Impacts of Land Abandonment on Flood Mitigation in Mediterranean Mountain Areas

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Contents

Abstract From the mid-twentieth century, Mediterranean mountains were affected by a rapid and generalized land abandonment process. This chapter (1) summarizes the impacts of land abandonment on the hydrological dynamics in Mediterranean mountain areas; (2) evaluates post-land abandonment management practices (LMPs) for flood mitigation based on nature-based solutions (NBS); and (3) briefly discusses some examples in the Central Pyrenees. In general, land abandonment resulted in a

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natural colonization by shrubs and forests, which, in turn, led to a decrease in river discharges and sediment yields. NBS, as mitigation measures to control flood occurrence, have been carried out including afforestation, shrub clearing, landscape changes, and recovery of terraces and stonewalls. In addition, in the most hydrogeomorphologically active areas, a combination of NBS and grey infrastructures was used to control floods. Grey infrastructures produce immediate effects but they are short-lived and expensive solutions. LMPs based on NBS present advantages and disadvantages: (1) afforestation was the most common practice, reducing floods, hydrological connectivity, peak flows, and sediment yields, in spite of their lower impact in extreme events; (2) shrub clearing decreases the number of forest fires and maintains the occurrence of the most frequent floods; (3) the recovery of mosaic landscapes produces environmental consequences, being important sources of ecosystem services, such as the regulation of floods; and (4) the recovery of agricultural terraces and stonewalls is highly expensive, but presents social and cultural benefits, reducing hydrological connectivity, peak flows, and runoff. In the near future, NBS in abandoned lands should be based on cost-effective and long-term strategies to mitigate flood risk. NBS should be cost-effective, ensure longer lifetime than grey infrastructures, and be adapted to different local objectives and global scenarios.

Keywords Afforestation, Agricultural terraces, Floods, Land abandonment, Nature-based solutions, Revegetation

1 Introduction: Land Abandonment in Mediterranean Mountain Areas

Large areas worldwide have been affected by farmland abandonment particularly in temperate and developed regions [1–4]. Campbell et al. [5] calculated that around 385–472 million hectares of agricultural land were abandoned worldwide between 1700 and 2000 m a.s.l., a process that has not finished yet, and that is forecasted to continue for the next few decades [6]. Particularly, in Mediterranean mountain areas a generalized farmland abandonment occurred during the second half of the twentieth century. For instance, more than 80% of cultivated land was abandoned in the Spanish Pyrenees [7], and around 70% in the eastern Alps [8]. Land abandonment is a major land use change and has resulted in dramatic landscape changes, leading to a massive invasion of shrublands and secondary succession forests [9, 10]. A high percentage of the agricultural land was located in steeply sloping hillsides, frequently exploited with no conservation measures [11]. When they were cultivated, these areas generated high runoff coefficients and high sediment concentrations [12], ultimately leading to thin stony soils and the activation of sheet wash erosion, gullying and rilling processes, as confirmed by experimental studies [3]. However, the management of these areas after land abandonment is still an unresolved “hottopic" [13], with different practices proposed by public administrations, land managers, and scientists. The choice of a particular practice is of crucial importance since, most of the abandoned areas in the Mediterranean region are located in mountain areas that are the main source of water for the demanding lowlands [14], and also represent opportunities for the development of biodiversity and land management programmes.

Post-land abandonment management practices (LMPs) can produce important changes in landscape, biodiversity, soil quality, and water resources. Each management practice is based on a particular treatment of the plant cover and, consequently, will likely have important environmental implications, particularly in water resources generation and overland flow. This makes water availability in the Mediterranean region challenging for the next decades [15]. However, most of the abandoned lands have been considered marginal, i.e. without direct interest to incorporate them into the global productive system, because of steep slopes, inaccessibility, and soil degradation. Hunting and light tourism should be the only perspective for these marginal lands, together with extensive stockbreeding, although this latter has been progressively displaced to a secondary interest, given the population decline [16–18]. For this reason, there were no specific plans for management, leading to a natural "rewilding" process or landscape naturalization (the process of passively woody encroachment). Until the beginning of the 1970s the most degraded landscapes, affected by gullying and sheet wash erosion, open plant cover, and high rates of overland flow were subjected to land rehabilitation plans, summarized in the afforestation of large areas, accompanied in the most extreme cases with the construction of certain infrastructures. With these plans, forest engineers tried to reduce sediment yield and floods and, occasionally, to increase the extent of forest for wood production. Consequently, since the end of the nineteenth century, the land rehabilitation plans consisted of two strategies intimately related: (1) civil (grey) infrastructures (the traditional ones made with cement) and (2) afforestation programmes mainly using conifers to control hydrological dynamics and reduce flood risk, soil erosion and land degradation, and decrease the rate of silting in reservoirs [19]. Thus, until the 1970s, most of the LMPs and restoration and rehabilitation projects were focused on artificial, man-made strategies (grey infrastructures) that are costly and that frequently are not efficient over a long period of time [20] and on afforestation programmes. More recently, different green infrastructures and nature-based solutions (NBS) have been also considered as sustainable and successful strategies. This is the case, for instance, of the active management of abandoned lands in order to promote and improve ecosystem services [13, 21], i.e. grazing in forest areas and shrubland clearing in order to favour extensive livestock systems, human presence in mountain areas, enhancing biodiversity, heterogeneity, and the control of overland flow and soil erosion. Therefore, for stakeholders, regional and national administrations, policymakers, and scientists there are three critical questions: (1) What can we do with abandoned lands? (2) How should be managed land abandoned areas in Mediterranean mountains to optimize ecosystem services and reduce environmental risks? and (3) Which are the most adequate long-term strategies in order to integrate the marginal mountains in the spatial organization of landscapes to emphasize holistic land conservation policies?

Abandoned agricultural lands and post-land abandonment management practices deserve special attention due to their influence on the water cycle, hydrological dynamics and their role in flood mitigation risks [22]. This chapter examines NBS compared to grey initiatives in abandoned farmland areas of Mediterranean mountains, and evaluates their effects in flood dynamics. The way in which LMPs build on NBS can manage flood mitigation in Mediterranean mountains is briefly discussed in a context of the Central Spanish Pyrenees.

2 Nature-Based Solutions for Flood Mitigation from an Environmental and Socioeconomic Point of View

The NBS concept is a new approach that was introduced in the late 2000s. In the last years, several definitions have been proposed for the NBS concept from different perspectives. Lilli et al. [23] indicate that NBS are actions that "use natural processes in a resource efficient manner to solve societal challenges". Other broader definitions proposed that NBS is a holistic approach integrating both the "engineering and ecosystem components in its implementation, being encouraged in both research and practice and policy-decision making processes" [24]. Similarly, Turconi et al. [25] indicate that NBS are usually defined as complementary or alternative solutions to grey infrastructures with the main aim of conserving and regenerating the functionality of a natural or semi-natural ecosystem. Cohen-Shacham et al. [26] provide a complete definition indicating that NBS are "actions to protect, sustainable management, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" based on principles such as the maintenance of biological and cultural diversity, the ability of ecosystems to evolve over time, and the application at a landscape scale. The European Commission [27] indicated that NBS is a concept that defined "the actions inspired by, supported by, or copied from nature, and uses complex system processes of nature" or "solutions that aim to help societies address a variety of environmental, social and economic challenges in sustainable way" [27]. Thus, the European Union has adapted NBS as a strategy for achieving the restoration of degraded ecosystems, climate change adaptation and mitigation, the improvement of the risk management, and resilience to extreme events, among other topics.

What can be considered as a nature-based solution? There are different responses depending on the authors. For example, Debele et al. [28] include (1) conservation and land management practices, (2) green and blue approaches mixed with hard engineering structures, and (3) large-scale climate adaptation and mitigation approaches as afforestation and bioengineering practices. Concerning flood risk management, NBS should be natural or semi-natural structures that reduce the prevalence of flooding events. These flood events can have serious impacts from an economic, social, and environmental point of view. Most of the literature and examples of NBS and green infrastructure related to flood risk are focused in urban and peri-urban contexts [29]. Conversely, few studies have been focused on land abandoned environments [30]. Other authors prefer the use of natural flood management (NFM) schemes (similar to NBS) to work with hydromorphological processes through soil and water management to reduce flood risk, including restoration [31].

During decades, grey infrastructures have been used to control flood risk and soil erosion in abandoned Mediterranean mountains. A variety of infrastructures have served, and still serve, to reduce peakflows, particularly reservoirs, which usually have been constructed with other purposes than flood control (mainly hydropower production and irrigation, in some cases water supply for large cities), although they are also used to reduce the peakflow [32]. The efficiency of reservoirs is controlled by their volume in relation to the total river discharge, the season of the year, and the volume of water accumulated in the reservoir prior to the peakflow. For instance, in Pyrenean rivers, floods that occur in autumn are almost absent, because the increase in discharge is used to recover the reservoir after the summer exhaustion, and those occurred in spring are also reduced to finally fulfil the reservoir immediately before the irrigation campaign [32]. In any case, reservoirs act as large sediment traps during the occurrence of floods, and therefore they contribute to the shortening of the lifetime of reservoirs, particularly in areas affected by strong plant cover disturbance [33].

In the case of small torrential ravines, the construction of a series of check dams is a strategy to reduce the velocity of the peakflow wave, although their main finality is the interruption of sediment transfer (particularly bedload) downstream of the dams [34]. They have been profusely used in mountain areas where sediment transfer is a problem, although they have collateral, undesirable consequences, such as the incision of the channel immediately downstream of the check dam and their possible collapse during extreme hydrological events [35–39]. Braided rivers and ravines have also been canalized to avoid the flooding of agricultural lands and human settlements, although the containment of stream beds between banks tends to accelerate the velocity of the flood wave and to increase the efficiency of bedload transfer [40]. Besides, during extreme floods the artificial banks can collapse or be overpassed, resulting in long-term damages in the alluvial plain. For these reasons, grey infrastructures are only recommended in exceptional cases, to save lives, settlements, and strategic buildings.

Nevertheless, a combination of grey and green approaches has been implemented in different Mediterranean environments. Generally, grey infrastructures produce immediate effects, however, they are often short-lived ($<$30–40 years) and they can lose their effectiveness few years after their construction. Contrary, NBS can be a cost-effective long-term solution for hydrological risks and land degradation processes [41], such that shifts from grey infrastructures to green infrastructures and NBS could provide similar effects but without some negative impacts. Boix-Fayos et al. [30] supported the idea that vegetation restoration in abandoned areas and NBS are more sustainable economically with a long-term efficacy, while hydrological control through grey infrastructures serves better for some specific problems and can be used as a short-term solution but with higher economic costs. Likewise, NBS offers many additional benefits than grey infrastructure as the increase in biodiversity or soil carbon sequestration.

Generally, NBS focused on soil and water conservation measures for flood mitigation should include catchment-based interventions at landscape scale and should improve infiltration processes, which slow down runoff velocity (as water passes slowly through the soil), and help in reducing erosion processes [42]. Below, a range of NBS options to control floods in abandoned Mediterranean mountain areas is briefly presented (Fig. 1). In general, these NBS, as suggested by Keesstra et al. [43], should be based on making the landscape less connected, facilitating rainfall to be less transformed into runoff, increasing soil moisture, and thus reducing flood risk, soil erosion, and land degradation.

2.1 Passive Rewilding

The main visible consequence of land abandonment in Mediterranean mountain areas is the natural expansion of shrublands and forests. Abandoned agricultural lands are usually occupied by natural revegetation of shrubland and forest cover in a slow-process that can lead around 100 years (rewilding) [44]. Natural revegetation alters the water cycle, the partitioning of rainfall between evapotranspiration, runoff and groundwater flows, increases water infiltration during rainstorm events, and reduces overland flow and sediment yields. Most of the studies in abandoned areas with a natural revegetation process suggested: (1) a decrease in river discharges, (2) a reduction of runoff coefficients and peak flows, and (3) changes in flood hydrographs characteristics, like slower time lags and longer recession limbs [3, 45–47].

However, it is also demonstrated that vegetation recover can present negative effects, as the decrease of runoff volumes especially during dry periods, due to the high evapotranspiration values and water demands of the forest cover, the increase of forest fire risks [43], and the loss of cultural landscapes [13] and biodiversity, although there are differing opinions on the latter [48].

2.2 Afforestation

Abandoned farmlands in Mediterranean mountains have also been afforested through large forest hydrological rehabilitation projects, carried out mainly during the second half of the twentieth century. Check dams (considered grey infrastructure) and afforestation programmes (greening-up processes) were used in both semi-arid and humid environments [30, 49]. The idea that abandoned fields and

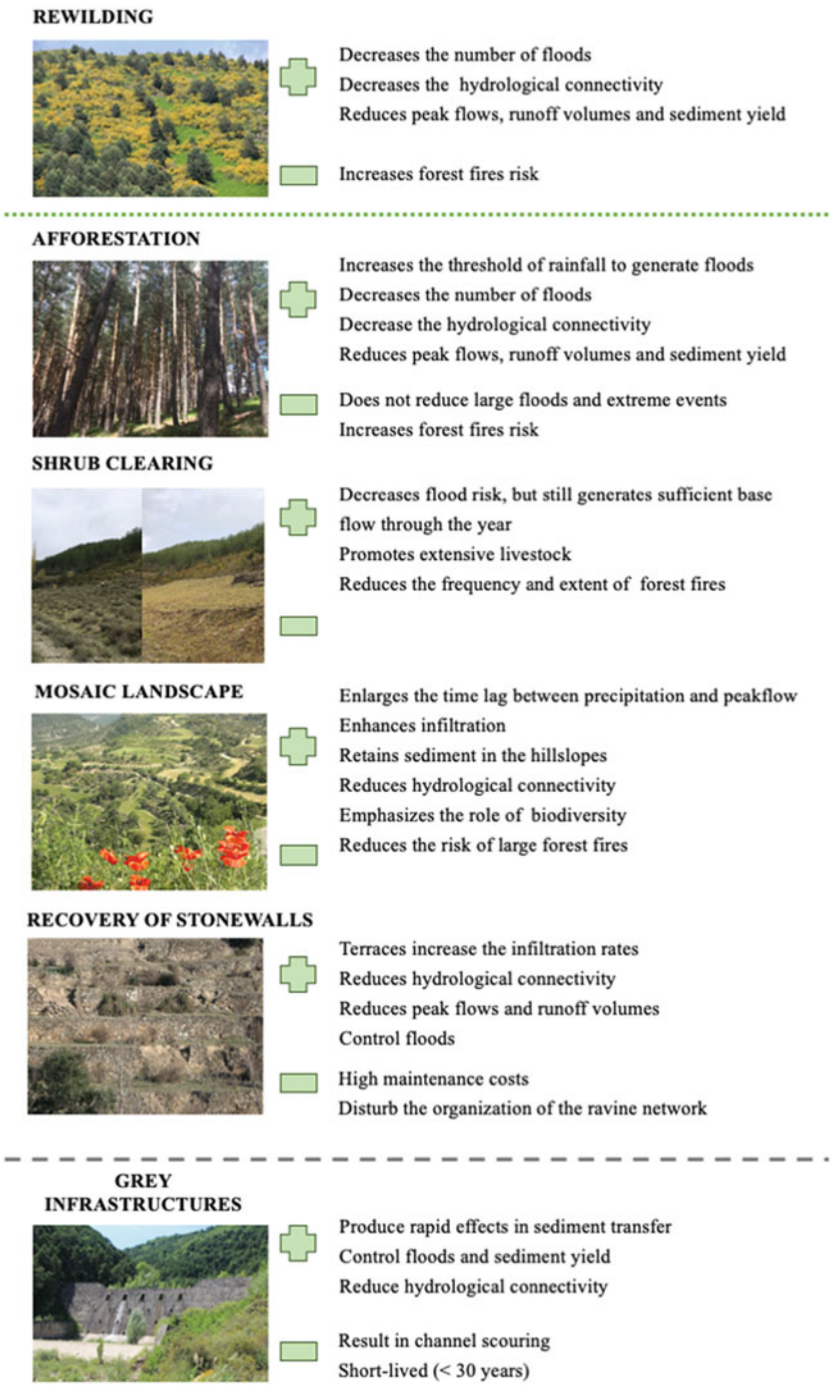

Fig. 1 Nature-based solutions and grey infrastructures to control floods in abandoned Mediterranean mountain areas and grey infrastructures. + means positive effects and – negative effects of the different NBS and grey infrastructures

shrublands were affected by soil erosion and degradation was widespread, thus motivating extensive afforestation programmes. In Mediterranean mountains (both semi-arid and humid environments), afforestation with conifers was used for land reclamation during many years, causing rapid landscape transformations. In most instances, afforestation is considered a landscape change that reduces water supply, whose primary effect is the increase of the threshold of the amount of rainfall needed to initiate flow and generate floods (the number of floods is reduced and many events produce no notable floods) [49]. Afforestation can potentially mitigate flood risk through increasing interception and infiltration rates, and attenuating runoff volumes. Thus, the effects of afforestations at catchment scale were: (1) a clear decrease in hydrological connectivity [50, 51], (2) lower peak flows [49, 52, 53], (3) a decrease in the number of floods [54], and (4) a reduction in sediment supply to streams [55, 56].

However, there remains a lack of consensus to the general efficacy of afforestation programmes in mitigating flood risk [57], particularly large floods and extreme events [31, 58–60]. Thus, afforestation may be helpful in moderating floods for small events, but this effect would be increasingly reduced as rainfall amount increase. For example, Didon-Lescot [61] showed that the effects of afforestation are restricted to less intense hydrological events (floods corresponding to a return period of approximately 5 years) and García-Ruiz et al. [62] considered that it only has notable effects in floods of less than 10-year return period. Furthermore, some studies and models suggest some other negative impacts, as the increase in soil erosion and geomorphological processes during the first years after afforestation (due to the use of heavy machinery) [63], and the increase in forest fires risk, that could be even stronger under the context of Global Change, due to longer drought periods and higher temperatures [64].

2.3 Shrubland Clearing

As already mentioned, scientists, as well as land managers and policy-makers, have taken different positions on how to deal with land abandonment [13]. Some support a passive management (rewilding) while others defend an active management (as afforestation). Likewise, during the last decades, a managed rewilding through shrub clearing has been proposed, leading to the promotion of extensive livestock and the reduction of forest fires [65], but also with significant hydrological consequences (Fig. 2a). This practice has been carried out during the last three decades by some Spanish Regional administrations with financial support of the European Union [13, 65, 66]. They argue that a managed rewilding may be a good NBS to come to a sustainable situation from multiple environmental points of view (i.e. water regulation, soil erosion, biodiversity). Likewise, shrub clearing leads to an increase in biodiversity [67, 68] and can also generate socioeconomic improvements, as the increase in extensive livestock [13, 66]. Alados et al. [68] and Gómez

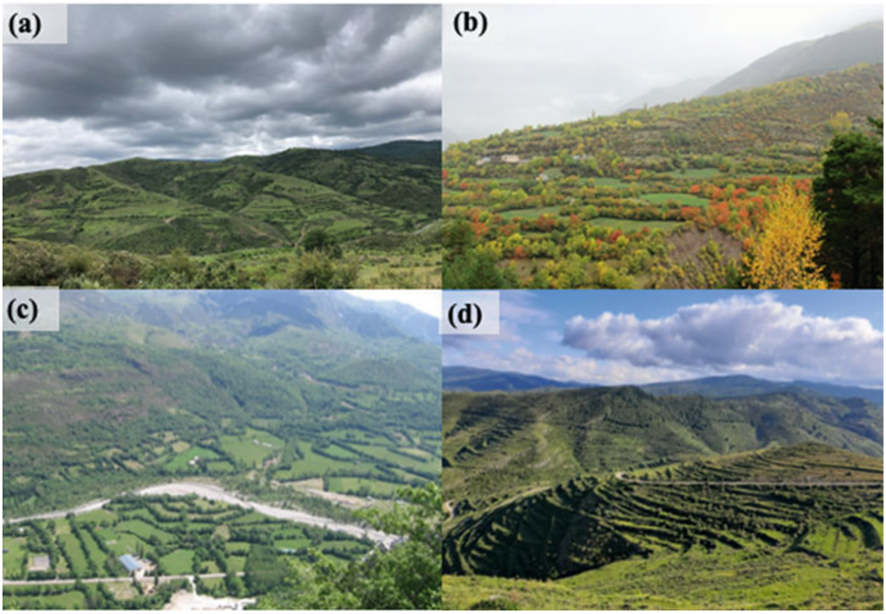

Fig. 2 Examples of NBS in Mediterranean mountain areas: (**a**) Shrubland clearing landscape in the Leza Valley (Iberian System, Spain) (Photo E. Nadal-Romero); (**b**) Example of mosaic landscape with meadows and shrublands in a south-facing slope in San Juan de Plan (Pyrenees, Spain) (Photo T. Lasanta); (**c**) Meadows in the bottom valley of the Esera River (Pyrenees, Spain) (Photo T. Lasanta); (**d**) Terraced slopes in Munilla (Iberian System, Spain) (Photo D. Lasanta)

et al. [69] also concluded that shrubland clearing is a better strategy than controlled burning to mitigate the effects of shrub encroachment.

Shrub clearing as a NBS can be considered a good water resource management, because of its capacity to decrease flood risk and to generate sufficient base flow through the year [13]. However, there are no catchment scale examples to contrast these results [70]. Nadal-Romero et al. [12] simulated shrub clearing in small plots in the Central Pyrenees, and compared it with natural shrub vegetation. The results showed that runoff coefficient in grassland areas (shrub clearing) are higher than in shrublands, because canopy interception is reduced, increasing overland flow especially during the wet period, whereas soil erosion values do not show changes. Currently, the LIFE project MIDMACC "Mid-mountain adaptation to climate change" funded by the European Commission implements shrub clearing practices in two abandoned and marginal mid-mountain areas in Spain, as a landscape management practice and NBS, and will evaluate the effects of this practice on water resources and hydrological dynamics (https://life-midmacc.eu/es/).

2.4 Recovery of Mosaic Landscapes

Landscape changes moving to a managed mosaic of land uses and land covers should be also considered as a NBS for abandoned lands. The disappearance of mosaic landscapes, after land abandonment, represents a significant loss of socio-cultural and ecological benefits, as the increment of forest fires or the decrease of water [71]. Landscape solutions and the recovery of these landscapes can incorporate high production values (e.g. timber), ecological (e.g. soil quality) and cultural values (e.g. leisure, cultural identity), the support of a large diversity of habitats, and the regulation of hydromorphological processes such as soil conservation, water production and quality, and flood control and mitigation (see Fig. 1).

In that sense, a slope or basin should be considered as a complex hydrological system, in which hydrological processes considered at the plot scale do not allow to understand the global response of the basin [72]. It is well known that runoff dynamics is conditioned by the structure of the landscape (topography and environment). It involves its composition (land uses and covers) and its configuration or spatial distribution of landscape elements, including paths, roads, ditches, ravines, etc. In mosaic landscapes, including *bocage* landscapes (mixed woodland and pasture areas), the spatial distribution of land uses and covers can disconnect (in some cases) sectors of the slope from the ravine or river (water course) (Fig. 2b, c) [73]; likewise, in other cases, the effects of topography, land use and road networks, hedges, ditches, among others, may be combined, to create a complex artificial drainage network, altering the topographic flow pattern [74, 75]. The scientific literature highlights that: (1) in hydrological efficiency the composition of the landscape is as important as the organization of the landscape elements, and (2) the density and spatial organization of the drainage networks determine the hydrological connectivity of a basin [76–79]. For instance, Malek et al. [80] showed, using a modelling approach that enhancing traditional mosaic-like landscapes improve the status of the water resources in the Mediterranean region.

2.5 Recovery of Stonewalls and Terraces

Agricultural terraces occupied important extents in the slopes of Mediterranean mid-mountain areas (Fig. 2d). Generally, terraces increase infiltration rates, reduce hydrological connectivity affecting contributing areas, peak flows, and runoff volumes, and consequently can control floods. Likewise, terraces alter the paths of runoff and sediment transport and erosion processes. Several authors suggest that terraces break up the continuity of water flows, imposing large rainfall thresholds on catchment-scale runoff production [81–84]. However, terrace walls require regular maintenance to continue retaining water and soil [85]. Furthermore, the development of a terraced landscape can lead to severe erosion problems, with the triggering of deep gullies. The reason is that farmers tried to alter the course of natural drainages in the hillslopes in order to concentrate the surface runoff out of the cultivated fields. In some cases, runoff concentration evolved into deep gullies in a few decades [86].

The abandonment of agricultural activities and consequently the lack of maintenance of agricultural terraces triggered a set of negative geomorphological impacts, as soil erosion or small mass movements [87, 88]. In addition, terraced abandonment largely alters runoff production, hydrological processes and connectivity [84]. Given the benefits of agricultural terraces (such as the reduction of flood risk or the enrichment of ground water potential due to the increased permeability of the soil), their maintenance or the restoration of stonewalls should be considered as a priority NBS practice to prevent off-site effects after land abandonment [89–91]. For example, Bellin et al. [82] indicated that terrace maintenance slowed runoff for events with a return period shorter than 8–10 years, and Calsamiglia et al. [92] concluded that terraces conservation encourages the dis-connectivity between the slopes and channels, reducing flood risk. Thus, active maintenance and rehabilitation of stone terraces is probably the most effective approach for controlling off-site effects and negative impacts of land abandonment (such as landslides or small mass movements). Tarolli et al. [93] considered that the reconstruction of the stonewalls should be also accompanied by the simultaneous reconstruction of irrigation and drainage channels and complementary structures of the terrace systems. However, the high costs make this NBS impracticable in most cases because of the large extent of terraced areas. However, despite the highest costs, an example of participatory framework approaches in Cyprus concluded that after land abandonment terraces rehabilitation had the best overall performance followed by afforestation, due to the high environmental benefices together with the local-socio cultural landscape context [94]. During the last decade, some private and public activities (i.e. UNESCO) have promoted the rebuilding of ruined stonewalls in those areas where the connectivity is high, being of interest for hydrological and forestry NBS projects. For example, some of these activities are supported by the LIFE programme (European Commission) and recently two new projects have been funded: "TERRACESCAPE" and "STONEWALLSFORLIFE". The main objective of the TERRACESCAPE project (http://www.lifeterracescape.aegean.gr/en/) is the restoration and re-cultivation of drystone terraces (as a prominent element of the Mediterranean landscape) in the Andros Island (Greece) to demonstrate the economic, cultural, and ecological benefits derived from such elements and to create and adapt green infrastructures to the context of Global Change. The STONEWALLSFORLIFE project (https://www.stonewalls4life.eu) aims at repairing wall terraces and ensuring their long-term maintenance, to protect the territory (Cinque Terre National Park, Italy) and its inhabitants against the effects of extreme climate events (such as floods or landslides).

3 Coping with Floods in the Central Spanish Pyrenees

The occurrence of floods is a common hydrological phenomenon in the Pyrenees, linked to long rainfall events or to short rainstorms. Most of floods concentrate between November and February, although the period between November and May includes important floods related with snowmelt (usually coinciding with rainfall events) [95]. Some floods have been particularly intense, accompanied by mass movements in the slopes, severe erosion periods, high costs in infrastructures and occasionally, casualties (Fig. 3). According to García-Ruiz et al. [96], the calculation of return periods of the most extreme rainfall events confirms that their occurrence shows an erratic spatial and temporal distribution. When precipitation between 150 and 200 mm in 24 h is considered, the relief explains the distribution of the rainfall values recorded, but in the case of precipitation over 200 mm, not any spatial organization explains their occurrence. The most extreme rainfall events can be considered as outliers, with magnitudes much higher than one would expect. For this reason, floods produced during such extreme pluviometric events cannot be controlled through NBS and grey structures, unless if a large reservoir is sufficiently empty to retain a large proportion of the flood. Nevertheless, even if reservoirs can reduce the peakflow downstream of the dams, the most relevant control of floods should be made in the hillslopes. There is where runoff generation and overland flow must be reduced, i.e. before runoff reaches the fluvial channel. This is particularly interesting for the low- and mid-mountain areas, where forests and shrublands can be managed to enhance rainfall interception and infiltration and slow overland flow.

Until the middle of the twentieth century, most of the south-facing slopes in the Central Spanish Pyrenees below 1,600 m a.s.l. were cultivated [11]. The abandonment resulted in the natural revegetation with shrubs and forests and the use of large afforestation programmes as well as hydrological control works that have been performed to regulate floods and control soil erosion and land degradation. During the last 30 years, researchers from the Instituto Pirenaico de Ecología (Spanish

Fig. 3 Some effects of the 19–21 October flood 2012 in the Central Spanish Pyrenees. (**a**) The bridge over the Aragón River at Jaca, dammed by a large mass of trees carried by the floodwaters; (**b**) A family house destroyed after the October flood (Aragón River) (Photos E. Nadal-Romero)

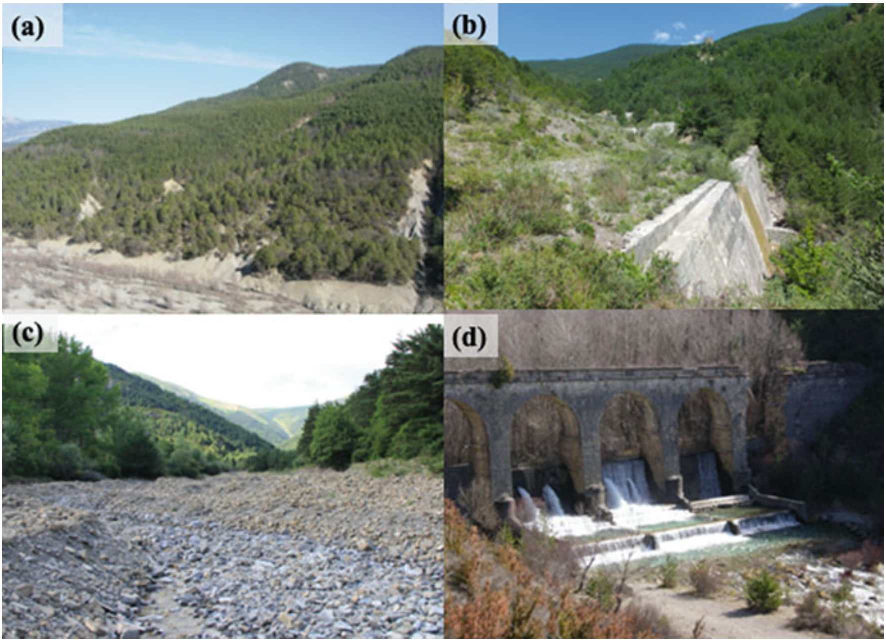

Fig. 4 (**a**) Afforestation carried out in the slopes around the Mediano Reservoir (Cinca River basin) to reduce runoff generation and the transfer of sediment to the reservoir (Photo JM. García-Ruiz); (**b**) A series of check dams in the Escuer Valley, a tributary of the Upper Gállego Valley. This valley was also almost totally afforested in the 1960s since it was affected by intense erosion processes after centuries of cultivation and grazing on steep slopes (Photo JM. García-Ruiz); (**c**) Afforestation carried out in the Ijuez River, a tributary of the Upper Aragón River. The whole basin was also afforested to reduce sediment yield and the magnitude of floods (Photo E. Nadal-Romero); (**d**) Large check dam in the lower course of the Ijuez River. It was constructed in the 1960s using the pillars of an ancient aqueduct (Photo JM. García-Ruiz)

Research Council, IPE-CSIC) have studied the effects of land abandonment and LMPs on water resources, flood generation and flood risk, and soil erosion in the Central Spanish Pyrenees [18]. The results from the Aisa Valley Experimental Station (AVES) with small plots that represent different old and current land uses (from 1991 to 2011) suggested that (1) farmland abandonment leading to dense shrub cover yields the lowest values of runoff generation and sediment yield; (2) cereal cultivation alternating with fallow on steep slopes produces the highest runoff coefficient and sediment yield, particularly in the case of shifting in agricultural practices; and (3) shrub clearing (grazing meadows) produces similar results than those obtained in the abandoned area covered with shrubs [12].

Afforestations have been a common NBS in the Central Pyrenees (Fig. 4a, b). Given the large extent of afforestation different studies were performed to detect changes in the hydrological behaviour of taluses and channels. García Ruiz and Ortigosa [97] reported that channels in afforested basins were those with the highest percentage of plant cover and the lowest average of bare soil and gravels. In the case of taluses located close to the channels, those in afforested basins had a greater plant cover, a greater proportion of no-erosion areas and a lower percentage of severe erosion. Therefore, a reduction in the magnitude and frequency of floods was deduced, together with a loss of energy to transport coarse sediment. Nevertheless, it may be noted that during the first years following the afforestation works, soil erosion and overland flow can be enhanced by the removal of soil, and that the afforestation techniques used are a major factor to explain the hydrological behaviour of afforestation [63], particularly in bench terraces made with machinery.

Other studies performed in some of the main Pyrenean rivers showed that streamflow and sediment yield have been declining in the Central Pyrenees since the middle of the twentieth century [98]. Beguería et al. [99] indicated that discharge clearly decreases from the last 60 years, suggesting that these changes were not attributable to a temperature increase or to a decline in precipitation, but rather to a generalized expansion of shrubs and forests following farmland abandonment. López-Moreno et al. [100] also detected a remarkable decrease in the discharges of Pyrenean rivers, with evidence that climate change alone only explains a small proportion of the observed decrease. Instead, the increase in evapotranspiration and rainfall interception due to the growth of vegetation in abandoned lands should be a major factor for these hydrological changes. Likewise, López-Moreno et al. [101] observed a decrease in the frequency and intensity of floods in most of the Pyrenean rivers, regardless of the evolution of precipitation. The results obtained show a negative trend in flood magnitude since the 1970s, although a change in the precipitation events was not detected. This difference between precipitation and runoff events has been explained as due to the expansion of plant cover in old cultivated fields and grasslands areas, as a consequence of depopulation, farmland abandonment, and the decline of extensive stockbreeding.

To check these general results four small headwater catchments have been monitored since the 1990s, with different history of land uses and land covers [102]. The Arnás, San Salvador, Araguás, and Araguás Afforestation catchments are located in the upper Aragón River basin (Central Pyrenees) between 875 and 1,340 m a.s.l., and all the catchments are close to each other such that they have similar climatic conditions [47]. The San Salvador catchment represents a dense natural forest of *Pinus sylvestris*, with *Fagus sylvatica* and *Quercus faginea*. The Arnás and Araguás Afforestation catchments were both cultivated and abandoned in the late 1950s: the Arnás catchment has been subject to a natural plant colonization process, including a complex vegetation mosaic with shrubs and forest patches, and the Araguás Afforestation catchment was afforested in the 1960s with *P. nigra* and *P. sylvestris.* Finally, the Araguás catchment represents a degraded environment, with a dense network of badlands. Significant hydrological differences were observed among the catchments [102, 103]. Focusing on land abandonment scenarios (Arnás and Araguás Afforestation), the primary effect of plant cover in both abandoned catchments is to raise the threshold for the amount of rain needed to initiate flow: both catchments experience fewer floods compared to the degraded area (Araguás), and many rainfalls produce no notable flow [60, 104]. However, these studies also noted that the number of floods recorded in these areas is twice the

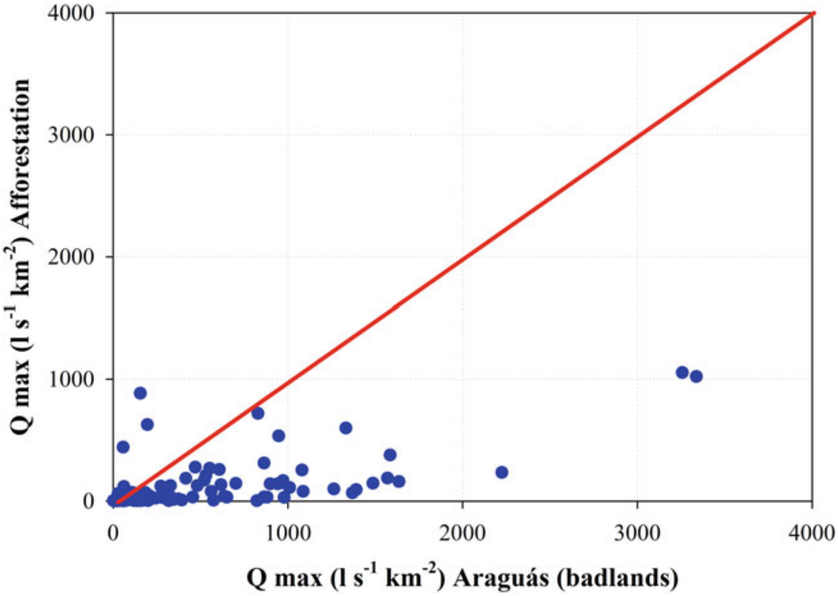

Fig. 5 Peak flows during concurrent floods in the afforested and badlands catchments (Araguás) in the Central Spanish Pyrenees (period 2013–2020). Data recorded by the Pyrenean Institute of Ecology (IPE-CSIC)

number of floods registered in the natural forest catchment (San Salvador). Besides, the abandoned areas are able to generate floods over the entire year, whereas the natural forest generate events mainly in spring.

Comparing the afforested area with the degraded area and the natural forest for the period 2013–2020, the number of floods is twice lower in the afforested area than in the degraded area (163 and 316 floods, respectively), but it is fourfold higher than in the natural forest catchment (163 and 41 floods, respectively). Most peak floods in the afforested catchment (except for extreme events, rainfall intensity >40 mm/h) have commonly recorded one order of magnitude lower than those on the unforested degraded area (Fig. 5). However, flood events lasted longer on the afforested catchment than in the degraded area (Fig. 5), due to a reduced connectivity and an enhanced infiltration in the afforested catchment.

Figure 6 shows the hydrological response in the four catchments during short and intense events recorded during late spring with similar rainfall amount and high rainfall intensity. We can observe that (1) a high peak flow was recorded in the degraded area; (2) in the natural forest a low response was observed, confirming the relevant role of rainfall interception and infiltration into the soil; (3) the time response is faster in the afforested area than in the natural revegetated area; and (4) longer recession times were observed in the afforested and natural revegetated areas, while in the degraded badland areas the rising and decreasing limbs are steeper, with high fast responses. These examples suggested that in afforested

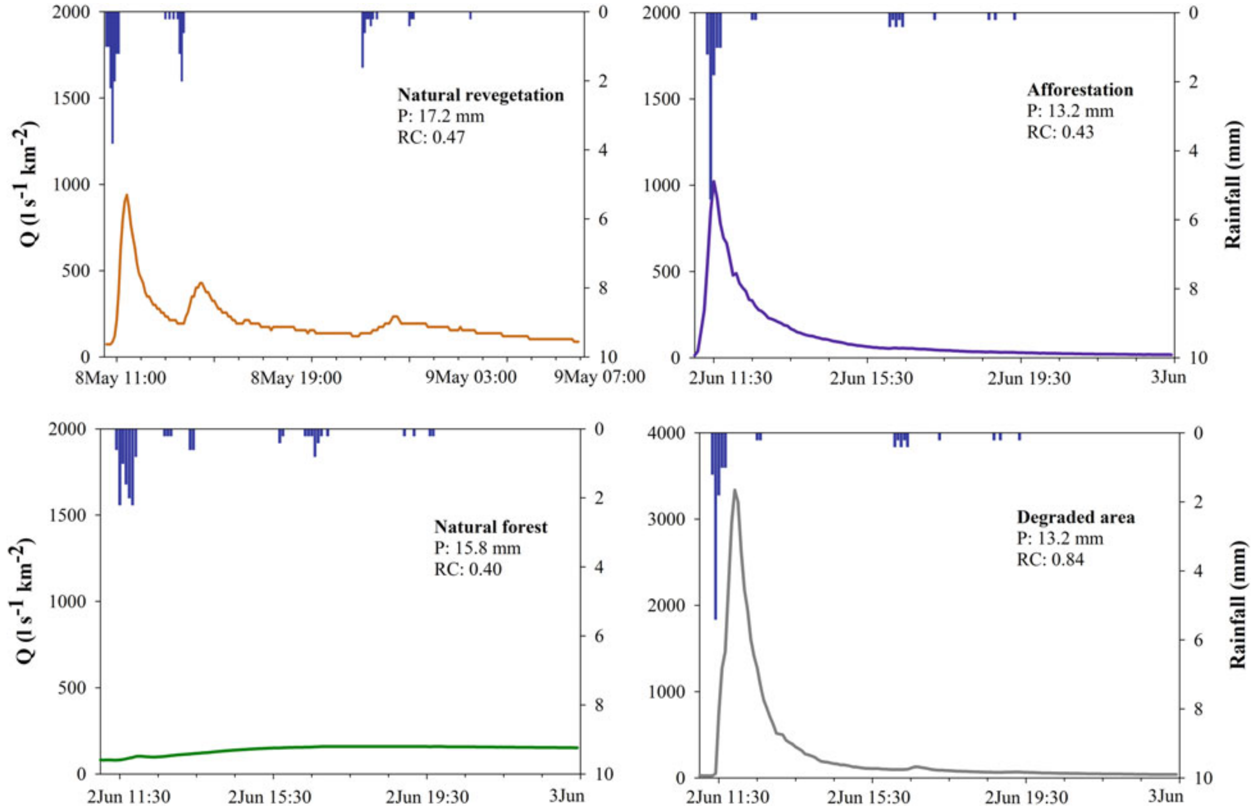

Fig. 6 Hydrological response during short floods recorded in late spring (May and June) in the four experimental catchments (natural revegetation, Arnás; Afforestation, Araguás afforested; Natural forest, San Salvador; and degraded area, Araguás). Note that the Q scale in the degraded area is different (twice the other Y axis). Data recorded by the Pyrenean Institute of Ecology (IPE-CSIC)

areas, flood mitigation effects are greatest for moderate floods, but have less impact during intense rainfall events as observed in Fig. 6.

A declining hydrological connectivity after land abandonment due to the growth of vegetation has been reported in a number of Mediterranean mountain areas [50]. Lana-Renault et al. [47] showed a decrease in connectivity in both abandoned catchments (Arnás and Araguás Afforestation). The largest decrease in the connectivity index was observed in the afforested catchment due to the significant changes from sloping, somewhat terraced fields to tree cover. López-Vicente et al. [51] showed that afforestation in the Araguás afforested catchment promoted lower and more stable connectivity both at hillslope and catchment scales.

Similarly, a decline in connectivity between slopes and the channel was observed in the Ijuez River basin (Central Pyrenees) that was also cultivated with sloping fields up to mid-twentieth century (Fig. 4c, d). The Ijuez River was highly affected by the occurrence of sudden floods with high volumes of sediment transport, mainly bedload, carried out by tributaries and frequent debris flows, resulting in a braided, extremely unstable fluvial channel (Fig. 4c) [56]. For this reason, in the 1950s the basin was purchased by the State Administration and afforested with *P. sylvestris* and *P. nigra* to reduce sediment yield and the transfer of sediments to the Yesa reservoir. A combination of green and grey infrastructures was carried out, with the construction of five small check dams to trap sediment production (Fig. 4d). Afforestation produced a rapid recovery of vegetation, and consequently a significant decrease in the area affected by erosion, declining sediment yield, and the connectivity between hillslope and channels [56]. This resulted in the narrowing and the incision of the channel and a progressive armouring of the bed [105].

Land abandonment and different LMPs based on NBS show also significant hydrological and geomorphological consequences during extreme events. It should not be forgotten that Mediterranean mountain areas are affected by intense rainstorms especially in summer and the beginning of autumn, with rainfall exceeding 200 mm in 24 h [62], and extreme floods are relative common in the area. In addition, an intensification of intense rainfalls due to climate change is also expected [106]. The occurrence of exceptional events can produce catastrophic floods, usually affecting small catchments. For instance, an exceptional hydrological event occurred during 19–21 October 2012 (250 mm in 2 days), in the Aragón River Basin (Fig. 3) [107]. The response was recorded in the four small experimental catchments [108] and the results indicated that: (1) the natural forested catchment showed a slow response and did not react to the most intense rainfall peaks at the beginning of the rainstorm, and only reacted during the final rainfall peaks, with a moderate peak flow; (2) the abandoned farmland catchment registered two moderate peaks at the beginning of the event, and only when the catchment was saturated a high peak flow was recorded; (3) a similar response was observed in the afforested catchment at the beginning of the flood, although unfortunately no data were available during the complete event; and (4) the degraded badland area showed a high fast response, almost immediately, with high peak discharges and high sediment yields coinciding with each rainfall peak.

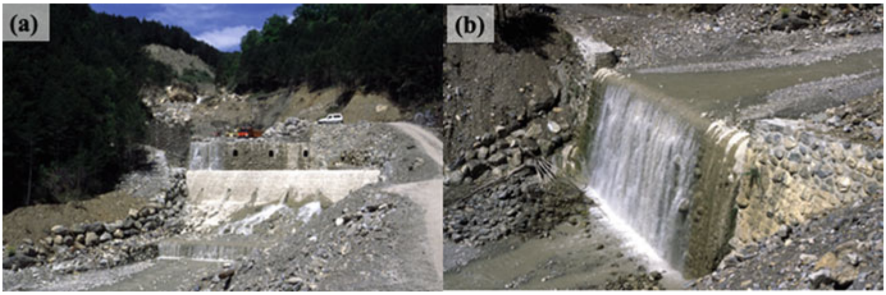

Fig. 7 (**a**) Construction of new check dams in the lower stretch of the Arás ravine (Upper Gállego basin), following the collapse of most of check dams during the extreme flood of August 1996; (**b**) New check dam in the lower course of the Arás ravine (Upper Gállego basin). It was constructed after the collapse of most of check dams during the extreme flood of August 1996 (Photos JM. García-Ruiz)

Finally, it should be also highlighted the consequences of extraordinary events, as the catastrophic flood recorded in the Arás river (Central Pyrenees, August 7, 1996), destroying a campsite situated in the alluvial fan of the torrent and killing 87 people [36]. The Arás catchment was characterized by the presence of a very steep stream channel (up to 20%) in the last 4 km, where the ravine crosses lateral moraines that behave as major sediment sources. As a consequence, the ravine developed a large and active alluvial fan that menaced the road from Saragossa to tourist resorts in the Central Pyrenees. An ambitious programme for reducing the magnitude of floods as well as erosion and sediment transfer from the moraines was designed at the beginning of the twentieth century. A combination of grey and green infrastructures was carried out, including (1) an artificial channel and 40 small check dams that were constructed between 1911 and 1950 in both the alluvial fan and the final stretch of the ravine, respectively; and (2) the afforestation of most of the catchment with *P. sylvestris*. In addition, decades later the forestry service carried out various correction works in the channel and constructed new check dams, as some of the old ones were already clogged (Fig. 7). The extreme rainfall (approx. 250 mm in 1 h and 15 min were indirectly estimated) produced an extreme peak flow of at least 300 $m^3\ s^{-1}$ that caused the collapse of a series of most of check dams in the Arás channel, carrying out around 120,000 t of sediment mainly coming from the collapsed check dams [109]. An event of these characteristics is always possible in the Central Spanish Pyrenees, and land management practices built on NBS should be considered as strategies to minimize and mitigate flood risks in these mountain areas.

A global and highly relevant question still emerges in Mediterranean mountains and in the Central Pyrenees: How should we manage abandoned lands? In that way, we encourage the use of the ecosystem services approach and NBS (as proposed in this chapter) in future public policies to manage land abandonment areas with different objectives as flood mitigation and water resources regulation.

4 Concluding Remarks

During the twentieth century, farmland abandonment has been the most relevant landscape change in Mediterranean mountain areas (as in other mountain areas), causing the expansion of shrublands and forests. The global consequences of this process have been widely discussed in the literature and several positive and negative effects have been identified (i.e. landscape homogenization, increasing forest fire risk and decreasing streamflows and sediment yield). However, the following question is still unresolved: how should we manage abandoned land to mitigate flood risk?

The impacts of land abandonment in flood mitigation in Mediterranean mountain areas depend greatly on how these areas are managed after abandonment (post-land management practices), which, at present is still a controversial topic. Nature-based solutions should consider the use of natural or semi-natural structures to reduce the occurrence of flooding events. The most used NBS in abandoned lands of mountain areas are natural plant recolonization, afforestation, shrub clearing, recovery of mosaic landscapes, and the reconstruction of terrace systems and stonewalls. These practices have been also combined with the implementation of grey infrastructures, as the construction of small check dams and sediment traps.

In general, worldwide land abandonment and the expansion of shrublands and forests (rewilding and afforestation) decrease hydrological and sediment connectivity, peak flows and sediment yield, and decline the frequency and magnitude of most frequent floods in mountain areas. However, some of these practices, as afforestation, have only remarkable effects on small and moderate floods, and have less impact in extreme and extraordinary rainfall events. In the case of extreme rainfall and hydrological events, the role of plant cover seems to be moderate in both slopes and channels, although it also depends on the antecedent conditions of the soil. In the most extreme hydrological events (outliers) not any influence of vegetation to reduce the peakflow has been detected. The construction of some infrastructures in the main and secondary fluvial channels (check dams) reduces sediment transfer, whereas artificial channels can provide a false sensation of safety. Obviously, the presence of large reservoirs tends to change the behaviour and seasonality of large floods, because floods occur when the reservoir is partially empty. In any case, NBS, focused on the reduction of runoff and connectivity, must be applied directly on the slopes, before runoff reaches the fluvial channels. Shrub clearing is another alternative strategy for organizing the landscape to improve grasslands productivity and at the same time controlling sediment yield and runoff generation. This needs a high-resolution knowledge of the landscape heterogeneity in order to decide the location of clearings and to reinforce the declining connectivity between slopes and channels. Finally, the maintenance or rehabilitation of agricultural terraces reduces flood risk because they decrease overland flow and connectivity on hillslopes. For this reason, permanent human intervention is needed to maintain NBS as strategies to flood mitigation in marginal Mediterranean mountains areas.

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