73, 859–875.

Cots-Folch, R., Martínez-Casasnovas, J.A., Ramos, M.C., 2006. Land terracing for new vineyard plantations in the north-eastern Spanish Mediterranean region: landscape effects of the EU Council Regulation policy for vineyards' restructuring. Agriculture, Ecosystems and Environment 115, 88–96.

Crosta, G.B., Dal Negro, P., Frattini, P., 2003. Soil slips and debris flows on terraced slopes. Natural Hazards and Earth System Sciences 3, 31-42.

Cyffka, B., Bock, M., 2008. Degradation of field terraces in the Maltese Islands – reason, processes and effects. Geografia Fisica e Dinamica Quaternaria 31, 119-128.

Debussche, M., Lepart, J., Dervieux, A., 1999. Mediterranean landscape changes: evidence from old postcards. Global Ecology and Biogeography 8, 3–15.

Faulkner, H., 2013. Badlands in marl lithologies: a field guide to soil dispersion, subsurface erosion and piping-origin gullies. Catena 106, 42-53.

Faulkner, H., 2018. The role of piping in the development of badlands. In: Nadal-Romero, E., Martínez-Murillo, J.F., Kuhn, N.J. (Eds.), Badlands Dynamics in the Context of Global Change. Elsevier, Amsterdam, pp. 191-216.

Faulkner, H., Ruiz, J., Zukowskyj, P., Downward, S., 2003. Erosion risk associated with rapid and extensive agricultural clearances on dispersive materials in southeast Spain. Environmental Science and Policy 6, 115-127.

Ferre, E., Asensi, M., Senciales, J.M., 1994. Procesos de erosión y dinámica de la vegetación en bancales abandonados en el valle del Andarax. In: García-Ruiz, J.M., Lasanta-Martínez, T. (Eds.), Efectos Geomorfológicos del Abandono de Tierras. Sociedad Española de Geomorfología, Zaragoza, pp. 31-42 (in Spanish).

Francis, C., 1990. Soil erosion and organic matter losses on fallow land: a case study from south-east Spain. In: Boardman, J., Foster, I.D.I., Dearing, J.A. (Eds.), Soil Erosion on Agricultural Land. John Wiley and Sons, Ltd., Chichester, pp. 331-338.

Francis, C.F., Thornes, J.B., 1990. Runoff hydrographs from three Mediterranean vegetation cover types. In: Thornes, J.B. (Ed.), Vegetation and Erosion: Processes and Environments. John Wiley and Sons Ltd., Chichester, pp. 363-384.

Gadot, Y., 2015. In the valley of the King: Jerusalem's rural hinterland in the 8th–4th centuries BCE. Journal of the Institute of Archeology of Tel Aviv University 42, 3–26.

Gallart, F., 2009. Algunos criterios topográficos para identificar el origen antrópico de cárcavas. Cuadernos de Investigación Geográfica 35, 215-221 (in Spanish).

Gallart, F., Clotet-Perarnau, N., 1988. Some aspects of the geomorphic processes triggered by an extreme rainfall event: the November 1982 flood in the eastern Pyrenees. Catena Supplement 13, 79-95.

Gallart, F., Llorens, P., Latron, J., 1994. Studying the role of old agricultural terraces on runoff generation in a small Mediterranean mountainous basin. Journal of Hydrology 159, 291–303.

Gallart, F., Llorens, P., Latron, J., Regüés, D., 2002. Hydrological processes and their seasonal controls in a small Mediterranean mountain catchment in the Pyrenees. Hydrology and Earth System Sciences 6, 527–537.

García-Estringana, P., Latron, J., Llorens, P, Gallart, F., 2013. Spatial and temporal dynamics of soil moisture in a Mediterranean mountain area (Vallcebre, NE Spain). Ecohydrology 6, 741-753.

García-Ruiz, J.M., Lana-Renault, N., 2011. Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region. A review. Agriculture, Ecosystems and Environment 140, 317–338.

García-Ruiz, J.M., Lasanta, T., Sobrón, I., 1988. Problemas de evolución geomorfológica en campos abandonados: El valle del Jubera (Sistema Ibérico). Zubía 6, 99-114 (in Spanish).

García-Ruiz, J.M., Nadal-Romero, E., Lana-Renault, N., Beguería, S., 2013. Erosion in Mediterranean landscapes: changes and future challenges. Geomorphology 198, 20-36.

Gimeno-García, E., Andreu, V., Rubio, J.L., 2007. Influence of vegetation recovery on water erosion at short and medium-term after experimental fires in a Mediterranean shrubland. Catena 69, 150-160.

Grove, A.T., Rackham, O., 2003. The Nature of Mediterranean Europe: An Ecological History. Yale University Press, New Haven.

Hammad, A., Børresen, T., Haugen, L.E., 2006. Effects of rain characteristics and terracing on runoff and erosion under the Mediterranean. Soil and Tillage Research 87, 39–47.

Heusch, B., 1986. Cinquante ans de banquettes de DRS – CES en Afrique du Nord: un bilan. Cahiers ORSTOM Série Pédologie 22, 153–162 (in French).

Hooke, J., Sandercock, P., 2012. Use of vegetation to combat desertification and land degradation: recommendations and guidelines for spatial strategies in Mediterranean lands. Landscape and Urban Planning 107, 389-400.

Hooke, J., Sandercock, P., Cammeraat, L.H., Lesschen, J.P., Borselli, L., Torri, D., Meerkerk, A., van Wesemael, B., Marchamalo, M., Barbera, G., Boix-Fayos, C., Castillo, V., Navarro-Cano, J.A., 2017. Mechanisms of degradation and identification of connectivity and erosion hotspots. In: Hooke, J., Sandercock, P. (Eds.), Combating Desertification and Land Degradation: Spatial Strategies Using Vegetation. Springer, Cham, pp. 13-37.

Inbar, M., Zgaier, A., 2016. Physical and social aspects of land degradation in Mediterranean highland terraces: a geodiversity approach. Annales, Series Historia et Sociologia 26, 419-431.

Jiménez-Olivencia, Y., 1990. Cambios medioambientales que suceden al abandono de los campos de cultivo en terrazas: la Acequia de Cachariche. Cuadernos Geográficos de la Universidad de Granada 18-19, 5-46 (in Spanish).

Keenleyside, C., Tucker, G., 2010. Farmland Abandonment in the EU: an Assessment of Trends and Prospects. Institute for European Environmental Policy, London.

Kizos, T., Koulouri, M., 2006. Agricultural landscape dynamics in the Mediterranean: Lesvos (Greece) case study using evidence from the last three centuries. Environmental Science and Policy 9, 330-342.

Koulouri, M., Giourga, C., 2007. Land abandonment and slope gradient as key factors of soil erosion in Mediterranean terraced lands. Catena 69, 274–281.

Lana-Renault, N., Regüés, D., Serrano, P., Latron, J., 2014. Spatial and temporal variability of groundwater dynamics in a sub-Mediterranean mountain catchment. Hydrological Processes 28, 3288-3299.

Lana-Renault, N., López-Vicente, M., Nadal-Romero, E., Ojanguren, R., Llorente, J.A., Errea, P., Regüés, D., Ruiz-Flaño, P., Khorchant, M., Arnáez, J., Pascual, N., 2018. Catchment based hydrology under post farmland abandonment scenarios. Cuadernos de Investigación Geográfica 44, 503-534.

Lasanta, T., Arnáez, J., Oserín, M., Ortigosa, Luis, M., 2001. Marginal lands and erosion in terraced fields in the Mediterranean mountains. A case study in the Camero Viejo (Northwestern Iberian System, Spain). Mountain Research and Development 21, 69–76.

Lasanta, T., Arnáez, J., Ruiz-Flaño, P., Lana-Renault, N., 2013. Agricultural terraces in the Spanish mountains: an abandoned landscape and a potential resource. Boletín de la Asociación de Geógrafos Españoles 63, 487-491.

Lasanta, T., Nadal-Romero, E., Errea, M.P., 2017a. The footprint of marginal agriculture in the Mediterranean mountain landscape: an analysis of the Central Spanish Pyrenees. Science of the Total Environment 599-600, 1823-1836.

Lasanta, T., Arnáez, J., Pascual, N., Ruiz-Flaño, P., Errea, P., Lana-Renault, N., 2017b. Space-time process and drivers of land abandonment in Europe. Catena 149, 810-823.

Lasanta, T., Khorchani, M., Pérez-Cabello, F., Errea, P., Sáenz-Blanco, R., Nadal-Romero, E., 2018. Clearing shrubland and extensive livestock farming: active prevention to control wildfires in the Mediterranean mountains. Journal of Environmental Management 227, 256-266.

Latron, J., Gallart, F., 2007. Seasonal dynamics of runoff-contributing areas in a small Mediterranean research catchment (Vallcebre, Eastern Pyrenees). Journal of Hydrology 335, 194-206.

Latron, J., Gallart, F., 2008. Runoff generation processes in a small Mediterranean research catchment (Vallcebre, Eastern Pyrenees). Journal of Hydrology 358, 206-220.

Lehmann, R., 1993. Terrace degradation and soil erosion on Naxos Island, Greece. In: Wicherek, S. (Ed.), Farm Land Erosion in Temperate Plains Environments and Hills. Elsevier Science, Amsterdam, pp. 429-450.

Lesschen, J.P., Kok, K., Verburg, P.H., Cammeraat, L.H., 2007. Identification of vulnerable areas for gully erosion under different scenarios of land abandonment in southeast Spain. Catena 71, 110-121.

Lesschen, J. P., Cammeraat, L.H., Nieman, T., 2008. Erosion and terrace failure due to agricultural land abandonment in a semi-arid environment. Earth Surface Processes and Landforms 33, 1574–1584.

Lesschen, J.P., Schoorl, J.M., Cammeraat, L.H., 2009. Modelling runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity. Geomorphology 109, 174–183.

Llorens, P., Latron, J., Gallart, F., 1992. Analysis of the role of agricultural abandoned terraces on the hydrology and sediment dynamics in a small mountainous basin. Pirineos 139, 27–46.

Llorens, P., Queralt, I., Plana, F., Gallart, F., 1997a. Studying solute and particulate sediment transfer in a small Mediterranean mountainous catchment subject to land abandonment. Earth Surface Processes and Landforms 22, 1027-1035.

Llorens, P., Poch, R., Latron, Gallart, F., 1997b. Rainfall interception by a *Pinus sylvestris* forest patch overgrown in a Mediterranean mountainous abandoned area. I. Monitoring design and results down to the event scale. Journal of Hydrology 199, 331-345.

Llorens, P., Gallart, F., Cayuela, C., Roig-Planasdemunt, M., Casellas, E., Molina, A.J., Moreno-de-las-Heras, M., Bertran, G., Sánchez-Costa, E., Latron, J., 2018. What have we learnt about Mediterranean catchment hydrology? 30 years observing hydrological processes in the Vallcebre research catchments. Cuadernos de Investigación Geográfica 44, 475-501.

Lodatti, L., 2012. Paesaggi Terrazzati tra Eredità Storica e Innovazione: il Caso del Canale di Brenta. PhD Thesis. Università degli Studi di Padova, Padua, Italy (in Italian).

López-Bermúdez, F., Torcal-Sáinz, L., 1986. Procesos de erosión en tunel (piping) en cuencas sedimentarias de Murcia. Estudio preliminar mediante difracción de rayos x y microscopio electrónico de barrido. Papeles de Geografía Física 11, 7-20 (in Spanish).

López-Bermúdez, F., Romero-Díaz, M.A., 1989. Piping erosion and badland development in south-east Spain. Catena Supplement 14, 59-73.

López-Vicente, M., Poesen, J., Navas, A., Gaspar, L., 2013. Predicting runoff and sediment connectivity and soil erosion by water for different land use scenarios in the Spanish Pre-Pyrenees. Catena 102, 62-73.

López-Vicente, M., Nadal-Romero, E., Cammeraat, E.L.H., 2017. Hydrological connectivity does change over 70 years of abandonment and afforestation in the Spanish Pyrenees. Land Degradation and Development 28, 1298-1310.

Lourenço, L., Nunes, A.N., Bento-Gonçalves, A., Vieira, A., 2014. Environmental concerns of Portuguese Mountains: a case study in the central mountains. In: Bento-Gonçalves, A.J., Vieira, A.A.B. (Eds.), Mountains: Geology, Topography and Environmental Concerns. Nova Science Publishers, New York, pp. 195-211.

Marco-Molina, M., Morales-Gil, A., 1995. Terrazas de cultivo abandonadas en el sureste peninsular: aspectos evolutivos. Investigaciones Geográficas 13, 81-90 (in Spanish).

Marco-Molina, M., Olcina Cantos, J.A., Padilla Blanco, J., Rico Amorós, A., 1996. Abandono de terrazas de cultivo: reconilización vegetal y erosión en el sureste peninsular. In: Grandal d’Anglade, A., Pagés Valcarlos, J. (Eds.), Libro de Ponencias de la IV Reunión Nacional de Geomorfología. Sociedad Española de Geomorfología, O Castro, pp. 133-146 (in Spanish).

Mariani, L., Parisi, S.G., 2014. Extreme rainfalls in the Mediterranean area. In: Diodato, N., Bellocchi, G. (Eds.), Storminess and Environmental Change, Climate Forcing and Responses in the Mediterranean Region. Springer, Dordrecht, pp. 17-37.

Martínez-Hernández, C., Rodrigo-Comino, J., Romero-Díaz, A., 2017. Impact of lithology and soil properties on abandoned dryland terraces during the early stages of soil erosion by water in south-east Spain. Hydrological Processes 31, 3095-3109.

Martínez-Casasnovas, J.A., Sánchez-Bosch, I., 2000. Impact assessment of changes in land use/conservation practices on soil erosion in the Penedès-Anoia vineyard region (NE Spain). Soil and Tillage Research 57, 101-106.

Meerkerk, A.L., van Wesemael, B., Bellin, N., 2009. Application of connectivity theory to model the impact of terrace failure on runoff in semi-arid catchments. Hydrological Processes 23, 2792–2803.

Modica, G., Praticò, S., di Fazio, S., 2017. Abandonment of traditional terraced landscape: a change detection approach (a case study in Costa Viola, Calabria, Italy). Land Degradation and Development 28, 2608-2622.

Molina, A.J., Latron, J., Rubio, C.M., Gallart, F., Llorens, P., 2014. Spatio-temporal variability of soil water content on the local scale in a Mediterranean mountain area (Vallcebre, North Eastern Spain). How different spatio-temporal scales reflect mean soil water content. Journal of Hydrology 516, 182-192.

Montanari, B., 2013. The future of agriculture in the High Atlas Mountains of Morocco: the need to integrate traditional ecological knowledge. In: Mann, S. (Ed.), The Future of mountain agriculture. Springer Geography, Berlin, pp. 51-72.

Morel, A., 2006. Réflexions sur les stratégies traditionnelles de gestión conservatoire de l’eau pratiquées en Ardèche depuis le XIXe siècle. In: Rose, E., Albergel, J., de Noni, G., Laouina, A., Sabir, M. (Eds.), Efficacité de la Gestión de l’Eau et de la Fertilité des Sols en Milieux Semi-arides. Éditions des Archives Contemporaines. Agence Universitaire de la Francophonie, Paris, pp. 93 – 97 (in French).

Moreno-de-las-Heras, M., Merino-Martín, L., Nicolau, J.M., 2009. Effect of vegetation cover on the hydrology of reclaimed mining soils under Mediterranean-continental climate. Catena 77, 39-47.

Moreno-de-las-Heras, M., Gallart, F., 2018. The origin of badlands. In: Nadal-Romero, E., Martínez-Murillo, J.F., Kuhn, N.J. (Eds.), Badlands Dynamics in the Context of Global Change. Elsevier, Amsterdam, pp. 27-59.

Nadal-Romero, E., Cammeraat, E., Serrano-Muela, M.P., Lana-Renault, N., Regüés, N., 2016. Hydrological response of an afforested catchment in a Mediterranean humid mountain area: a comparative study with a natural forest. Hydrological Processes 30, 2717-2733.

Nasri, S., Lamachère, J.M., Albergel, J., 2004. Impact des banquettes sur le ruissellement d’un petit bassin versant. Revue des Sciences de l'Eau 17, 265–289 (in French).

Newson, P., Barker, G., Daly, P., Mattingly, D., Gilbertson, D., 2007. The wadi Faynan field systems. In: Barker, G., Gilbertson, D., Mattingly, D. (Eds.), Archaeology and Desertification: The Wadi Faynan Landscape Survey, Southern Jordan. Oxbow Books, Oxford, pp. 141–174.

Nunes, J.P., Bernard-Jannin, L., Rodríguez-Blanco, M.L., Santos, J.M., Alves-Coelho, C.O., Keizer, J.J., 2016. Hydrological and erosional processes in terraced fields:

observations from a humid Mediterranean region in northern Portugal. Land Degradation and Development 29, 596-606.

Ore, G., Bruins, H.J., 2012. Design features of ancient agricultural terrace walls in the Negev desert: human-made geodiversity. Land Degradation and Development 23, 409-418.

Paliaga, G., Giostrella, P., Faccini, F., 2016. Terraced landscape as cultural and environmental heritage at risk: an example from Portofino Park (Italy). Annales, Series Historia et Sociologia 26, 513-522.

Pallarès-Bou, J., Calvo-Cases, A., 1994. Variación espacial de la morfología de muros de bancales en tramos próximos a roturas. In: García-Ruiz, J.M., Lasanta, T. (Eds.), Efectos Geomorfológicos del Abandono de Tierras. Sociedad Española de Geomorfología, Zaragoza, pp. 135-148 (in Spanish).

Pardini, G., Gispert, M., 2012. Soil quality assessment through a multi-approach analysis in soils of abandoned terrace land in Spain. Cuadernos de Investigación Geográfica 38, 7-30.

Pardini, G., Gispert, M., Emran, M., Doni, S., 2017. Rainfall/runoff/erosion relationships and soil properties survey in abandoned shallow soils of NE Spain. Soils Sediments 17, 499–514.

Perlotto, C., D’Agostino, V., 2016. Performance assessment of bench-terraces through 2-D Modelling. Land Degradation and Development 29, 607-616.

Petanidou, T., Kizos, T., Soulakellis, N., 2008. Socioeconomic dimensions of changes in the agricultural landscape of the Mediterranean basin: a case study of the abandonment of cultivation terraces on Nisyros Island, Greece. Environmental Management 41, 250-266.

Petit, C., Konold, W., Höchtl, F., 2012. Historic terraced vineyards: impressive witnesses of vernacular architecture. Landscape History 33, 5–28.

Preti, F., Guastini, E., Penna, D., Dani, A., Cassiani, G., Boagga, J., Deiana, R., Romano, N., Nasta, P., Palladino, M., Errico, A., Giambastiani, Y., Trucchi, P., Tarolli, P., 2017. Conceptualization of water flow pathways in agricultural terraced landscapes. Land Degradation and Development, doi:10.10002/ldr.2764

Preti, F., Errico, A., Caruso, M., Dani, A., Guastini, E., 2018. Dry-stone wall terrace monitoring and modelling. Land Degradation and Development 29, 1806-1818.

Ramos, M.C., Martínez-Casasnovas, J.A., 2007. Soil loss and soil water content affected by land levelling in Penedès vineyards, NE Spain. Catena 71, 210–217.

Ries, J.B., 2010. Methodologies for soil erosion and land degradation assessment in Mediterranean-type ecosystems. Land Degradation and Development 21, 171-187.

Robledano-Aymerich, F., Romero-Díaz, A., Belmonte-Serrato, F., Zapata-Pérez, V.M., Martínez-Hernández C., Martínez-López, V., 2014. Ecogeomorphological consequences of land abandonment in semiarid Mediterranean areas: integrated assessment of physical evolution and biodiversity. Agriculture, Ecosystems and Environment 197, 222–242.

Rodríguez-Aizpeolea, J., Pérez-Badia, R., Cerda-Bolinches, A., 1991. Colonización vegetal y producción de escorrentía en bancales abandonados: Vall de Gallinera, Alacant. Cuaternario y Geomorfología 5, 119-129 (in Spanish).

Rogger, M., Agnoletti, M., Alaoui, A., Bathurst, J.C., Bodner, G., Borga, M., Chaplot, V., Gallart, F., Glatzel, G., Hall, J., Holden, J., Holko, L., Horn, R., Kiss, A., Kohnová, S., Leitinger, G., Lennartz, B., Parajka, J., Perdigão, R., Peth, S., Plavcová, l., Quinton, J.N., Robinson, M., Salinas, J.L., Santoro, A., Szolgay, J., Tron, S., van den Akker, J.J.H., Viglione, A., Blöschl, G., 2017. Land use change impacts on floods at the catchment scale: challenges and opportunities for future research. Water Resources Research 53, 5209-5219.

Romero-Díaz, A., Marín-Sanleandro, P., Sánchez-Soriano, A., Belmonte-Serrano, F., Faulkner, H., 2007. The causes of piping in a set of abandoned agricultural terraces in southeast Spain. Catena 69, 282-293.

Romero-Díaz, A., Marín-Sanleandro, P., Sánchez-Soriano, A., 2009. Procesos de piping en la Región de Murcia (Sureste de España). Cuadernos de Investigación Geográfica 35, 87-117 (in Spanish).

Romero-Díaz, A., Alonso-Sarría, F., Sánchez-Soriano, A., 2011. Influencia de los factores topográficos en los procesos de piping. Cuadernos de Investigación Geográfica 37, 41-66 (in Spanish).

Romero-Díaz, A., Martínez-Hernández, C., Belmonte-Serrano, F., 2016. Procesos de erosión en áreas abandonadas de la Región de Murcia. In: Romero-Díaz, A. (Ed.), Abandono de Cultivos en la Región de Murcia, Consecuencias Ecogeomorfológicas. Servicios de Publicaciones de la Universidad de Murcia, Murcia, pp. 85-110 (in Spanish).

Romero-Díaz, A., Ruiz-Sinoga, J.D., Robledano-Aymerich, F., Brevik, E.C., Cerdà, A., 2017. Ecosystem responses to land abandonment in Western Mediterranean Mountains. Catena 149, 824–835.

Ruecker, G., Schad, P., Alcubilla, M.M., Ferrer, C., 1998. Natural regeneration of degraded soils and site changes on abandoned agricultural terraces in Mediterranean Spain. Land Degradation and Development 9, 179–188.

Sandor, J.A., 1998. Steps toward soil care: ancient agricultural terraces and soils. In: Sandor, J.A., Eash, N.S. (Eds.), Transactions of 16th International Congress of Soil Science. Montpellier, France.

Savo, V., Caneva, G., McClatchey, W., Reedy, D., Salvati, L., 2014. Combining environmental factors and agriculturalists' observations of environmental changes in the traditional terrace system of the Amalfi Coast (Southern Italy). Ambio 43, 297-310.

Seeger, M., Ries, J.B., 2008. Soil degradation and soil surface process intensities on abandoned fields in Mediterranean mountain environments. Land Degradation and Development 19, 488–501.

Solé-Benet, A., Lázaro, R., Domingo, F., Cantón, Y., Puigdefábregas, J., 2010. Why most agricultural terraces in steep slopes in semiarid SE Spain remain well preserved since their abandonment 50 years ago? Pirineos 165, 215-235.

Stanchi, S., Freppaz, M., Agnelli, A., Reinsch, T., Zanini, E., 2012. Properties, best management practices and conservation of terraced soils in Southern Europe (from Mediterranean areas to the Alps). A review. Quaternary International 265, 90-100.

Tarolli, P., Preti F., Romano, N., 2014. Terraced landscapes: from an old best practice to a potential hazard for soil degradation due to land abandonment. Anthropocene 6, 10-25.

Tarolli, P., Sofia, G., Calligaro, s., Prosdocimi, M., Preti, F., Dalla Fontana, G., 2015. Vineyards in terraced landscapes: new opportunities from LiDAR data. Land Degradation and Development 26, 92-102.

Thornes, J.B, Wainwright, J., 2003. Environmental Issues in the Mediterranean. Processes and Perspectives from the Past and the Present. Routledge, London.

Trabuco, A., Zomer, R.J., 2009. Global Aridity Index and PET Dataset. CGIAR Consortium for Spatial Information. Published online, available from the CGIAR-CSI Geoportal at www.cgiar-csi.org

Tricart, J., Cailleux, A., 1965. Introduction à la Gèomorphologie Climatique. Société d'Édition d'Enseignement Supérieur (SEDES), Paris (in French).

UNEP. 1992., World Atlas of Desertification. United Nations Environmental Program (UNEP), Edward Arnold, London.

Varotto, M., Lodatti, L., 2014. New family farmers for abandoned lands: the adoption of terraces in the Italian Alps (Brenta Valley). Mountain Research and Development 34, 315-325.

Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J., Smith, C.J., 2009. Tolerable versus actual soil erosion rates in Europe. Earth-Science Reviews 94, 23-38.

Vicente-Serrano, S.M., Lasanta, T., Cuadrat, J.M., 2000. Influencia de la ganadería en la evolución del riesgo de incendio en función de la vegetación en un área de montaña: el ejemplo del valle de Borau (Pirineo aragonés). Geographicalia 38, 31-54 (in Spanish).

Watts, G., 1991. The relationship between soil piping and changing farming techniques on semi-arid agricultural terraces. In: Nachtnebel, H.P., Kovar, K. (Eds.), Hydrological Basis of Ecologically Sound Management of Soil and Groundwater. International Association of Hydrological Sciences, Wallingford, pp. 81-89.

Zgaier, A., Inbar, M., 2005. The influence of soil saturation on the stability of abandoned agricultural hillslope terraces under Mediterranean climatic conditions. In: Garcia, C., Batalla, R.J. (Eds.), Catchment Dynamics and River Processes: Mediterranean and Other Climate Regions. Elsevier B.V., Amsterdam, pp. 69-86.

Zoumides, C., Bruggeman, A., Giannakis, E., Camera, C., Djuma, H., Eliades, M., Charalambous, K., 2017. Community-based rehabilitation of mountain terraces in Cyprus. Land Degradation and Development 28, 95-105.

Zurayk, R.A., 1994. Rehabilitating the ancient terraced lands of Lebanon. Journal of Soil and Water Conservation 49, 106-112.

## Figure captions

Figure 1. Active traditional cultivation terraces in the Mediterranean region: (a) Cinque Terre (Italy) protected denomination-of-origin terraced vineyards; (b) subsistence agricultural terraces in Amenzel (Marrakech Atlas, Morocco). Image authorship: (a) photo by Arsheffield; licensed under CC BY-NC 2.0; (b) photo courtesy of Jean Claude Latombe.

Figure 2. Contrasting hydro-geomorphological results of terrace abandonment in Mediterranean landscapes: dense colonization of (a) grass and (b) pine forest cover provides strong stabilization of abandoned terraces in (left) Cal Parisa and (right) Can Vila (Vallcebre catchments, Catalan Pyrenees, NE Spain); (c) progressive degradation of terrace risers by the effects of small soil slips and dry-stone wall collapses in Camero Viejo (Iberian Range, N Spain); (d) gully expansion by aggressive piping/tunnelling phenomena in abandoned terraces of the Rambla de Algeciras (Murcia, SE Spain). Image source/authorship: (a) F. Gallart, (b) M. Moreno-de-las-Heras, (c) photo courtesy of José Angel Llorente, (d) Moreno-de-las-Heras and Gallart (2018).

Figure 3. Distribution and general characteristics of the abandoned terrace sites that were included in this review and meta-analysis study: (a) distribution of the sites and their corresponding climate conditions (aridity, Ai, expressed as the ratio of mean annual precipitation, MAP, to potential evapotranspiration, PET; UNEP, 1992) throughout the Mediterranean region; (b) vegetation cover; (c) hillslope gradient; (d) lithology; (e) terrace wall structure; (f) subjects of research covered in the sites; and (g) applied research approaches. A detailed list containing the name, location and general characteristics of the sites, the references for their corresponding original studies and the

applied research topics can be found in Supplementary Appendix A. Ai, MAP and PET in (a) follow the CGIAR-CSI Global aridity and PET database (Trabucco and Zomer, 2009).

Figure 4. Hydrological consequences of terrace abandonment: (a) key factors controlling local-scale runoff and infiltration dynamics; (b) the inner part of a terrace bed becomes saturated after the incidence of prolonged rainfall in a humid, abandoned landscape (Cal Rodó, Vallcebre catchments, Catalan Pyrenees, NE Spain); (c) key factors controlling wider-scale (catchment/landscape) hydrological connectivity; (d) channel clogging and overflow induces the recuperation of natural surface-flow patterns during a high-peak flood in an abandoned terraced landscape (Can Vila, Vallcebre catchments, Catalan Pyrenees, NE Spain). The size of the bars in (c) indicates the relative frequency of citation (% of sites) of the identified key factors in the bibliographic references of the terrace sites explored in this study. Bar and arrow colours indicate the direction of the hydrological impact (green, positive; red, negative) for the key factors. Image authorship: (b) J. Latron, (d) F. Gallart.

Figure 5. Geomorphological consequences of terrace abandonment: rates of soil loss in abandoned terrace systems of the Mediterranean region. Dominant erosion form and scale of analysis are indicated in the graph using different colours and symbol shapes, respectively. Code values between brackets indicate time after abandonment. Soil-loss estimation approach is indicated with asterisks at the bottom of the graph. For comparison, a boundary of sustainable erosion limits is displayed in the graph (grey area), according to the natural rates of soil formation for the European region (Veheijen et al., 2009).

Figure 6. Surface wash erosion and gullying: (a) key factors controlling the dynamics of surface wash erosion; (b) key factors controlling gullying dynamics; (c) gully incision on terrace risers destabilized by the effects of soil slips and wall collapses in an abandoned, dry-subhumid landscape (Estanque de Arriba, Ebro basin, NE Spain); (d) dense grass colonization of wall collapses prevents gully incision in abandoned terraces of a humid landscape (Can Vila, Vallcebre catchments, Catalan Pyrenees, NE Spain). The size of the bars in (c) indicates the relative frequency of citation (% of sites) of the identified key factors in the bibliographic references of the terrace sites explored in this study. Bar and arrow colours indicate the direction of the geomorphological impact (green, positive; red, negative) for the key factors. Image authorship: (c) photo courtesy of Manuel López-Vicente, (d) F. Lindenberger.

Figure 7. Mass movements: (a) small soil slip affecting the wall of an abandoned terrace (Camero Viejo, Iberian Range, N Spain); (b) terrace-cascading landslide triggered by extreme rainfall (the 25 October 2011 event) in abandoned terraces of the Vernazza basin (Cinque Terre, Liguria, Italy); (c) key factors controlling the activity of mass movements in abandoned terraced landscapes. The size of the bars in (c) indicates the relative frequency of citation (% of sites) of the identified key factors in the bibliographic references of the terrace sites explored in this study. Bar and arrow colours indicate the direction of the geomorphological impact (green, positive; red, negative) for the key factors. Image authorship: (a) N. Lana-Renault, (b) photo courtesy of Ruth Manfredi (Save Vernazza ONLUS).

Figure 8. Subsurface erosion dynamics: (a) gully systems and large surface collapses developed by aggressive piping/tunnelling in abandoned terraces of Corvera-Brianes (Region of Murcia, SE Spain); (b) key factors controlling aggressive piping dynamics; (c) detail of an 8–m-deep gully developed by tunnel expansion and collapse in piping-prone abandoned agricultural terraces of Campos del Río (Region of Murcia, SE Spain). The size of the bars in (c) indicates the relative frequency of citation (% of sites) of the identified key factors in the bibliographic references of the terrace sites explored in this study. Bar and arrow colours indicate the direction of the geomorphological impact (green, positive; red, negative) for the key factors. Image source: (a) Romero-Díaz et al. (2009), (b) Romero-Díaz et al. (2007).

Figure 9. Environmental patterns of terrace stability: relative frequency distribution (% of sites) of stable (non-erosive), unstable (erosive) and inconclusive abandoned terrace behaviour as a function of climate type, vegetation cover, local lithology and hillslope gradient. Stable terrace behaviour (displayed in green within the classification bars) refers to identified terraced landscapes in our data base that were described in the reviewed bibliography as showing no (or negligible) erosion activity. Unstable, erosive behaviour (in red) applies to reviewed landscapes that were reported in the literature to have suffered significant terrace degradation by intense surface erosion, aggressive piping/tunnelling and/or generalized mass movements. Inconclusive behaviour (light grey) applies to reviewed terrace systems lacking definitive information for evaluating terrace behaviour in the explored bibliography. N-values displayed between brackets (vertical axis) indicate the total number of sites represented for each level of the environmental conditions. Specific percentage values for the frequencies of the different terrace behaviours (i.e., stable, unstable, inconclusive) are detailed within the

classification bars displayed for those environmental condition levels with an unbalanced representation (i.e., ratio of frequencies above 1.5) of erosive and stable terrace behaviour.

Figure 10. Absolute frequency distribution (number of sites) of terraced landscapes reported in the explored bibliography to have suffered: (a) aggressive piping/tunnelling phenomena and (b) mass wasting problems (i.e., terrace sliding failure) in relation to their local environmental characteristics (i.e., climate type, vegetation cover, local lithology and hillslope gradient).

Fig. 1.

Fig. 2.

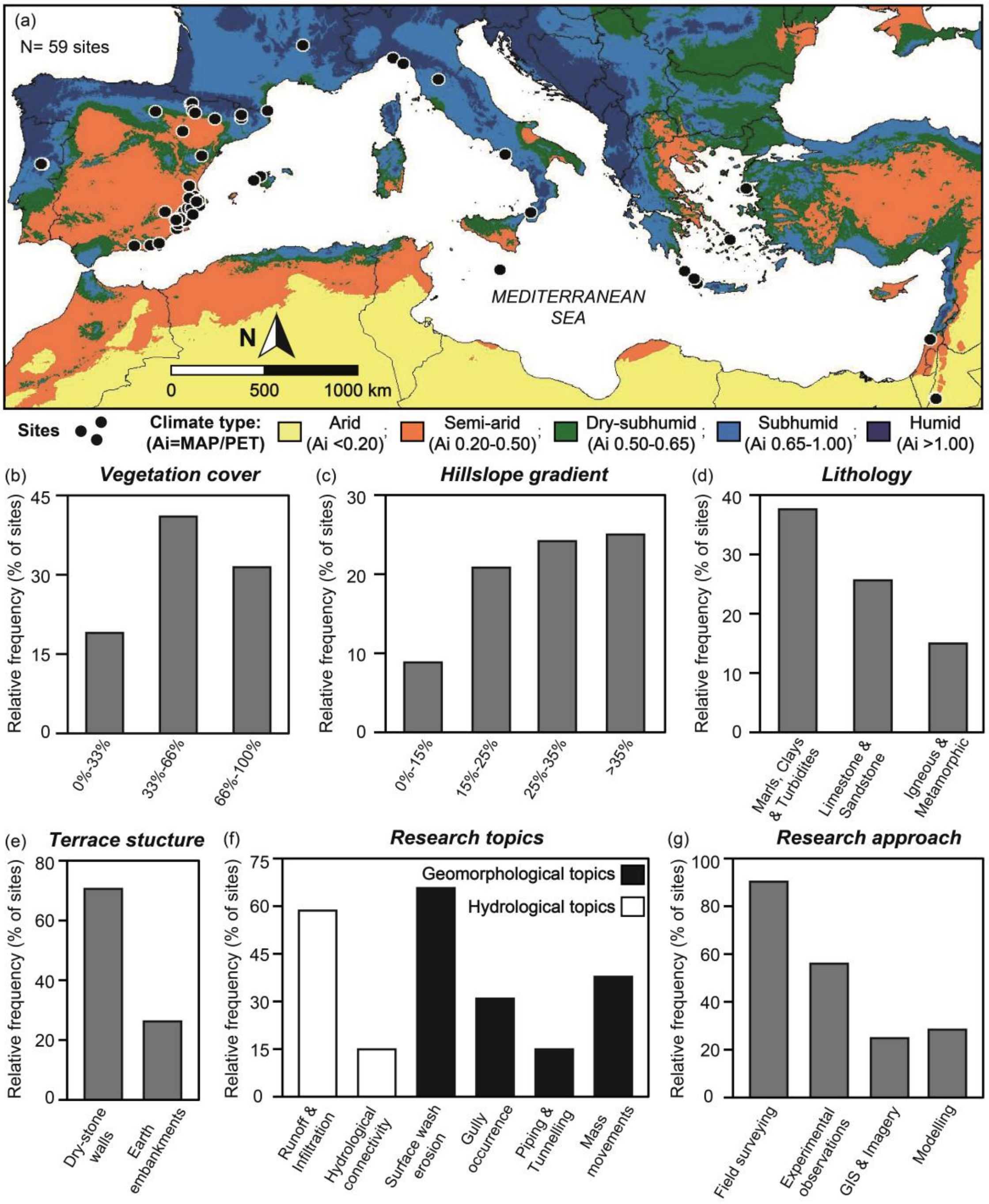

(a)
N= 59 sites
MEDITERRANEAN SEA
N
0
500
1000 km
Sites
Climate type: (Ai=MAP/PET)
Arid (Ai <0.20)
Semi-arid (Ai 0.20-0.50)
Dry-subhumid (Ai 0.50-0.65)
Subhumid (Ai 0.65-1.00)
Humid (Ai >1.00)
(b) Vegetation cover
Relative frequency (% of sites)
0
15
30
45
0%-33%
33%-66%
66%-100%
(c) Hillslope gradient
Relative frequency (% of sites)
0
10
20
30
0%-15%
15%-25%
25%-35%
>35%
(d) Lithology
Relative frequency (% of sites)
0
10
20
30
40
Marls, Clays & Turbidites
Limestone & Sandstone
Igneous & Metamorphic
(e) Terrace stucture
Relative frequency (% of sites)
0
20
40
60
80
Dry-stone walls
Earth embankments
(f) Research topics
Relative frequency (% of sites)
0
15
30
45
60
75
Geomorphological topics
Hydrological topics
Runoff & Infiltration
Hydrological connectivity
Surface wash erosion
Gully occurrence
Piping & Tunnelling
Mass movements
(g) Research approach
Relative frequency (% of sites)
0
20
40
60
80
100
Field surveying
Experimental observations
GIS & Imagery
Modelling

Fig. 3.

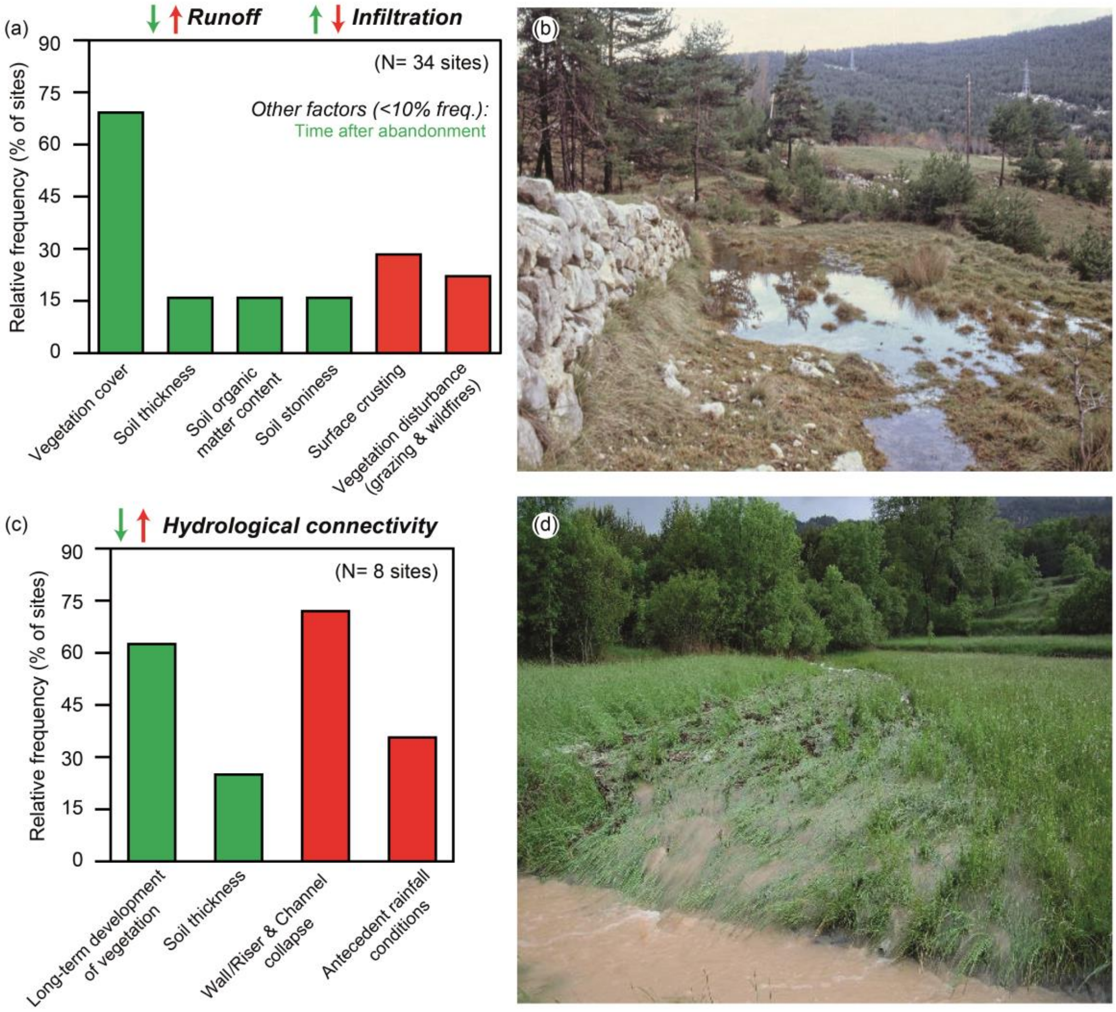
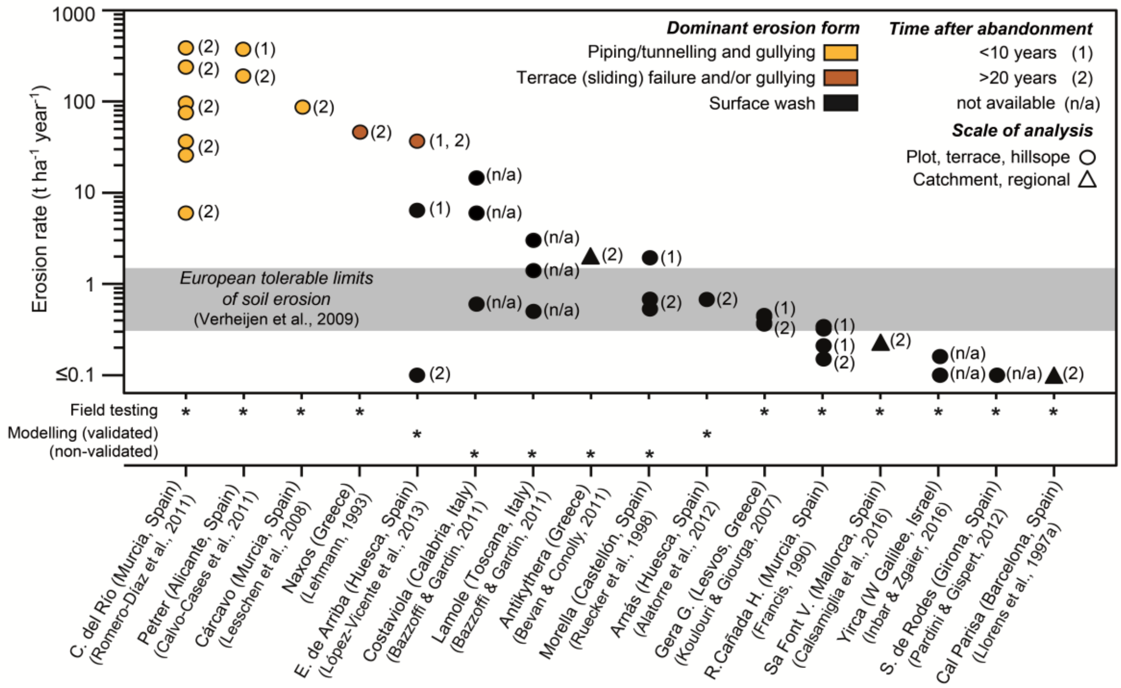

(a)
↓↑ Runoff
↑↓ Infiltration
(N= 34 sites)
Other factors (<10% freq.):
Time after abandonment
Relative frequency (% of sites)
90
75
60
45
30
15
0
Vegetation cover
Soil thickness
Soil organic matter content
Soil stoniness
Surface crusting
Vegetation disturbance (grazing & wildfires)
(b)
(c)
↓↑ Hydrological connectivity
(N= 8 sites)
Relative frequency (% of sites)
90
75
60
45
30
15
0
Long-term development of vegetation
Soil thickness
Wall/Riser & Channel collapse
Antecedent rainfall conditions
(d)

Fig. 4.



Erosion rate (t ha$^{-1}$ year$^{-1}$)
1000
100
10
1
≤0.1
Dominant erosion form
Piping/tunnelling and gullying
Terrace (sliding) failure and/or gullying
Surface wash
Time after abandonment
<10 years (1)
>20 years (2)
not available (n/a)
Scale of analysis
Plot, terrace, hillsope ○
Catchment, regional △
European tolerable limits of soil erosion (Verheijen et al., 2009)
(1)
(2)
(1, 2)
(n/a)
Field testing
Modelling (validated)
(non-validated)
C. del Río (Murcia, Spain) (Romero-Díaz et al., 2011)
Petrer (Alicante, Spain) (Calvo-Cases et al., 2011)
Cárcavo (Murcia, Spain) (Lesschen et al., 2008)
Naxos (Greece) (Lehmann, 1993)
E. de Arriba (Huesca, Spain) (López-Vicente et al., 2013)
Costaviola (Calabria, Italy) (Bazzoffi & Gardin, 2011)
Lamole (Toscana, Italy) (Bazzoffi & Gardin, 2011)
Antikythera (Greece) (Bevan & Conolly, 2011)
Morella (Castellón, Spain) (Ruecker et al., 1998)
Arnás (Huesca, Spain) (Alatorre et al., 2012)
Gera G. (Lesvos, Greece) (Koulouri & Giourga, 2007)
R.Cañada H. (Murcia, Spain) (Francis, 1990)
Sa Font V. (Mallorca, Spain) (Calsamiglia et al., 2016)
Yirca (W Galilee, Israel) (Inbar & Zgaier, 2016)
S. de Rodes (Girona, Spain) (Pardini & Gispert, 2012)
Cal Parisa (Barcelona, Spain) (Llorens et al., 1997a)

Fig. 5.

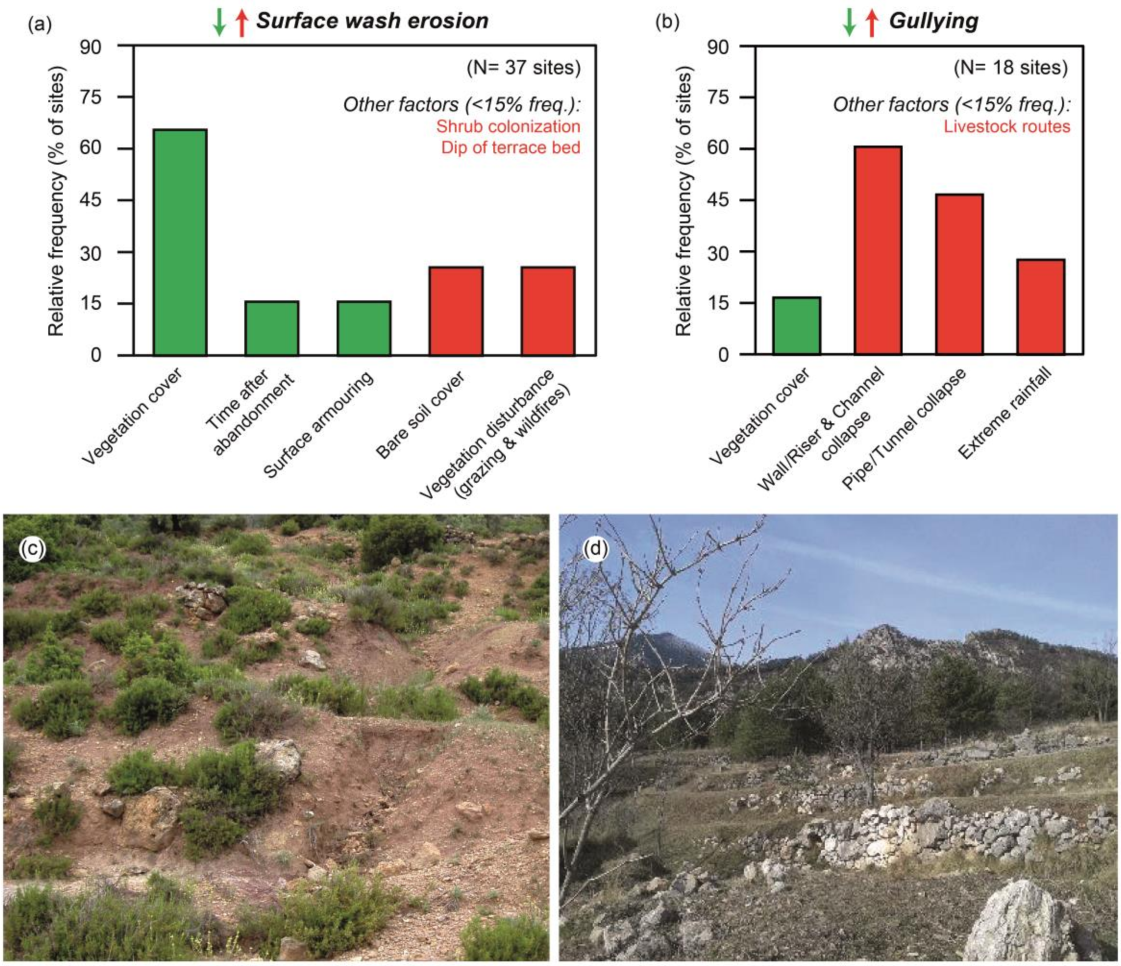

(a)
Surface wash erosion
90
75
60
45
30
15
0
Relative frequency (% of sites)
(N= 37 sites)
Other factors (<15% freq.):
Shrub colonization
Dip of terrace bed
Vegetation cover
Time after abandonment
Surface armouring
Bare soil cover
Vegetation disturbance (grazing & wildfires)
(b)
Gullying
90
75
60
45
30
15
0
Relative frequency (% of sites)
(N= 18 sites)
Other factors (<15% freq.):
Livestock routes
Vegetation cover
Wall/Riser & Channel collapse
Pipe/Tunnel collapse
Extreme rainfall
(c)
(d)

Fig. 6.

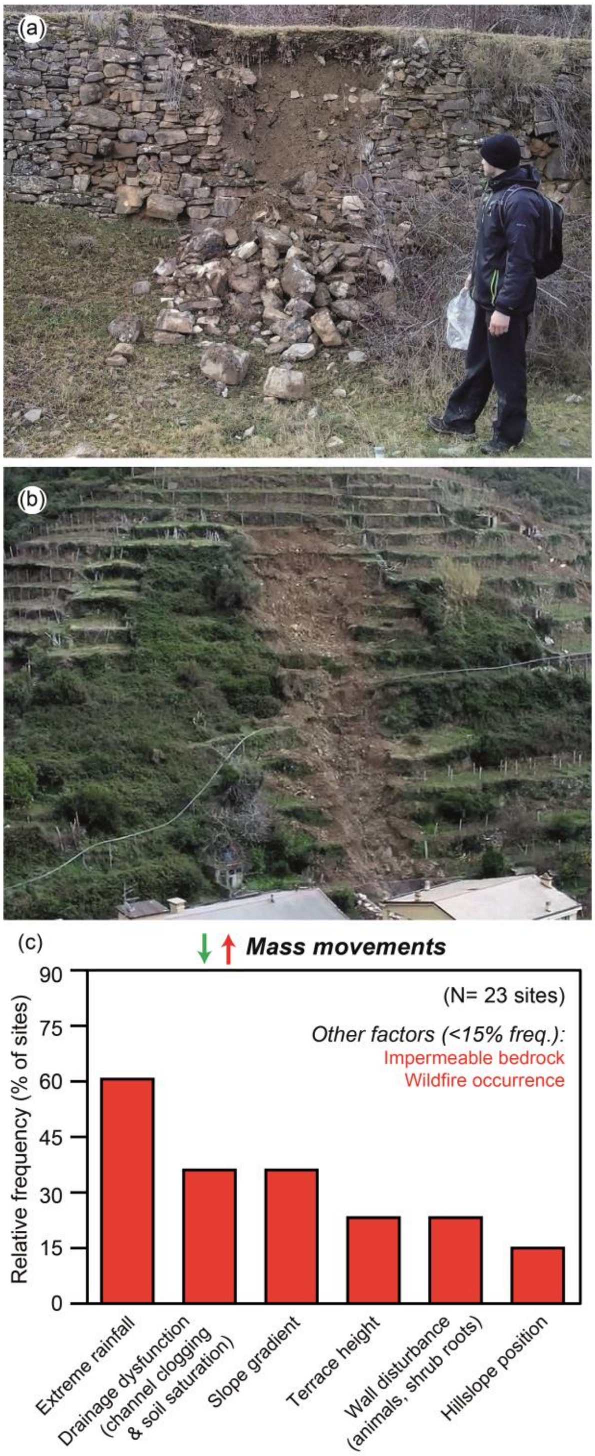

(a)
(b)
(c)
↓ ↑ Mass movements
(N= 23 sites)
Other factors (<15% freq.):
Impermeable bedrock
Wildfire occurrence
Relative frequency (% of sites)
90
75
60
45
30
15
0
Extreme rainfall
Drainage dysfunction (channel clogging & soil saturation)
Slope gradient
Terrace height
Wall disturbance (animals, shrub roots)
Hillslope position

Fig. 7.

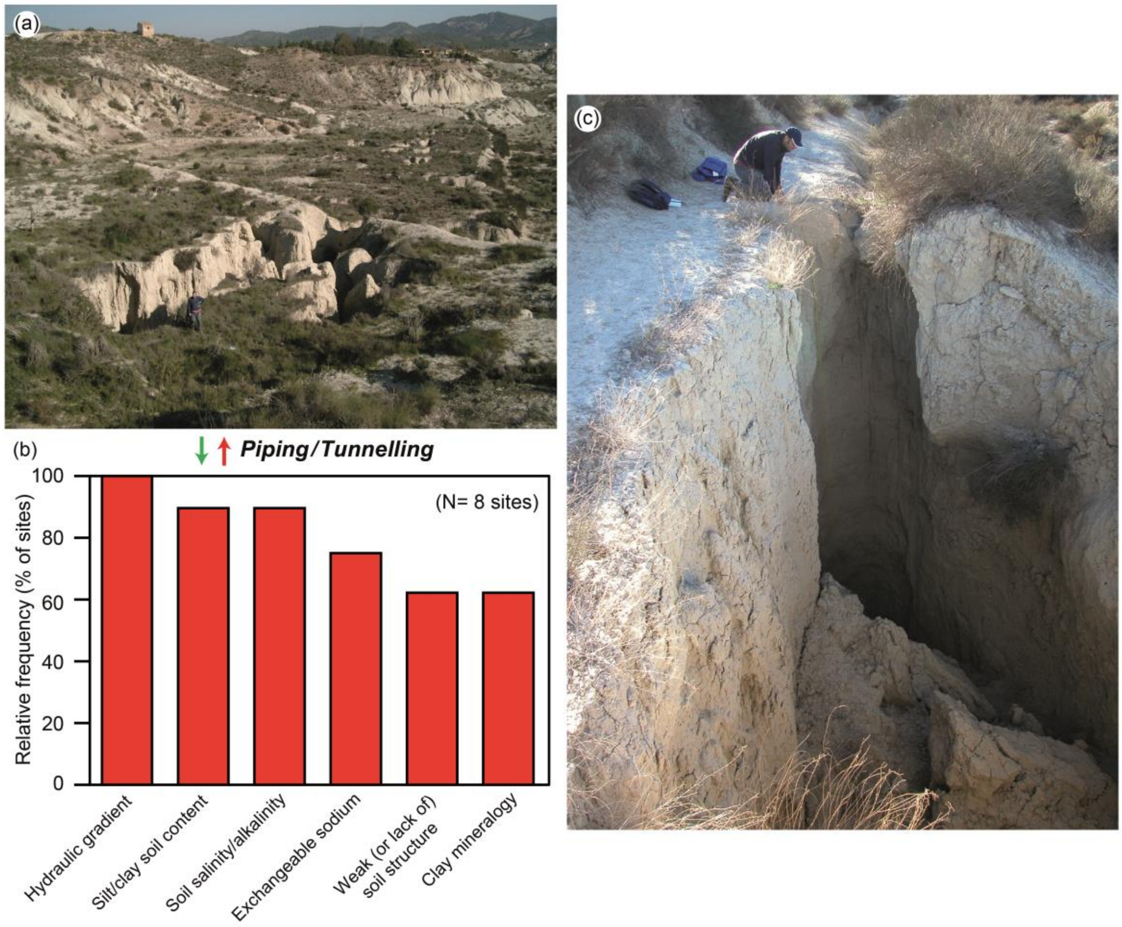

(a)
(b)
↓ ↑ Piping/Tunnelling
(N= 8 sites)
Relative frequency (% of sites)
100
80
60
40
20
0
Hydraulic gradient
Silt/clay soil content
Soil salinity/alkalinity
Exchangeable sodium
Weak (or lack of) soil structure
Clay mineralogy
(c)

Fig. 8.

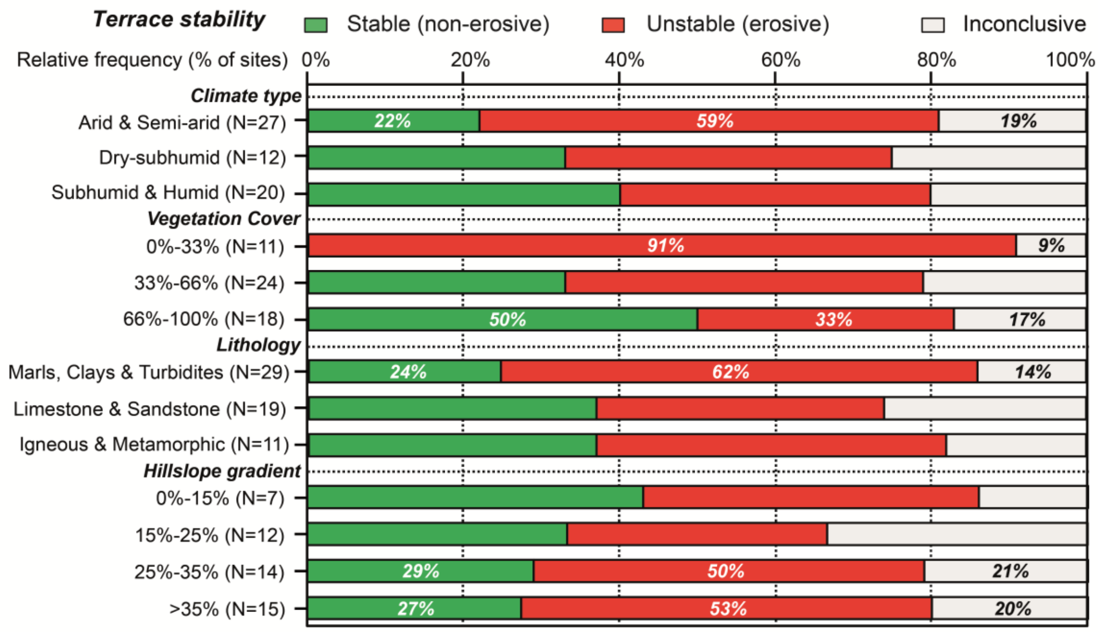

Terrace stability
Stable (non-erosive)
Unstable (erosive)
Inconclusive
Relative frequency (% of sites)
0%
20%
40%
60%
80%
100%
Climate type
Arid & Semi-arid (N=27)
22%
59%
19%
Dry-subhumid (N=12)
Subhumid & Humid (N=20)
Vegetation Cover
0%-33% (N=11)
91%
9%
33%-66% (N=24)
66%-100% (N=18)
50%
33%
17%
Lithology
Marls, Clays & Turbidites (N=29)
24%
62%
14%
Limestone & Sandstone (N=19)
Igneous & Metamorphic (N=11)
Hillslope gradient
0%-15% (N=7)
15%-25% (N=12)
25%-35% (N=14)
29%
50%
21%
>35% (N=15)
27%
53%
20%

Fig. 9.

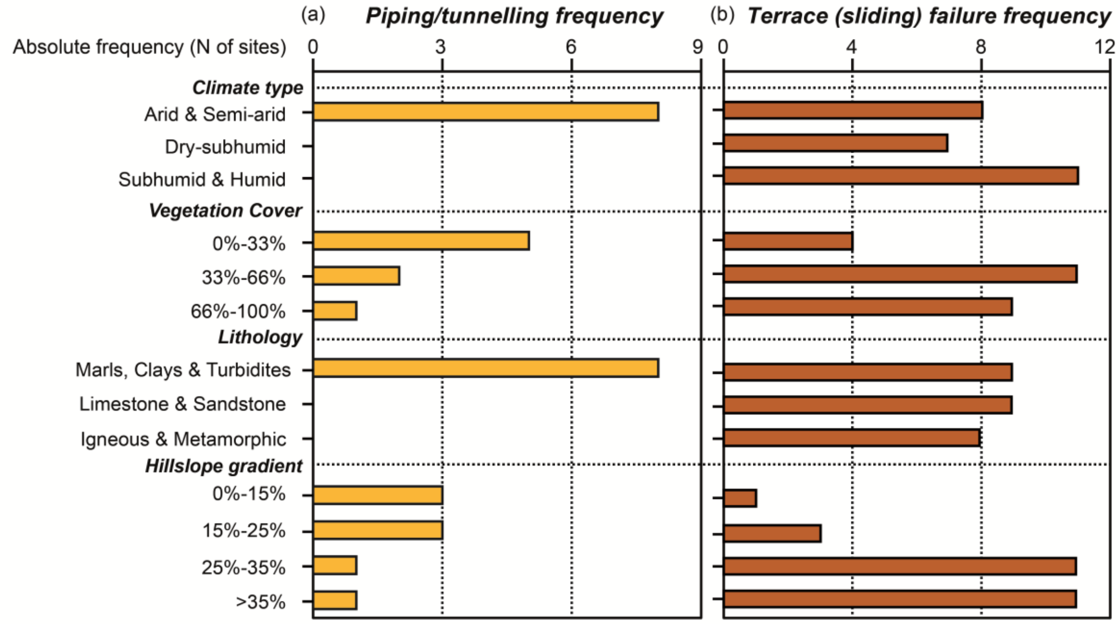

(a)
Piping/tunnelling frequency
(b)
Terrace (sliding) failure frequency
Absolute frequency (N of sites)
0
3
6
9
0
4
8
12
Climate type
Arid & Semi-arid
Dry-subhumid
Subhumid & Humid
Vegetation Cover
0%-33%
33%-66%
66%-100%
Lithology
Marls, Clays & Turbidites
Limestone & Sandstone
Igneous & Metamorphic
Hillslope gradient
0%-15%
15%-25%
25%-35%
>35%

Fig. 10.