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Observations on different post-fire bio-engineering interventions and vegetation response in a *Pinus canariensis* C. Sm. forest

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ABSTRACT On the Canary Islands, during the 2007 (30 July - 2 August) wildfire, about 18,000 hectares of forest were destroyed. After the event, to avoid erosion, a series of mixed check dams (wooden elements and stones with a core filled with forest residues) were built in the gullies created by the surface runoff. This first study aims to investigate the different responses of vegetation and its recovery after fire, with three different types of structures. We analyzed the performance and evolution of the mixed check dams nine years after their construction and the post-fire response of vegetation with the different types of bio-engineering techniques applied. The effects of the mixed check dams are expressed in terms of plant density, frequency, and cover both in absolute and in relative terms and the same effects were compared with those of the rocks, check dams, wattle fences, and structure in the surrounding areas. Our observations show that fire adaptation in the Canary Islands vegetation (pyrophyte plants), coupled with selected bio-engineering techniques, facilitated resprouting, seeds germination and a quick restoration of the forest ecosystem. The study confirms that simple, nature-based and low cost bio-engineering measures, which use local materials and are consistent with traditional building experiences effectively contribute to site restoration.

KEYWORDS: pyrophyte plants, Point-Centered Quarter method, forest resilience, soil erosion, mixed check dams.

Introduction

High-severity fires have significant impacts on ecosystems. Commonly, the degree of fuel consumption in the understory or canopy layer (Perez and Moreno 1998) or the level of crown damage (Pausas et al. 2003) are considered, but the degree of mortality of trees and shrubs is also used to estimate fire severity (Chappell and Agee 1996). Fire modifies the soil protection provided by plants and consumes the soil surface organic layer (Neary et al. 2005a). High-severity fires may also burn the organic matter in the uppermost layer of the mineral soil, and the resulting loss of soil aggregates can greatly increase the soil erodibility (DeBano et al. 2005). Fires can also induce formation of a water-repellent layer on or near the soil surface (DeBano 2000). The consequences of the latter are low infiltration rates and high overland flow velocities which, in turn, increase the size of peak flows and surface erosion rates by sheetwash, rill, and channel erosion (Shakesby and Doerr 2006). Rills and gullies readily form where there is a surface runoff buildup caused by topography, rocks or logs (Fig. 1c).

After each fire event, the reduction of surface roughness with the loss of vegetation can increase the velocity of surface runoff, and the combination of reduced infiltration and high overland flow velocities can increase the size of peak flows by one or two orders of magnitude (Scott 1993, Moody and Martin 2001, Neary et al. 2005b). The net effect is that high-severity fires can increase sediment yields by two or more orders of magnitude (Robichaud et al. 2000, DeBano et al. 2005, Shakesby and Doerr, 2006). The severity of the fire reflects its impact on vegetation and soil (Whelan 2002). The combination of intense rainfall and increased soil erodibility is critical in post-fire scenarios due to the water flow resulting in carving, gullies, and instability of slopes.

Forest fires are frequent in Canary Islands mainly due to the high human pressure, the large forested area, the botanical composition of these forests, which usually include highly flammable plants and, the alternation of wet and dry seasons (Neris et al. 2016). Several large and recurrent wildfires have occurred in the Canary Islands over the last 45 years. The average number of wildfires per year is 70 and the average area affected is 2,560 ha per year (Instituto Canario de Estadística 2015).

Particularly, the Teide National Park was affected in 2007 by a major forest fire, that burned over 17,000 ha between 30 June and 2 August (Ministerio de Medio Ambiente y Medio Rural y Marino 2008). The fire in 2007 spread very fast due to exceptionally high air temperatures (40 °C), very low air humidity (20%) and strong eastern winds from Africa (Rudiger et al. 2010).

The loss of the protective effect of vegetation cover, and the increased surface repellency as a consequence of the fire, increased the loss of organic matter and soil by water runoff (Poulenard et

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al. 2001, Morales et al. 2013, Neris et al. 2013). The combination of intense rainfall and increased soil erodibility is critical in post-fire scenarios due to the water flow resulting in carving, gullies, and instability of slopes.

To fight against these effects, the erosion control techniques traditionally used in the Tenerife Islands are: gabion walls, masonry walls, and rock fills. By the time when the 2007 huge wildfire occurred, a tradition in the use of soil bio-engineering techniques was lacking in The Tenerife Islands.

Soil bio-engineering, also termed eco-engineering, makes use of living plants or cut plant material, either alone or in combination with inert structures, to control soil erosion, the mass movement of land and fulfills engineering functions (Schiechtl et al. 1980). The self-repairing characteristics of the vegetation used and the resilience capacity of the bioengineered area (Mickovski 2014) are very important allies in the eco-engineering design philosophy.

Knowing that bio-engineering works can decrease flow speed, increase ground roughness and trap sediments (Vennetier et al. 2014), structures such as mixed check dams and wattle fences were built (Tardío-Cerrillo. and Caballero-Serrano 2009) during the post-fire emergency period. These were used as the main treatment to reduce ephemeral or small-order channels or gullies, in combination with complementing treatments such as rock dams and gabions dams in larger channels and road cuts (Fig. 1b).

Plant roots can reduce soil degradation processes such as surface erosion and shallow landslides (Gyssels and Poesen 2003, Stokes et al. 2014, Giadrossich et al. 2016, Giadrossich et al. 2017, Cohen and Schwarz 2017).

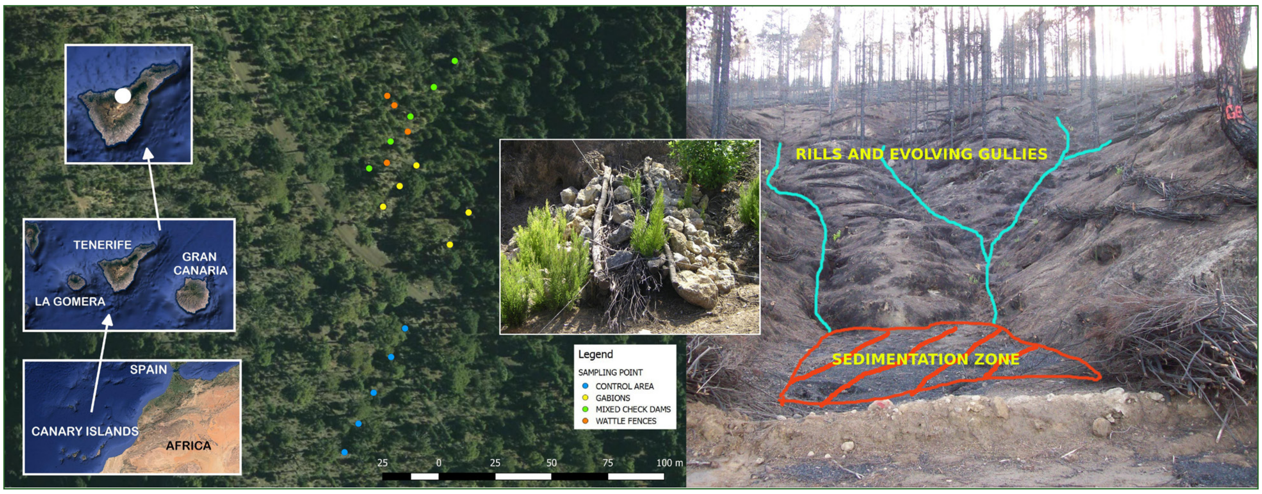
Our research aims to add further information to previous studies and it has the specific purpose of understanding how the different types of interventions of bio-engineering works influenced the dynamics of post-fire vegetation during the nine years since interventions. In this study we report on observations carried out in summer 2016 at Tenerife island on different vegetation responses in terms of regeneration, density, frequency, and vegetation cover in relation to the bio-engineering works. We also critically evaluate the performance and evolution of the vegetation around mixed check dams nine years after their construction, aiming to enhance the available knowledge on bio-engineering work performance.

Study area

The study area is located in the Teide Forestry Crown (Tenerife Island, Canary Islands, Spain), at the north-facing side of the island (Fig. 1a). Here, a wide variety of meso- and micro-climates can be found (Del Arco et al. 2006) under a different range of vegetation including grasses, shrubs and trees. The forest is a natural stand dominated by *Pinus canariensis* C. Sm, mixed with *Myrica faya* Aiton, *Cistus symphytifolius* Lam. and *Erica arborea* L.

Steep (30° to 50°) hillslopes characterize the study area. The mean annual precipitation is between 600 and 1,000 mm, characterized by intense rainfalls. Annual precipitation reaches 800 mm in the most humid sites on the northern slopes at about 1,000 m, whereas fog drip can substantially increase overall precipitation (Marzol 2008). The high-intensity rainfall events enhance the erosive processes as the main deconstructing agent in the study area. The soils of the study area are mostly Andisols (Ustands and Udands) due to the volcanic nature of the island. These soils have a high structural development, porosity and, therefore, high water infiltration rates. Nonetheless, in the pine forest area, the soil permeability has relatively low values (Neris et al. 2013) due to the pine forest duff which forms a continuous hard layer on the soil surface and has a higher water repellency compared to the surrounding rainforest

Figure 1 - Location of the sequences of survey points (a). Mixed check dam and wattle fences (b). The first storms after the fire carved a network of channels extending from the ridgetop (c).



formations (Neris et al. 2013). The elimination of the forest floor as a result of land use change (or of a wildfire) can trigger extensive erosive phenomena (gullies). Soil nutrients (mg/kg soil) were taken from the study of Durán et al. (2008).

Pinus canariensis C.Sm. fire adaptation

Pinus canariensis C. Sm. has numerous adaptive traits related to fire resistance specifically thick bark, long needles, thick buds, tall growth habit, deep rooting, longevity, and sprouting capability. Serotinous cones ensure post-fire recruitment adding to the sprouting capability of adult trees being one of the most striking characteristics of the Canary Islands pine (Ceballos and Ortuño 1976) (Fig. 2).

Figure 2 - Re-sprouting *Pinus canariensis* C. Sm trees.

This pine produces a considerable proportion of serotinous cones, similar to Mediterranean serotinous pines such as *Pinus halepensis* Mill. and *Pinus pinaster* Aiton (Tapias et al. 2004). The degree of serotiny of the Canarian pine seems to be higher for stands in the north of Tenerife, reaching 60% (Tapias et al. 2004), than in the south of the island, which was related to higher levels of productivity and to higher frequency and intensity of fires in the north of the island (Climent et al. 2004).

It has been shown that *Pinus canariensis* C. Sm. seeds resist heat better than small seeds of other pine species and that seedlings developing after heat treatment are larger than those deriving from non-heatedseeds (Escudero et al. 2000).

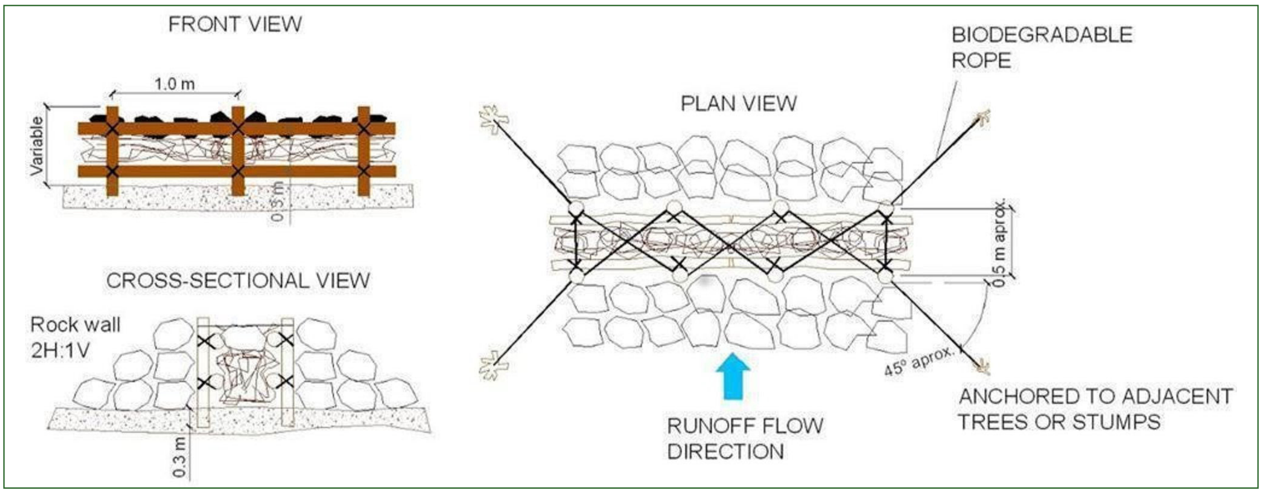
A recent study (Mèndez et al. 2015) indicating that seed rain production is not affected by fire age but very likely varies depending on environmental characteristics. The number of large (high diameter) adults with the capacity to produce large numbers of seeds together with elevation and precipitation appear to be the most influential variables in the regeneration of *Pinus canariensis* C. Sm.. In natural pine forests of Tenerife, tree density was also an essential factor conditioning seed availability (Otto et al. 2010). Despite favouring seed production, high adult density can produce adverse conditions for regeneration by reducing light in the understory, or by competing for water and nutrients, thus increasing seedling mortality, as has already been shown for *Pinus canariensis* C. Sm. (Arévalo and Fernández-Palacios 2008, Peters et al. 2001).

The behaviour of *Pinus canariensis* C. Sm., in which both serotinous and non-serotinous cones combine to produce seed rain over the whole year. This continuous supply of seeds allows a transient seed bank throughout the year, offsetting the problem of rapid loss of seed viability on the ground, which is typical of many pine species on field conditions (Keeley and Zedler 1998). Additionally, seeds can be wind dispersed over distances of 1.6 km, allowing low-productive stands to receive seed inputs from near high-productive stands (López de Heredia et al. 2010). Durán et al. (2008) found that soil nitrogen content is affected by forest fires, showing lower values in burned than unburned stands and suggested that these differences could cause long-term reductions in productivity. The recovery of nitrogen content in the long term may be masked or exceeded in importance by other stand conditions such as the modification of nutrients spatial heterogeneity (Rodríguez et al. 2009). Consequently, the existence of suitable microsites for germination and recruitment seems crucial for *Pinus canariensis* C. Sm. regeneration, as shown in other pine species (de Groot et al. 2004, Bonnet et al. 2005, Vega et al. 2008).

Mixed check dams in Tenerife: description and work strategy

In addition to the traditional channel treatments, an innovative structure adapted to local conditions called rock and biomass mixed check dam, was developed. Due to the severity of the wildfire and the resulting risks, the mixed check dam structure was designed to be low-cost, easily and rapidly implemented to reduce hydrological risks. The mixed check dam is a temporary structure that combines different mitigation techniques such as contour logs, contour trenches, and rock dams. Similarly, to other channel or gully treatments, its main objective and engineering function is to reduce the water velocity and enhance infiltration and sediment deposition. The mixed dam consists of vegetal debris used as vertical stakes (mainly burned logs of *Erica* sp. and *Myrica faya* Aiton), horizontal logs (mainly from burned *Pinus canariensis* C. Sm.), and biodegradable rope to tie the stakes and logs together as a trench while anchoring the whole structure to adjacent trees. The trench is reinforced on the outside by a rock slope (revetment) to gain stability (less than 50% slope angle); the inside is filled with vegetal debris obtained from the local silvicultural work and topped again

Figure 3 - Schematic of a typical mixed check dam.



with rocks. The dimensions of a mixed dam vary depending on the channel width, ranging from 1 to 2 m in height and 8 to 10 m in length (Fig. 3).

This innovative structure can provide several benefits for erosion control such as reduction of the channel slope and, thus, of water speed and detachment capacity; promotion of infiltration and sedimentation; reduction in resources and construction time by using on-site material; enhancement of the colonization of vegetation due to the biodegradable nature of most of its components. The advantages of a mixed check dam are its notable sediment storage capacity, mainly for large material such as vegetal debris or rocks; high adaptability of the design and the components to the environment conditions; notable vegetation recovery and colonization of the channels (Tardío-Cerrillo and Caballero-Serrano 2009, Tardío-Cerrillo and García-Rodríguez 2016).

Vegetation survey

The difficult working conditions on the terrain, due to the rugged and steep slopes, led us to choose the point-centered quarter (PCQ) sampling method (Cottam and Curtis 1956, Mitchell 2015) as the most appropriate for our survey. The PCQ method is a plotless approach to density and 'cover' estimation that can take into consideration, with equal effort, all species, as it is not focused on forest trees. Campus et al. (2014) evaluated PCQ as an effective and efficient alternative approach that addresses a variety of features directly related to functionality and complexity assessment. It is relatively easy to manage and implement and less expensive compared with more conventional and laborious area-based tally surveys.

The PCQ is a plot-less distance-based technique. Four quarters are established around a sampling point and four distances are measured from the point to the nearest element being analyzed. The parameters obtained in this distance method can be: species distribution, total and components density; average quantitative characteristics (diameter at brest height) and corresponding component dominance (Fig. 6).

PCQ can provide a wider and more uniform coverage of different forest stand components while allowing the information concerning the trees to be well represented. To complement the qualitative description of the study area with a minimum of measurements, four sequences of points have been traced crossing and subjectively sampling the different kinds of interventions:

A a sequence in a gully with gabions upslope and downslope

B one in a gully with mixed check dams

C a slope with wattle fences

T a slope where no anti-erosion structures were built.

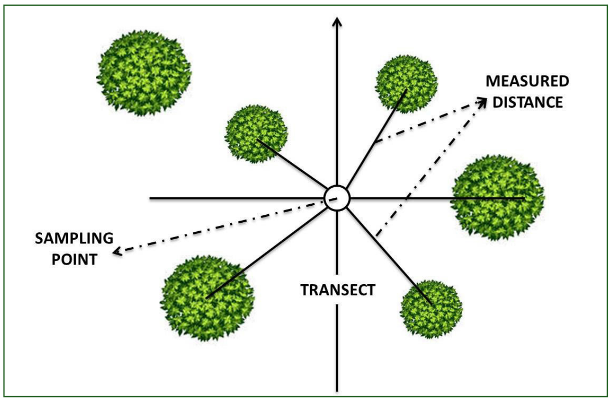
The stands were analyzed considering the following three disjoint sub-populations (or 'vertical layers'):

* 'trees', with stems dbh greater than 3 cm
* 'shrubs', shrub species
* 'saplings', tree species with dbh up to 3 cm

The lengths of the points sequences ranged between 80 and 100 m, with a limited number of survey positions considered for each treatment (5 for all other, 4 for 'wattle fences' sequence). Applying the PCQ approach, four distances, one for each quarter, were measured from the center to the nearest element of each vertical layer (Fig. 4) at each sampling point.

Several measurements were taken on each plant present, before and after the fire, for each sample: species, height, crown radius and, for 'trees', diameter at breast height (dbh). Survey data have been processed following Mitchell's suggestions (Mitchell 2015) and finally producing a graphical representation of the main characteristics of the forest stand structure, of species composition and of the small differences that could be quantitatively assessed among the local conditions where different structu-

Figure 4 - Sampling design Point Centered Quarter measurements method.



res were built. The vegetation cover is assessed by multiplying the average crown area by the species density. This measure, expressed as percent of the terrain area, offers the most significant synthesis of the PCQ based survey (Fig. 6).

First observations on different post-fire bio-engineering interventions and vegetation response in a *Pinus canariensis* C. Sm. Forest

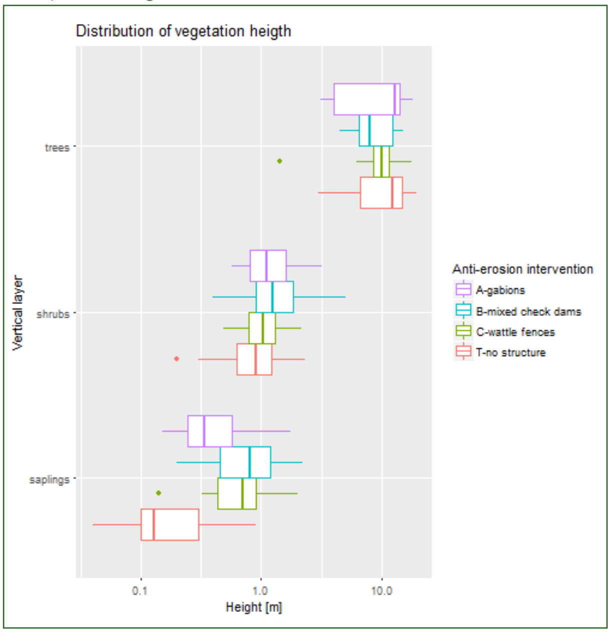
Silvicultural practices on the affected area were carried out immediately after the fire, including the removal of dead individuals and the pruning of charred branches of surviving trees to reduce infestation threats and strengthen their recovery. Recent observations, after a forest fire that affected La Gomera in 2012, suggest that silvicultural practices could delay vegetation recovery after fire (Neris et al. 2016).

The vegetation survey offers some details for the characterization of the forest stands interested by the different kinds of anti-erosion interventions considered. Due to operational constraints (slope, time, etc.) only a limited number of points could be surveyed. The points have hence been positioned subjectively. Representativity of the considered situations relies on the subjective evaluation as it was not possible to survey the same intervention in different conditions (e.g. slopes with different aspect). Moreover, as will be further commented, intensity of post-fire silvicultural interventions (and possibly fire severity) where not (as usual) uniformly distributed.

The three layers considered (saplings, shrubs and trees) are, as expected, vertically stacked and relatively similar, across treatments (Fig. 5), without relevant differences in term of height. Within each layer, heights distributions, syntetised by the box and wiskers, are relatively similar, except in the regeneration born in the controlled area which has low height values compared to the estimated regeneration in the other bioengineering structures.

The different attributes that were measured are quite tightly correlated (Fig. 6). Some minor diffe-

Figure 5 - Basic characteristics: distribution of vegetation heights, by anti-erosion intervention and vertical layer. Height scale is logarithmic. Boxes represent the first and third quartile, with the median in between as bold line, while whiskers are extended 1.5 times the interquartile range.



rences can be evidenced in the distribution of crown area versus element height. Crown dimensions appear to be reduced for trees in the 'wattle fences' area and for saplings in the 'no structure area'.

The higher presence of seedlings of *Pinus canariens* C. Sm. in points with wattle fences and mixed check dams (Tab. 1) is probably due to the higher number of adult trees and also to the favorable edaphic conditions created by the bio-engineering structures made with natural materials.

The seed bank depends on the presence of the mother plants but the germination and the growth in the early and subsequent years of the pine seedlings are strongly influenced by the environmental conditions that regeneration finds on the ground (pedological and hydrogeological microclimatic) (Leone et al. 2004).

Figure 6 - PCQ estimate of total crown cover by species as percent (logarithmic scale) of the forest area.

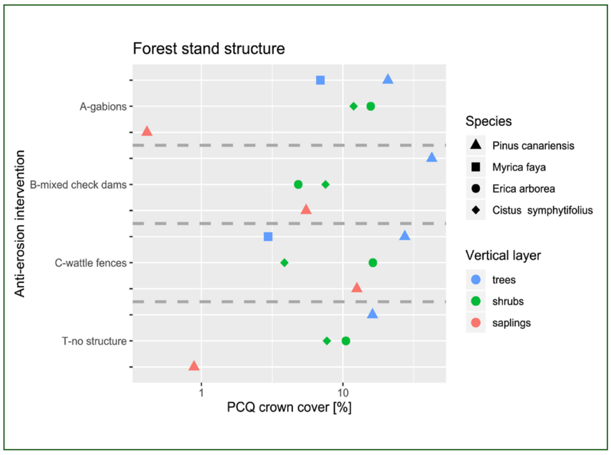


Table 1 - PCQ based density estimates, number of elements per hectar.

Anti-erosion intervention	Vertical layer		
	Saplings	*Shrubs*	*Trees*
A-gabions	1016.1	5461.6	85.6
B-mixed check dams	3921.5	6453.3	288.6
C-wattle fences	3334.2	5631.0	453.7
T-no structure	2153.5	8456.6	207.1
Average	2606.3	6500.6	282.7

Initial seedling density can be negatively influenced by high levels of crown damage (Fernandes et al. 2008, Vega et al. 2008). This has, on the one hand, been interpreted as a result of a partial destruction of the aerial seed bank due to high fire intensity.

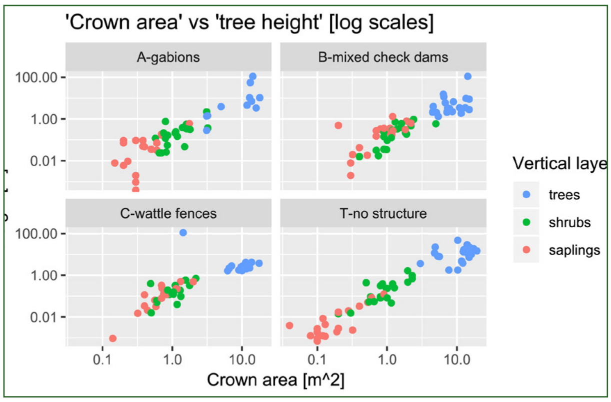
Apart from fire severity, other factors such as topography, exposure, aspect and climatic conditions during the growing season, after fire or micro-environmental conditions, have been reported to influence post-fire regeneration in pine forests (Daskalakou and Thanos 2004, Bonnet et al. 2005).

The above is also confirmed by a recent study (Mèndez et al. 2015) indicating that seed rain production is not affected by fire age but very likely varies depending on environmental characteristics.

It is therefore very likely that, after several years after the fire, the components of the biodegradable nature of these mixed controls may also facilitate plant colonization (Tardío-Cerrillo and Caballero-Serrano 2009).

The analysis showed that Pinus trees always provide the most relevant coverage (reaching 42.5%) followed by *Erica arborea* L. Shrubs coverage is significant, though variable in terms of species composition while saplings present quite different coverage values. The presence of anti-erosion structures is associated with larger coverages by saplings of *Pinus canariens* C. Sm.

Figure 7 - Basic characteristics: height and crown area (logarithmic scales) are tightly correlated (p<0.001), analyzed conditions present minor differences in values distributions.



Where wattle fences are present, the tree layer (almost exclusively characterized by *Pinus canariensis* C. Sm.) exhibits higher density (Tab. 1) and higher tree cover (Fig. 7). To some extent though, compared to other parts of the study area, here post-fire silvicultural treatment has been less intensive.

The regeneration of *Pinus canariensis* C. Sm. is well developed where mixed check dams are present, possibly due to locally better edaphic conditions around the wattle fences and, in addition, due to the presence of a higher number of seed trees (Tab. 1 and Fig. 7). The shrub layer, mainly represented by *Cistus* spp., is scarcely present due to the strong competition of the tree layer. The density, frequency and relative vegetal cover values of the tree layer indicate that *Pinus canariensis* C. Sm. grows in a rather reduced mixture (17%) with *Myrica faya* Aiton; the density and relative frequency of shrub species reflect the homogeneous distribution of *Cistus symphytifolius* Lam. and *Erica arborea* L.; the relative vegetal cover values in shrub layer indicate a better growth of crown, thus of vegetal cover, in *Erica arborea* L. than in *Cistus symphytifolius* Lam.

The concept note exploits descriptions and data collected thanks to a short but intensive survey conducted in this burnt and restored forest area located on the Canary island. The survey took place nine years after the different bio-engineering structures had been built, a long enough time lap in order to start the evaluation of the effects of vegetation post fire restroration with and without anti-erosion interventions.

The advantages attributable to these mixed dams are:

(i) notable sediment storage capacity, mainly large material as vegetal debris or rocks;

(ii) high adaptability of the design and the components used to the environment conditions;

(iii) notable vegetation recovery and colonization of the channels due to the nature of its components (Neris et al. 2016). The data suggest that, where mixed check dams are present, this type of post-fire management favors the development (density and absolute cover) of the regeneration of *Pinus canariensis* C. Sm.

Conclusions

Fire adaptation in pines is explained by the use of two different strategies: individual resistance and stand resilience (Keeley and Zedler 1998). The first implies the survival of the adult plants while the second ensures seedling recruitment after the depletion of the original stand. Even when some species seem to have predominantly selected one of the two strategies, both can be simultaneously or alternatively advantageous depending on endogenous factors (e.g. age, vigour) or environmental variation [site quality and fire recurrence (Agee 1998)]. It is also important to consider that the serotinous cones in *Pinus canariensis* C. Sm. are "xeriscent" rather than "pyriscent" (Nathan et al. 1999, Nathan and Ne'eman 2000) since seed dispersal occurs after a variable time lapse after the presence of fire.

Our first results show the fire adaptation of the Canary Islands vegetation (pyrophyte plants) coupled with selected bio-engineering techniques, facilitated the seedlings germination and allowed the restoration of the forest ecosystem while reducing the soil erosion rates. In terms of resilience, the rehabilitation measures adopted in the study site obviously have positive influence on the detrimental effects of key biophysical processes including the extreme rainfall episodes, fires, and the erosion processes. Stable states are represented by the pyrophytic vegetation associated with the pine forest community.

Additionally, *Erica* also exhibits high sprouting capacity after fire (Lloret et al. 2003). Within the gullies, the transition between the post-fire temporary situation and the stable pine forest community is mediated and markedly accelerated by the mixed check dam series. Once the woody community is established within and around the dams, due to local favorable conditions, the soil will be well preserved and the woody community can persist for a long time (or until the next disturbance). This would be the natural dynamic in the intervention area. Our observations confirm that simple, nature-based and low-cost bioengineering measures, which use local materials and are consistent with traditional building experiences effectively contribute to site restoration.

The rationale behind these interventions was that once the sediment entrapment is initiated and a more stable soil system is developed behind the retaining structure, colonization by the local plant species can begin and a new recovery dynamic would be created.

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