Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

Article

Impacts of land management on the resilience of Mediterranean dry forests to fire

Matteo Jucker Riva[1 2*], Hanspeter Liniger[2], Gudrun Schwilch[2], Alejandro Valdecantos[3]

[1] Institute of Geography, University of Bern, Switzerland

[2] Centre for Development and Environment (CDE), Switzerland

[3] Mediterranean Centre for Environmental Studies (Foundation CEAM), Spain

* Correspondence: matteo.jucker@cde.unibe.ch ; Tel.: +41765590724

Abstract:

Wildfires have always been a part of the history of Mediterranean forests. However, forest regeneration after a wildfire is not certain. It depends on many factors, some of which may be influenced by land management activities. Failure of regeneration will cause a regime shift in the ecosystem, reducing the provision of ecosystem services and ultimately leading to desertification. How can we increase Mediterranean forests' resilience to fire? To answer this question, we did a literature review, investigating chains of processes that allow forests to regenerate (which we label "regeneration mechanisms"), and assessed the impact of selected management practices documented in the WOCAT database on the regeneration mechanisms.

We identified three distinct regeneration mechanisms that enable Mediterranean forests to recover, as well as the time frame before and after a fire in which they are at work, and factors that can hinder or support resilience. The three regeneration mechanisms enabling a forest to regenerate after a fire consist of regeneration (1) from a seed bank; (2) from resprouting individuals; and (3) from unburned plants that escaped the fire.

Management practices were grouped into four categories: (1) fuel breaks, (2) fuel management, (3) afforestation, and (4) mulching. We assessed how and under what conditions land management modifies the ecosystem's resilience. The results show that land management influences resilience by interacting with resilience mechanisms before and after the fire, and not just by modifying the fire regime. Our analysis demonstrates a need for adaptive – i.e. context- and time-specific – management strategies.

Keywords: Keywords: resilience, land management, wildfire, Mediterranean dry forest

PACS: J0101

---

1. Introduction

Dry Mediterranean ecosystems are said to be particularly resilient to fire due to their long history of exposure to this type of disturbance. Many of the plant species found in Mediterranean forests and shrublands show some degree of adaptation to fire and even rely on fire events to complete certain stages in their life cycle [1]. However, some previously forested areas in Mediterranean drylands have experienced a regime shift following a wildfire. While the most evident trigger of such a regime shift is a change in the fire regime (i.e. frequency and/or intensity of fire), the root causes are systemic

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

and linked to multiple factors that interact within the local ecosystem, including climate, soil properties, land use, land use history, and others [2].

According to the concept of "ecological resilience" [3], an ecosystem can be considered resilient if it is able to recover its composition, structure, and main functions following a disturbance. Thus, we can label a forest as resilient if it is able to recover its previous vegetation structure (e.g. a tree layer and a shrub/ground layer) after a disturbance and the regenerated community is composed of the same set of species. In this way, the regeneration of trees that constituted the pre-disturbance canopy is not only the most visible display of resilience, but also the main concrete process that fosters resilience [4]. The recovery of the vegetation depends on specific chains of physical processes that take place before, during, or after the disturbance. We refer to them as "regeneration mechanisms".

Land management practices in Mediterranean forests are generally focused on reducing fire occurrence or on mitigating its impacts. However, these interventions interact with all components of the ecosystem: vegetation, soil, fauna, and human action. There is little research on the effectiveness of these management practices on canopy regeneration due to the long time span needed for assessments as well as the variability in time and space of forest ecosystems, fire events, and management approaches. Most of the available literature focuses on changes in the fire regime. Nevertheless, land management practices are the most effective way of increasing forests' resilience in the short term; assessing their impacts is an important means of "learning by doing", which is essential to improving the sustainability and management of our ecosystems [5]. Documenting how management is implemented on the ground, and studying the direct and indirect impacts on the ecosystem is crucial if we want to increase the resilience of Mediterranean forest ecosystems.

In this paper we begin by reviewing the scientific literature on regeneration mechanisms in Mediterranean forest ecosystems, which we believe sets a good foundation for subsequent resilience assessments and evidence-based management decisions. We then present the results of land managers' and other experts' assessments of systemic interactions between land management practices and forest regeneration mechanisms. These assessments and corresponding analytical framework can enable forest managers to better understand the vulnerabilities of their own specific system, and can enable researchers to identify knowledge gaps in our scientific understanding of the resilience of real-world forest ecosystems.

2. Materials and Methods

2.1 Identification of regeneration mechanisms

In order to identify regeneration mechanisms in Mediterranean forests, we analysed 41 peer-reviewed articles on responses to fire in Mediterranean dryland ecosystems. The articles belonged to 3 different categories (from largest to smallest): (1) direct observations of fire impact or of vegetation recovery after fire; (2) studies (including reviews) on functional traits related to recovery after fire; and (3) articles providing information on key Mediterranean species. For categories (1) and (3) we selected only articles on Mediterranean vegetation, while in category (2) we also included articles on ecosystems similar to the Mediterranean but located outside the Mediterranean basin. In addition, we also considered published databases as sources of information about specific species.

Those physical and biological processes that directly foster vegetation recovery from a fire event were identified as "regeneration mechanisms". Regeneration mechanisms are characterized by the following properties:

- Processes involved: biological processes that enable the forest to recover and constitute the actual regeneration mechanism. One example is the constitution of a seed bank prior to the fire.
- Preparation period: the time needed before a fire for the regeneration mechanism to become effective and to enable forest regeneration after the disturbance. For example, plant recolonization from a seed bank requires that the plant had time to reach maturity before the fire event; in the case of Pinus halepensis, this takes 15 to 20 years [6].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

- Effectiveness period: the time span after the fire event during which the regeneration mechanism is effective, from the appearance of first signs of recovery to the time when no further recovery may be expected. For example, seeder species are likely to germinate in the next wet season following a fire[7] but no longer than 2 years after the fire.
- Hindering and supporting factors: factors that may reduce (hindering factors) or increase (supporting factors) the regeneration mechanism's effectiveness. For example, frequent fires will reduce the capacity of plants to resprout, preventing regrowth of forest resprouter species[8].

To evaluate the impacts of land management on the resilience of Mediterranean forests to fire, we investigated how different management practices affect these regeneration mechanisms.

2.2 Data on Land Management Practices

The World Overview of Conservation Approaches and Technologies (WOCAT) database contains information about sustainable land management practices from around the world that have been documented in a standardized and scientific manner [9]. Information about benefits and disadvantages of management practices is derived from semi-quantitative assessments based on consultation with stakeholders, combined, wherever possible, with scientific data and observations. We selected the land management practices for this study according to three criteria that, taken together, define Mediterranean forests: (1) the land use type is forest/woodland; (2) the agro-climatic zone is sub-humid to semiarid; and (3) the practice is applied in a Mediterranean country. The land management practices were then grouped according to their main objectives: fuel breaks (prevention), fuel management (prevention), reforestation (rehabilitation), and soil protection (mitigation).

2.3 Assessing the impact of management practices on regeneration mechanisms

First, we established a link between the indicators of ecological benefits and disadvantages used in the WOCAT Technology Questionnaire and the hindering and supporting factors of the three regeneration mechanisms. On this basis, we then analysed how the land management practices influence the hindering and supporting factors of each regeneration mechanism, thus identifying hindering and supporting interactions between land management and the resilience of Mediterranean forest to fire. In doing so, we also considered differences between land management practices belonging to the same group.

3. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

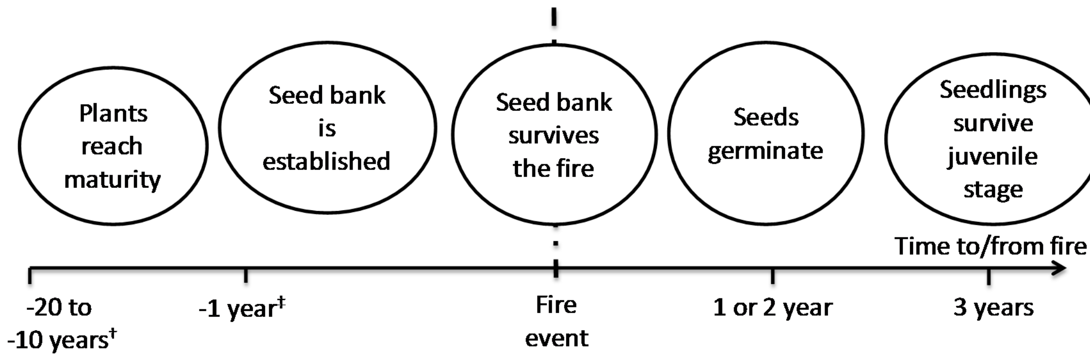
3.1. Regeneration mechanism 1: Forest regenerates from a seed bank

3.1.1 Processes involved

Post-fire regeneration from a seed bank refers to forest regrowth from seeds produced before the fire event and left in the soil or the canopy. This regeneration mechanism includes multiple processes. For the forest to regenerate after a fire, plants must first reach sexual maturity and produce viable seeds, which need to be stored in the canopy or in the soil, creating a seed bank. The seeds then have to survive the fire, germinate, and produce seedlings that survive their juvenile stage and reach maturity again (Figure 1).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981



(a)

Figure 1. Processes involved in forest regeneration from a seed bank (Regeneration mechanism 1) †Time needed for trees to reach maturity. Shrubs take between 5 and 10 years (see table 1) ‡For transient /ground seed banks. Seeds can resist in the canopy for up to 50 years

Post-fire regeneration from a seed bank refers to forest regrowth from seeds produced before the fire event and left in the soil or the canopy. This regeneration mechanism includes multiple processes. For the forest to regenerate after a fire, plants must first reach sexual maturity and produce viable seeds, which need to be stored in the canopy or in the soil, creating a seed bank. The seeds then have to survive the fire, germinate, and produce seedlings that survive their juvenile stage and reach maturity again.

Even if most plants produce seeds, a reduced number of species only recover from seeds while the rest combine this strategy with resprouting organs. ([10]). The traits that characterize a so-called "seeder plant" include a high production of seeds, mechanisms for seed dispersal, and a high germination rate [11].

Some of the common seeders of the Mediterranean area appear to have adapted specifically to fire: their seed bank is protected in the canopy (e.g. in cones) rather than in the soil, and seed dispersal is triggered by heat, increasing the chances of successful germination [12]. Table 1 presents common seeder species in the Mediterranean basin.

Seeder species are often highly flammable and, especially when the germination is stimulated by heat, they tend to form a highly dense canopy structure, which increases the risk of intense fires.

Table 1. Common seeder species in the Mediterranean basin and their traits related to Regeneration mechanism 1

Species	**Longevity of seed bank**	**Heat-stimulated germination†**	**Post-fire seedling emergence ‡**	**Seedling survival after first summer §**	**Type of seed bank**ǀ	**Age of maturity (years) ¶**
Cistus salvifolius	>1 year††	+	high	high	soil	1–2
Erica umbellata	<1 year‡‡	0	yes	high	soil	<5
Cupressus sempervirens	>15 years	no data	yes	high	aerial	6
Pinus halepensis	>5 years	0/+	high	high	aerial	10–20
Pinus brutia	<1 year	-/0	high	high	aerial	9
Rosmarinus officinalis	<1 year	0	yes	high	soil	4–10

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

Thymus vulgaris	<1 year	0	yes	no data	soil	<5
Ulex parviflorus	>1 year	+	high	high	soil	2

Sources: [6,13,14];
† +: positive effect of heat on germination; 0: no effect; -: negative effect
‡ yes: seedlings have been observed after a fire but no quantitative data is available; high: the number of seedlings emerging after the fire is higher than the number of individuals before the fire
§ high: more than 25% of seedlings survive the first summer
ǀ soil: once the seeds are fully developed, they immediately detach themselves from the plant; aerial: seeds remain in the canopy after reading full development
¶ time needed for new seedlings to reach sexual maturity and start producing seeds
†† Indicates a non-transient seed bank
‡‡ Indicates a transient seed bank

3.1.2 Preparation and effectiveness periods

For this regeneration mechanism to function, the vegetation has to produce seeds before the fire event. The length of the preparation period depends on the time required for the plants to reach sexual maturity and constitute a seed bank. The age of maturity depends primarily on the plant genotype and can vary between 1 year (*Cistus salvifolius*) to 15–20 years (*Pinus halepensis*) (Table 1). However, environmental conditions and events in the plants' life history can delay or even prevent this process [15]. Once the fire event has occurred, the time it takes until the vegetation can begin to recover depends on two interacting processes: (1) Seed persistence, defined as the period during which a seed will be able to germinate; (2) dormancy, or the period during which a seed will not germinate despite being alive and able to grow [16]. Generally, the more a seed is exposed (to climatic variation, predation by animals, chemicals, etc.), the shorter it will survive and be able to germinate. Dormancy can be influenced by genetics, environmental factors (the seed germinates when light, temperature, humidity, or nutrient conditions are above a certain threshold), or a combination of the two (ibid.). The high temperatures of fire events seem to break dormancy in certain species (see "Heat-stimulated germination", Table 1), making them particularly efficient in recovering from fire [2].
Scientists classify seed banks into transient (if seeds survive less than a year) and persistent (seeds survive more than a year) (see "Seed bank longevity", Table 1). A transient seed bank experiences substantial seasonal fluctuations between autumn and spring [14].
Seasonal climatic variation, seed persistence, and dormancy combine to determine an optimal window for post-fire seed germination. It is difficult to obtain quantitative information about this window for individual Mediterranean plant species, but Quintana et al. (2004) suggest, based on empirical measurements, that this optimal window might be pinpointed as the next wet season (i.e. first autumn, winter, and spring) after the fire, and extend to no more than the next two years[17].

3.1.3 Hindering and supporting factors

The most widely examined hindering factor by far in the ecological literature is the fire regime [18], constituted by fire frequency and fire severity. The interval between two fires (which determines the fire frequency) has to be longer than the time the plants take to reach maturity and produce seeds, otherwise there will be no seeds to start the recovery process anew. Fire severity, or the amount of biomass that is burned during a fire event [19] influences seed mortality both in the soil and in the canopy.

Plant development and seed production can be affected by poor environmental conditions, and especially by water scarcity [15]. Besides climatic variations, topography and soil type will reduce the

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

soil's water holding capacity, moisture, and stability. Once the seeds have reached full development, they have to survive the fire event to enable regeneration.
In the case of a transient seed bank, the timing of a fire event in relation to the flowering period is crucial: recovery is less likely if a fire occurs during flowering (normally spring) or late in the season (autumn), as this will drastically reduce the amount of fertile seeds [20]. In a soil seed bank, sheltering from the weather and animal predation appears crucial to ensure seed survival. Accordingly, soil erosion can be considered a hindering factor, whereas the presence of organic litter and mosses can be considered a supporting factor. Animal predation is another major factor of seed mortality. The relevance of this process depends on the types of seeds and animals, but also on the exposure of seeds: it is negatively correlated to burial depth [21].
Germination in post-fire conditions depends, first of all, on water availability. Thus, meteorological anomalies and especially dry spells in autumn and winter can heavily harm regeneration. Fire-stimulated germination (by heat or smoke) increases the chances of seedling survival, because new seedlings will emerge before other plants and will not have to compete for resources. But if germination occurs in hostile environmental conditions (i.e. during a dry spell), the whole recovery process may fail, leading to a regime shift. Seeder species communities affected by (late) winter fires are especially sensitive to collapse, as germinated seedlings have not produced well-developed belowground systems to overcome the expected summer drought.
While the impact of ashes on germination is controversial, the presence of litter – both pre-fire litter or mosses and burned residues – is important for germination, as it increases soil humidity and nutrients, reduces erosion, and protects seedlings [2].
After germination, plants go through a period of high vulnerability to scarcity of water and nutrients, which is generally considered to last three years. In a post-fire situation, competing plants include grasses and resprouting species that take less time to regrow than seedlings [17]. Intra-specific competition may also occur several years after the fire in case of massive post-fire recruitment but these situations only affect the individual and not the population level.

3.2. Regeneration mechanism 1: Forest regenerates from a seed bank

3.2.1 Preparation and effectiveness periods

Instead of working with Regeneration mechanism 1 and creating seeds that survive a fire, some plants have the ability to regrow stems, branches, and leaves from unburned protected organs. Regeneration mechanism 2, which builds on this ability, includes the processes of such "resprouter plants" establishing themselves in the area, developing a bud bank (also soil or aerial) and protected organs, storing nutrients and water to survive the fire, and regrowing their burned tissues (Figure 2).

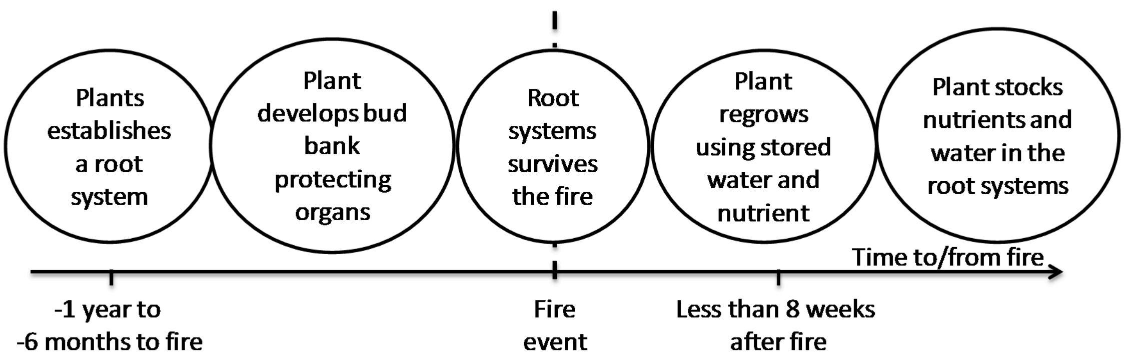


Figure 1: Processes involved in forest regeneration from resprouting plants (Regeneration mechanism 2).

We included establishment of individuals in the regeneration mechanism because this process is much more difficult for resprouters than for seeder species under natural conditions. In fact, species

 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

that work with Regeneration mechanism 2 are normally characterized by lower seed production (and even years without production at all) and a low germination rate [22]. This influences the structure of the forest where resprouter species are dominant, characterized by large trees of varying heights and shapes as well as a high variety of species. Resprouters in Mediterranean forest ecosystems are often associated with older, less disturbed forest stands that tend to be highly resistant to fire [23].

The following traits enable plants to use Regeneration mechanism 2: a bud reserve from where new sprouts will grow; mechanisms to protect these bud banks, such as thick bark, height, or an underground bud bank; a deep and thick root system; and the ability to store nutrients and water in the roots or stem. Scientists have identified a variety of resprouting strategies that differ mainly in the location of new buds, but also include various strategies for bud protection and nutrient storage. Table 2 presents common Mediterranean basin species that rely on Regeneration mechanism 2.

Table 1: Common resprouter species of the Mediterranean basin and the location of their buds.

Plant name	Bud location
Acer campestre	root and crown
Arbutus unedo	root and crown
Buxus sempervirens	non specified
Ceratonia silique	branches
Daphne gnidium	stem buds
Fraxinus ornus	roots
Juniperus oxicedrus	root and crown
Laurus nobilis	non specified
Phyllirea angustifolia	non specified
Pistacia lentiscus	roots
Prunus spinosa	root and crown
Quercus ilex	lignotuber
Rhamnus alaternus	root and crown

Sources:[6,24].

3.2.2. Preparation and effectiveness periods

The length of the preparation time required for this regeneration mechanism to work depends, first, on the time needed for seed arrival and germination and, second, on the ability of the plant to develop a root system and organs it needs to survive the fire and accumulate resources for post-fire growth (e.g. a bud bank and bark or some other protection system).

The time resprouter species require to establish a consistent presence in forests is very difficult to forecast because it depends on environmental factors, genetic factors, and contingent events in the life history each individual [11,25]. In general, the drier and less stable the climate, and the less fertile the soil, the more difficult it is for seeds of resprouter species to germinate and reach maturity [22].

Depending on the plant's strategy, its ability to resprout will reach its maximum before or during maturity and will then decrease as the plant undergoes senescence [26]. However, post-fire resprouting capacity seems to appear a few months after root establishment, as has been observed for *Quercus ilex*. (personal observation). At the level of the individual plant, resprouting is a dichotomous event, in the sense that after a fire, the plant either resprouts or dies [27]. If it resprouts, this happens immediately after the fire: Malanson and Trabaud (1988) [28] suggest that if no resprouts have been observed during the first eight weeks after the fire, the individual is dead.

At the level of the forest stand, locally unfavourable environmental conditions or high fire intensity might delay this regeneration mechanism (or the plants' "resprouting vigour", ibid.). However, the

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

negative impact of these factors appears to be relevant only in the first months to years after a fire. Empirical studies conclude that differences even out within three years after the event [29].

3.2.3. Hindering and supporting processes

Compared to seed regeneration (Regeneration mechanism 1), resprouting (Regeneration mechanism 2) is considered a much more secure and rapid path to recovery with fewer hindering factors [10]. However, the presence of resprouting plants can be greatly reduced by human activities: logging, uprooting, and heavy grazing can cause plants to die, and the typically low recruitment rate of resprouter species will limit or prevent regeneration once an individual is dead [26]. Furthermore, seeds of resprouting species are much more sensitive to unfavourable environmental conditions than those of seeder species, and may fail to germinate if, for example, the rainfall regime is unstable and soil fertility is low.

Once a resprouter plant is established, it has to develop the underground and above-ground organs (depending on bud location, see Table 2). Soil depth is crucial at this stage, as it determines the plant's root development and how well its underground bud banks are sheltered [30]. Non-structural carbohydrates are the nutrients that plants need most in order to resprout. The amount stored in the plants is subjected to considerable seasonal variations. Studies based on prescribed burning suggest that fires have a stronger negative impact on resprouting if they occur in the later seasons, when nutrient reserves are lower [27]. Coppicing is a traditional way of exploiting the valuable wood of resprouter trees (in particular *Quercus ilex* and *Q. pubescens*), which involves cutting back branches or parts of the trunks of trees and allowing them to resprout. This technique appears to stimulate the resprouting capacity of the plant, also increasing its post-fire resprouting vigour [31].

During the fire event, fire intensity, or the energy released during the fire [19], is the main factor inducing mortality in resprouter plants, as high temperatures can burn the bud bank and damage the protected aerial buds and the root system [32]. Another important hindering factor is plant size at the time of the fire. Stem size in particular is correlated to root system development. The bigger the stem and root system, the greater the chances of survival after a fire [27].

After a fire, plants have to rely on stored water and nutrients until they regrow leaves and return to photosynthesis. The relationship between the use of stored energy and photosynthesis varies among species and depends on their resprouting strategy [26]. Regrowth and resprouting vigour may be delayed during the first years after a fire by factors such as reduced water availability – which, in turn, may be the result of aspect, competition, or seasonality [28].

If no fire occurs during a long enough time, resprouters may reach the senescent stage and lose their capacity to resprout. This can also prevent their recovery from a subsequent fire event [26].

3.3 Regeneration mechanism 3: Forest regenerates from unburned plants or patches

3.3.1 Processes involved

If the vegetation in a burned area is unable to resprout or to recover from seeds after a fire, recovery will be driven by unburned vegetation. This regeneration mechanism has been referred to as "indirect regeneration" [23] or "recolonization" [10], as it does not involve the individuals directly affected by the fire nor their seeds, but relies on those plants that escape the fire or grow outside its boundaries. While this regeneration mechanism can restore the pre-fire vegetation structure (i.e. shrubland or forest), it may induce important changes in the species composition, especially if the canopy consists of heterogeneous vegetation patches. Moreover, as it takes time for seeds to spread in the burned area and germinate, Regeneration mechanism 3 will only be relevant if Regeneration mechanisms 1 and 2 fail, and only in the case of fires where the distance from the boundaries or

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

unburned patches to the core of the burned area is compatible with the dispersion mechanisms, distances, and life cycles of the species involved.
Regeneration mechanism 3 includes the processes of plants escaping the fire, producing seeds, the seeds being dispersed across the burned area, and finally germination (Figure 3).

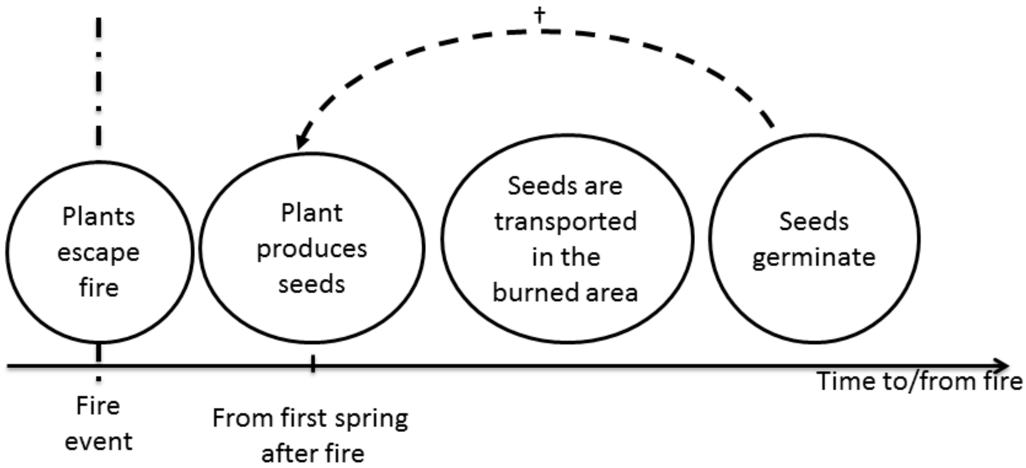


Figure 3: Processes involved in forest regeneration from unburned plants (Regeneration mechanism 3).

† The arrow indicates that the process of seed creation transport and germination must be repeated several times, for the regeneration mechanism to be effective at the landscape scale

Only a few plants rely mainly on this regeneration mechanism: those that combine low or no resprouting capacity and low seed survival include *Juniperus oxicedrus* and *Pinus brutia*. When other regeneration mechanisms fail, plants rely on unburned individuals or patches to recover from a fire. Plant traits that are relevant to this particular regeneration mechanism include: adaptation to facilitate dispersal by wind or animals, bigger size that increases chances of seed dispersal by wind and birds / insects and the number of seeds produced, the presence of a fleshy fruit protecting seeds. Regeneration mechanism 3 thus generally favours seeder species. Table 3 presents common species of the Mediterranean Basin and their traits related to Regeneration mechanism 3.

Table 3: Common species of the Mediterranean Basin and traits related to forest regeneration from unburned plants (Regeneration mechanism 3)

Plant species	Average height (m)	Dispersal unit (propagule)	Dispersal mode (vector)
Arbutus unedo	3	fruit	internal animal transport
Buxus semperivirens	2.5	seed	hoarding animals or fruit explosion
Ceratonia siliqua	15	fruit	internal animal transport
Daphne gnidium	1.5	fruit	internal animal transport
Erica umbellata	0.6	seed	wind
Fraxinus onus	10	fruit	wind or water
Juniperus oxicedrus	10	fruit	internal animal transport or gravity
Phyllirea angustifolia	1.7	fruit	internal animal transport
Pinus brutia	25	seed	wind
Pinus halepensis	20	seed	wind
Pinus nigra	30	seed	wind
Pistacia lentiscus	2	fruit	internal animal transport

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

Prunus spinosa	2	fruit	internal animal transport
Quercus coccifera	2	fruit	hoarding animals
Quercus faginea	20	fruit	hoarding animals
Quercus ilex	15	fruit	hoarding animals

Sources: [6]

3.3.2. Preparation and effectiveness periods

Regeneration mechanism 3 relies only on vegetation existing prior to the fire. Accordingly, the preparation period cannot be adequately defined. At the individual level, however, plants have lower chances of survival at the seedling stage and greater chances when they are fully grown and equipped with a thick bark and deep root system [33]. Thus, although not a necessity, the presence of mature plants will increase this regeneration mechanism's effectiveness and speed (Table 1). Moreover, mature or bigger plants tend to produce a higher number of seeds.

Given that Regeneration mechanism 3 relies on the ability of unburned plants or patches to produce seeds that are then dispersed across the burned area, the regeneration process can begin almost immediately after the fire, with the first seed dispersal event. But it may take a very long time for the entire burned area to be covered, depending on the size and shape of the burned patch and on the seed transport vectors (wind, water, or animals; see Table 3). At the scale of the forest stand, Regeneration mechanism 3 is certainly the slowest, and the process of dispersal may continue for several decades after a fire [23].

3.3.3 Hindering and supporting factors

The main condition for this regeneration mechanism to be effective is the existence of forest patches that have survived the fire unburned, be it within or outside the fire's boundaries. These so-called "fire refugia" are vital, not only for the vegetation but also for animals, whom they offer shelter from the fire [34]. Heterogeneity of land forms, also referred to as roughness of the terrain, is a factor that increases the number of unburned patches within the fire's boundaries. Other crucial forest characteristics that foster unburned patches include heterogeneity in terms of flammability, height of cover, land use, and type of canopy [33]. At the individual level, tree height, trunk size, and bark thickness are directly correlated with survival after a fire (ibid.).

However, the above factors progressively lose importance with increasing fire intensity. This, in turn, depends on the type and amount of fuel and on the environmental conditions at the time of ignition: key factors are wind speed, air humidity, and temperature.

After the fire, surviving plants have to be capable of producing seeds. As mentioned with regard to Regeneration mechanism 1, seed production may be influenced by competition, water and nutrient availability, and soil quality. Moreover, seed production is highly variable over time: external and genetic factors can trigger enormous differences from year to year [35] .

Once they have been produced, seeds are then dispersed by wind, gravity, and animal vectors. Depending on the vector, environmental conditions, and their own physical characteristics, the seeds may be deposited at various distances from the parent individual. When it comes to primary dispersal, which normally occurs by wind or gravity, most studies concur that the vast majority of seeds are deposited within a radius of 20 to 50 m, depending on the seed type, wind conditions, and height of the parent plant and landform (ibid.).

Once the seeds are on the ground, their fate depends on the behaviour of animals. Animals play an ambivalent role: they eat and damage the seeds (predation) but also transport them to new areas (secondary dispersal) [36]. Secondary dispersal of seeds by animals is crucial to the recolonization of post-fire areas. Thus, animals act as both a hindering and a supporting factor. The relative influence

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

of predation and dispersion remains difficult to quantify [35]. Once dispersed, seeds may germinate if the microhabitat is favourable; this process is influenced by the same hindering and supporting factors as those affecting germination within Regeneration mechanism 1 (see Section 2.1.3.).

3.4. Impacts of land management on resilience

As part of our analysis of the processes that affect resilience to fire in Mediterranean forests, we identified factors that hinder or support these processes. These factors include different ecosystem components apart from the vegetation. Some of them can be influenced by management (Table 4 and 5).

Table 4: Overview of factors hindering Regeneration mechanisms

Hindering factors	**RM1: forest regenerates from seed bank**					**RM2: forest regenerates from resprouting individuals**				**RM3: forest regenerates from unburned plants or patches**				
Processes†	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4
Vegetation														
Old age of trees						x								
Dense vegetation	x													
Soil properties														
Low water availability						x						x		
Low nutrient availability						x						x		
Soil erosion				x‡										
Soil compaction				x‡										
Climate														
dry spells					x	x								x
Fire regime														
Intense fires			x					x						
Frequent fires	x	x			x									x
Fire during flowering season		x§												
Large burned area													x	
Human activities														
Logging / uprooting						x								
Fauna														
Presence of wild animals				x	x									
Total ¶	2	2	1	3	3	5	0	1	0	0	0	2	0	2
Total (grouped)#	11					6				4				

†Refers to the processes related to each Regeneration mechanism as presented in figures 1, 2, 3.
‡Only for a soil seed bank
§Only for a transient seed bank

 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

¶Total number of hindering factors identified for each process of the Regeneration mechanisms. Gives a rough indication of the vulnerability of the process
Total number of hindering factors identified per Regeneration mechanism

Table 2: Overview of factors supporting Regeneration mechanisms.

Supporting factors	RM1: forest regenerates from seed bank					RM2: forest regenerates from resprouting individuals					RM3: forest regenerates from unburned plants or patches			
Processes†	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4
Vegetation														
Big stem / root system								x						
Tall trees													x	
Soil properties														
Presence of litter and veg. cover			x	x‡										x‡
High water and nutrient content				x	x									x
Deep soils							x	x						
Human activities														
Coppicing									x					
Fauna														
Presence of wild animals													x	
Other														
Landscape heterogeneity											x			

†Refers to the processes related to each Regeneration mechanism as presented in figures 1, 2, 3.
‡If it is not thick enough to prevent seed germination

3.4.1 Relationship between WOCAT ecological indicators and factors hindering and supporting resilience

Nine land management practices in the WOCAT database [37] were identified as relevant for this study. They cover prevention (before the fire), fire impact mitigation, and rehabilitation (after the fire). For the purpose of the subsequent analysis we grouped them according to their objectives: (1) fuel breaks, (2) fuel management, (3) afforestation, and (4) mulching (Table 5). Three of the management practices were documented and assessed in Spain (SPA), three in Portugal (POR), two in Italy (ITA), and one in Morocco (MOR). The result sheet for each management practice referenced in table 5 is available as supplementary material 1.

Table 3: Land management practices for Mediterranean forests from the WOCAT technology database, categorized according to their objective.

WOCAT	Technology name
	1. Fuel breaks (prevention)
POR001	Primary strip network system for fuel management
SPA009	Cleared strip network for fire prevention (fuel breaks)
ITA007	Unvegetated strips to reduce fire expansion

 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

	2. Fuel management (prevention)
POR002	Prescribed fire
SPA010	Selective forest clearing to prevent large forest fires
ITA008	Selective cutting
	3. Reforestation (rehabilitation)
SPA012	Afforestation with Pinus halepensis after the fire of 1979
MOR013	Assisted cork oak regeneration
	4. Soil protection (mitigation)
POR003	Post-fire forest residue mulch

Among other information, the WOCAT assessment method includes an evaluation of the technology based on indicators of benefits and disadvantages. Many of these can be related to the hindering and supporting factors identified for the three regeneration mechanisms. Figure 4 provides an overview of these relations.

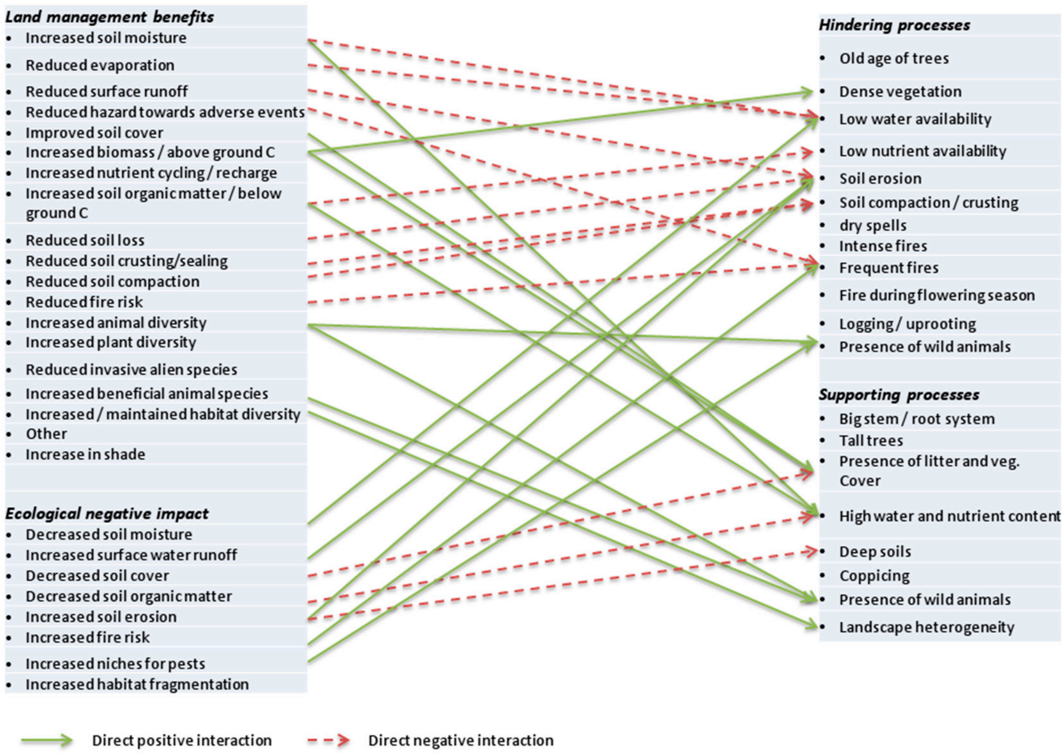


Figure 2: Direct relations between WOCAT indicators of ecological benefits and disadvantages (left) (Source: WOCAT technology questionnaire, Section 3.1.1.3 [37]) and hindering and supporting factors of resilience (right). Solid arrows represent direct positive (reinforcing) relations; dashed arrows represent a negative relationship. The full matrix of relations, including also indirect relations, is part of Appendix A.

In the following subsections, we present the four groups of land management options and assess how their ecological indicators relate to the factors hindering and supporting each regeneration mechanism. In doing so, we identify hindering and supporting interactions between land management practices and resilience.

3.4.2. Fuel breaks

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

Fuel breaks are linear features within the forest where the vegetation has been removed. Their placement depends on the slope, location of roads, and average wind direction. They are probably the most common management practice and are often the first staple in national programmes to reduce the risk of fire [38]. Researchers and technical experts stress that fuel breaks not only help prevent fires from spreading, but also make it easier to access areas and conduct interventions during a fire event [5].

Fuel breaks are implemented in networks over large areas of forests. Resulting forest structures are characterized by wide forest areas interspersed with linear discontinuities of varying width. Thus, fuel breaks have a limited effect on the forest structure as a whole [39].

Reported aims of this land management practice are to reduce forest continuity and the area potentially affected by fire (SPA), to slow down the progress of fire (ITA), to provide access and increase safety for fire fighters during interventions (SPA, ITA, POR), and to protect roads, infrastructures, and areas of special value (POR). In the case of large fuel breaks, their central part is cleared to the mineral soil, while adjacent areas are left with an increasing density of vegetation (SPA, POR), with a selection of the biggest and most fire-resistant species (SPA).

The main benefit of fuel breaks, as assessed with the WOCAT methodology, is the reduction of fire risk (SPA, ITA, POR). Disadvantages include decreased soil cover (SPA, POR), increased surface water runoff (SPA, POR), decreased soil organic matter (SPA, POR), increased soil erosion (SPA, POR), and increased habitat fragmentation (SPA) (see table 7). The decrease in soil cover and soil organic matter, as well as the increase in runoff only affect the area actually occupied by the fuel break and have no relevant impact on the surrounding forested area (see table 7, "Average value")

Table 4. Benefits and disadvantages of fuel breaks as assessed with the WOCAT technology questionnaire.

Benefits of fuel breaks		**Disadvantages of fuel breaks**	
Indicator	Average value †	Indicator	Average value†
reduced hazard towards adverse events	2.7	increased surface water runoff	1.0
reduced fire risk	2.7	decreased soil cover	1.5
		decreased soil organic matter	1.0
		increased soil erosion (locally)	1.0
		increased habitat fragmentation	1.0

†Values are attribute on a scale from 1 (little) to 3 (High) for each management practice

Figure 6 gives an overview of supporting and hindering interactions between fuel breaks and the three regeneration mechanisms. As shown in Section 2.1.3., fire frequency is a major hindering factor for Regeneration mechanism 1. By limiting the spread of fire, fuel breaks reduce the number of fires occurring in a specific area, thus increasing the likelihood of plants reaching maturity [38,39]. This is shown as interactions (a) and (d) in Figure 6. Fuel breaks might indirectly reduce the occurrence of fires in spring or autumn, thereby increasing the probability of a healthy seed bank existing at the moment of fire (b). The negative impacts of fuel breaks on soil (increased erosion, runoff, decreased cover, decreased organic matter: see table 7) could decrease germination rate, on the fuel break or in its proximity (c).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

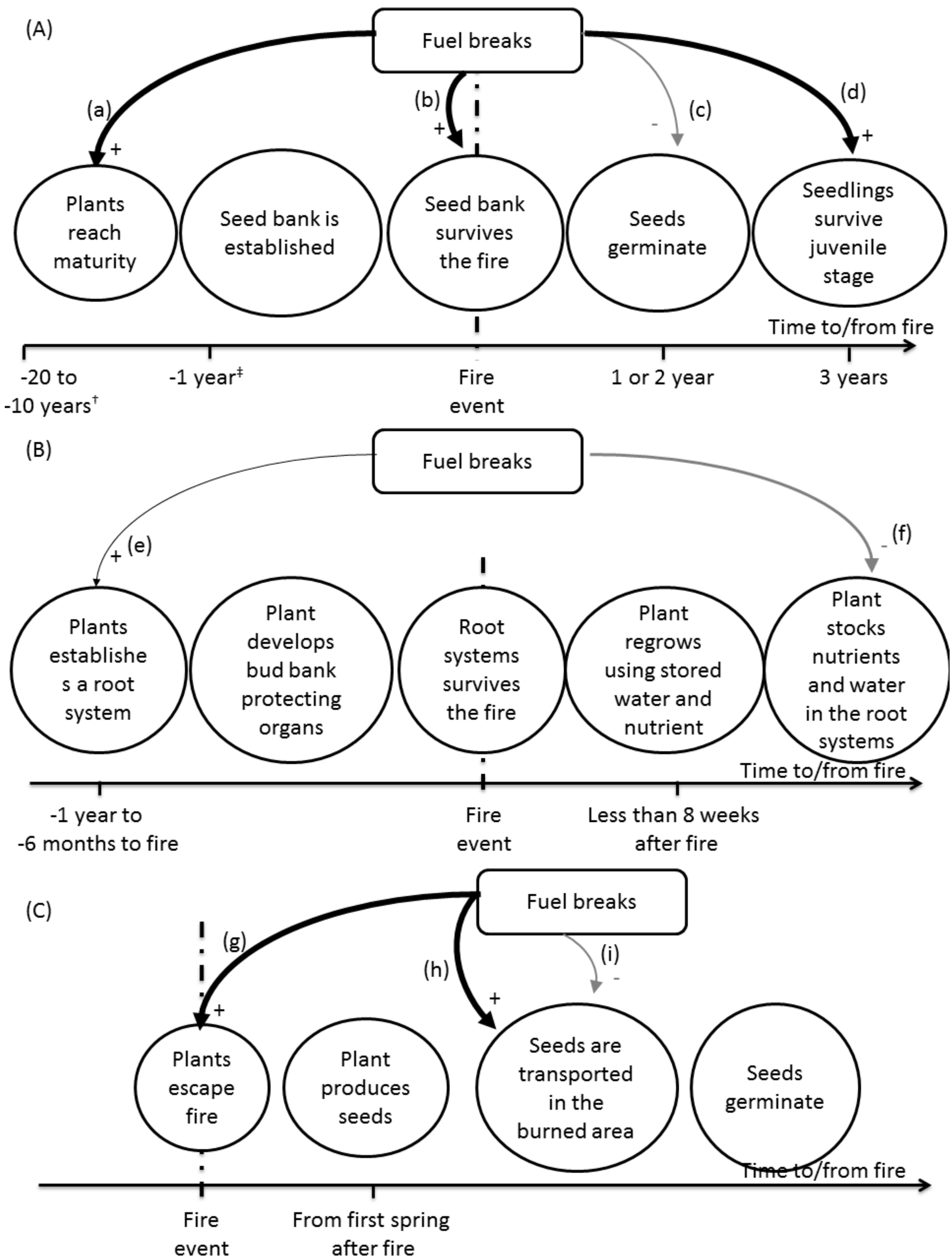


Figure 3: Impact of fuel breaks on the resilience of Mediterranean forest to fire. A) Impact of fuel breaks on Regeneration mechanism 1; B) Impact of fuel breaks on Regeneration mechanism 2. C) Impact of fuel breaks on Regeneration mechanism 3. The width of arrows indicates the relative importance of supporting (+) and hindering (-) interactions.

Fuel breaks have no relevant effect on Regeneration mechanism 2, as they do not affect fire intensity, and local soil conditions have no impact on resprouting trees outside the fuel break area. If selective cutting is applied at the margins of the fuel break, this could increase the average size of

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

plants and the presence of resprouters (e) [40]. The only potential negative effect might occur if fire were excluded permanently from the area, as this would enable resprouter plants to reach senescence age and lose their resprouting capacity (see Section 2.2.3) (f).

The size of the burned area and canopy continuity are major hindering factors for Regeneration mechanism 3, as they affect the number of patches that survive the fire unburned and the probability of seeds reaching the burned area. By reducing both factors, fuel breaks play an important role in ensuring the effectiveness of the regeneration mechanism (g, h)(ibid.). However, fuel breaks of the largest category, whose total width may reach up to 90 m (SPA, POR), may act as an ecological barrier to recolonization, and increase the possibility of alien species proliferation, hindering forest resilience through Regeneration mechanism 3 [41] (k).

3.4.3 Fuel management

One of the ways to reduce fire risk is by removing part of the flammable material from the forest. This can be dead material, the understory, or selected individuals, for example fire-prone species and senescent or ill plants. It may even involve temporary total removal of the canopy, as in prescribed burning. This group of forest management practices, while having the same objective, is indeed very diverse in effects and measures. Selective clearing is the more labour intensive option, which not only enables modification of the fuel load, but also modification of species composition and the structure of the forest stand. Depending on the type of forest, it can involve removal of seedlings and young trees to facilitate the development of bigger, less flammable trees; it can also include pruning the lower branches of the trees in order to reduce the possibility of fire spreading from the ground to the tree level canopy. Prescribed burning does not allow for direct selection of material for removal, and it includes risks of losing proper control and generating a wildfire. Moreover, many researchers stress the negative impacts of prescribed burning on soils, but debate over the trade-offs of this management practice remains ongoing [42].

Reported objectives include reducing the amount of fuel present in the area (SPA, POR, ITA), creating or increasing discontinuity in the canopy (SPA, POR), preventing the spread of alien species and pests (SPA, POR), and changing canopy composition to include more fire-resistant species or increase diversity (SPA, POR). Fuel management can be achieved through prescribed burning (POR), cutting and removal of vegetation (SPA), or cutting and chipping of wood which is then used as mulch (SPA, ITA).

Relevant benefits of these management practices are: reduced wildfire risk (ITA, SPA, POR), increased biological pest/disease control (POR), and increased habitat diversity (SPA, POR). In the case of selective cutting, benefits also include a reduction in alien/invasive species (POR). Further benefits occur if the wood is chipped and dispersed on site as mulch: among others, the proportion of soil covered by litter increases, nutrients are recharged, soil moisture increases, and soil crusting or sealing is reduced (SPA). Negative impacts of fuel management technologies include increased soil erosion, decreased soil cover and organic matter (if mulching is not applied), and increased habitat fragmentation (Table 8).

Table 5. Benefits and disadvantages of the fuel management practices

Benefits of fuel management		Disadvantages of fuel maangement	
Indicator	Average value	Indicator	Average value
increased soil moisture	3	increased surface water runoff	1
reduced evaporation	1	decreased soil cover ‡	1.5
reduced hazard towards adverse events	2.5	decreased soil organic matter	1

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

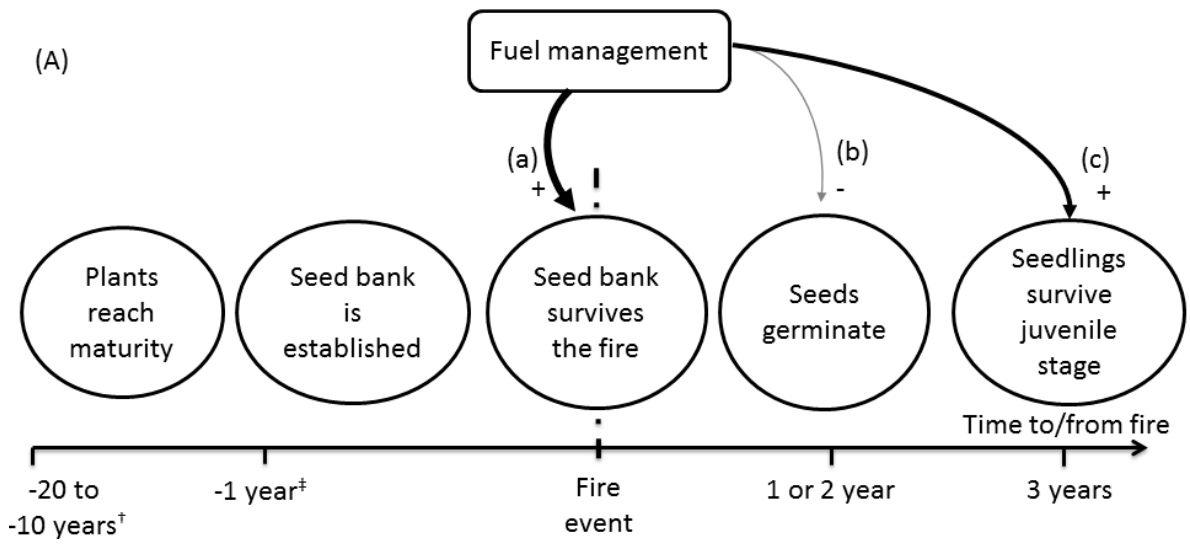
Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

improved soil cover	1 †	increased soil erosion (locally)	1
increased biomass / above ground C	1.5	increased habitat fragmentation	1
increased nutrient cycling / recharge	1		
increased soil organic matter / below ground C	1		
reduced soil crusting/sealing	1		
reduced fire risk	3		
increased animal diversity	1		
reduced invasive alien species	3		
increased / maintained habitat diversity	3		
reduced soil surface temp	1		

†If mulching is applied, otherwise there is an increase in bare soil.

‡Only if mulching is not applied

The impacts of fuel management on the three regeneration mechanisms are shown in Figure 7. Looking at Regeneration mechanism 1, a reduction in fuel decreases fire intensity, with a positive impact on seed bank survival [40](a). However, if fuel management is implemented through prescribed burning, it will have a negative impact on the soil (De Bano, 2000), resulting in a reduced germination rate (b). Positive impacts on Regeneration mechanism 1 further include reduced vegetation density, leading to reduced competition and hence increased probability of seedlings reaching maturity and producing seeds. Mulching increases soil fertility and seed sheltering, and most likely leads to an increase in the germination rate (c) [43], if the mulch layer is not too thick.



Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

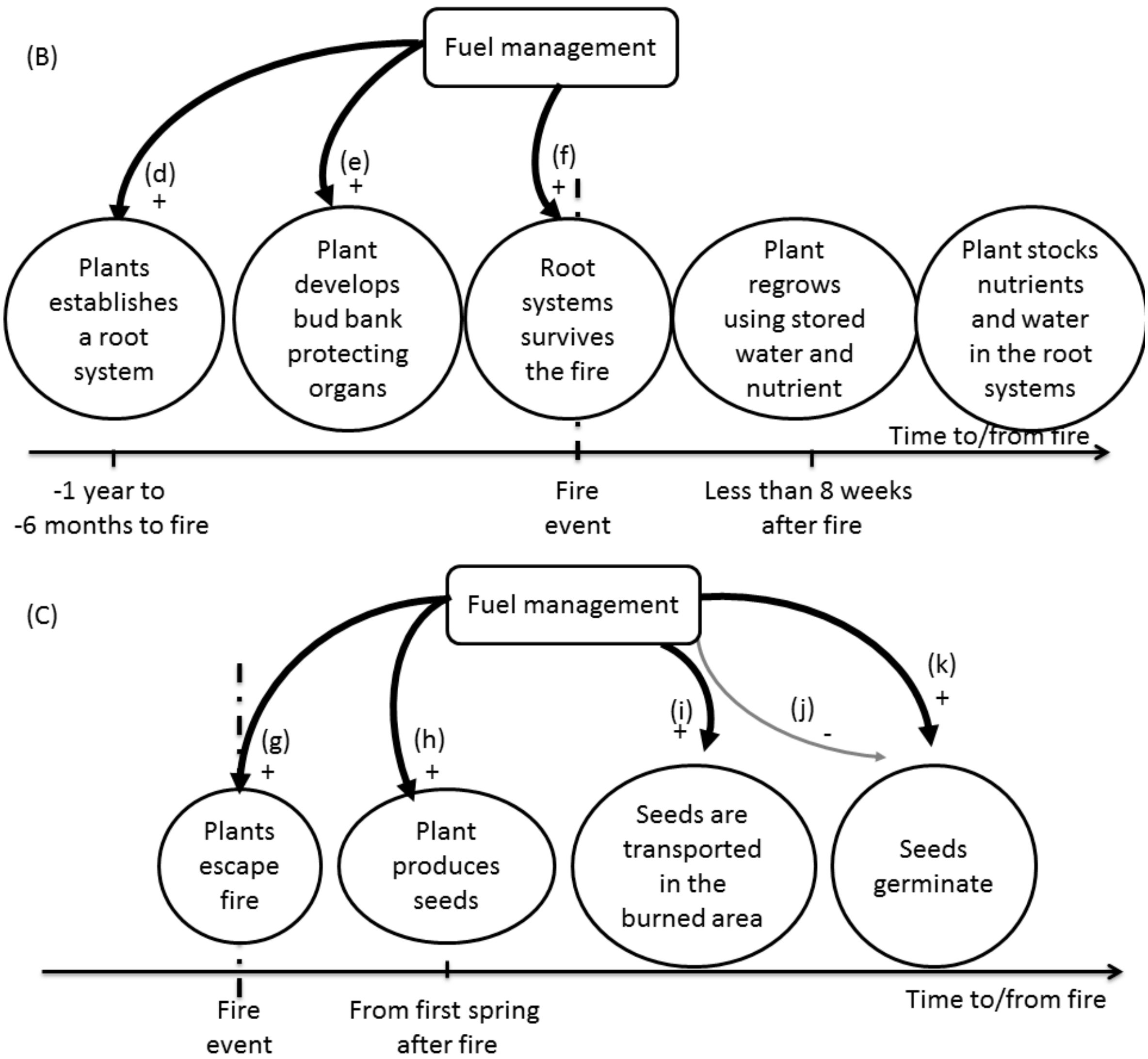


Figure 7: Impact of fuel management on the resilience of Mediterranean forest to fire: A) Impacts on RM1; B) Impacts on RM2; C) Impacts on RM3. The width of arrows indicates the relative importance of supporting (+) and hindering (-) interactions.

Resprouter species, who use Regeneration mechanism 2, benefit above all from reduced competition with seeder species before the fire, increasing their chances of survival and their resprouting vigour (d); this applies to both selective clearing and prescribed burning. In the case of selective clearing, the most fire-prone species are usually cut, allowing more fire-resistant species such as Quercus, Juniperus, and Fraxinus species to grow in size, increasing their chances of surviving and resprouting after a fire (SPA) (e). Improved soil and moisture conditions from mulching might improve conditions for recruitment of resprouter species, which are generally much more demanding than seeders in terms of water and nutrients [44] and are favoured by gaps within the understory (see Section 3.2.1) (f).

Reduction of fire intensity is crucial to Regeneration mechanism 3, as it increases the chances of individuals and patches surviving a fire unburned and acting as sources of forest regeneration [5] (g). This positive effect is even more important if the healthiest and largest individuals are left in place during selective clearing, as this leads to increased survival as well as increased seed production and dispersal after the fire (h). Clearing of understory through prescribed fire can result in an increase in highly palatable grasses, leading to increased animal presence and potentially to increased seed dispersal [45] (i). As in the case of Regeneration mechanism 1, fuel reduction might lead to an increase

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

in soil erosion that can reduce the germination rate and seedling survival by diminishing soil fertility (j). However, this negative interaction can be countered by applying mulching, which improves soil fertility and reduces fire-related degradation (k).
Aside from the direct ecological impact of fuel management, the wood gathered from fuel management operations can be sold and gains can be reinvested in management measures [46]. This applies in particular to selective forest clearing (ITA, SPA), where increased wood production was reported as a socio-economic benefit.

3.4.4 Afforestation

Direct planting of trees is applied when natural regeneration fails. The aim is to restore the canopy and increase the soil cover; the planted vegetation is expected to gradually develop into a secondary forest. The management practices documented in the WOCAT database used *Pinus halepensis (SPA)* or *Quercus ilex* (MOR).
These management practices are common in forest areas that have failed to regenerate or have been otherwise deforested. *Pinus spp* or other seeder species are used because of their high growth rate and ability to withstand low availability of essential resources. However, resulting forests tend to have lower species diversity and very dense, homogeneous canopies that present a high risk of fire. Researchers have highlighted the negative impacts of this practice [47], stressing the importance of using a broader mix of species[5]. In some management plans, restoration projects include a second afforestation phase that introduces resprouters (e.g. *Quercus ilex*, *Q. faginea*) in the pine afforestation, thereby reducing the risk of fire and increasing the diversity of the forest stand.
Afforestation with Cork Oak (MOR) follows this latter idea, thereby increasing the benefits of the management in the long term. However, *Quercus ilex* seedlings are much more vulnerable to drought, which is why water has to be provided through an irrigation system. Moreover, growth is much slower compared to *Pinus*, leading to reduced benefits in the short term.
The technique used to plant the trees is important, as it affects the soil and the remnant vegetation. For the *Pinus* afforestation (SPA), machinery was used to create an individual hole for each seedling; seedlings were then planted by hand. In the assisted Cork Oak regeneration, land managers dug straight furrows able to hold a row of multiple seedlings.

Table 9: Benefits and disadvantages of afforestations

Benefits of afforestations		Disadvantages of afforestations	
Indicator	Average value	Indicator	Average value
increased soil moisture	2.5	increased fire risk †	2.0
reduced evaporation	1	increased niches for pests (birds, slugs, rodents, etc.)	2.0
reduced surface runoff	2.5		
improved soil cover	2		
increased biomass / above ground C	2		
increased nutrient cycling / recharge	2		
increased soil organic matter	2		
reduced soil loss	2.5		
reduced soil crusting/sealing	1.5		
increased animal diversity	1.5		
increased plant diversity	1		

 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

Reported benefits mainly relate to the soil and include increased soil cover, increased soil moisture, reduced runoff, and reduced soil crusting. Reported disadvantages include a heightened fire risk and an increase in niches for pests.

Figure 8 provides an overview of how afforestation influences the regeneration mechanisms. For regeneration mechanism 1, increasing the number of seeder individuals might be expected to have a positive effect on forest resilience to fire via a larger seed bank (a). However, many seeder trees, including Pinus halepensis, are highly flammable, so afforestation based on such species greatly increases the amount of fuel and the risk of fire [47]. Flammability of Cork Oak is instead much lower. If the time between two fires is too short for the plants to reach sexual maturity, a subsequent fire can cause total failure of afforestation. But even without such a catastrophic shift, afforestation with *Pinus halepensis* may have an adverse effect on resilience to fire: its seeds are dispersed by fire, so after a fire the new canopy could become extremely dense, reducing seedling growth and further development of the canopy.

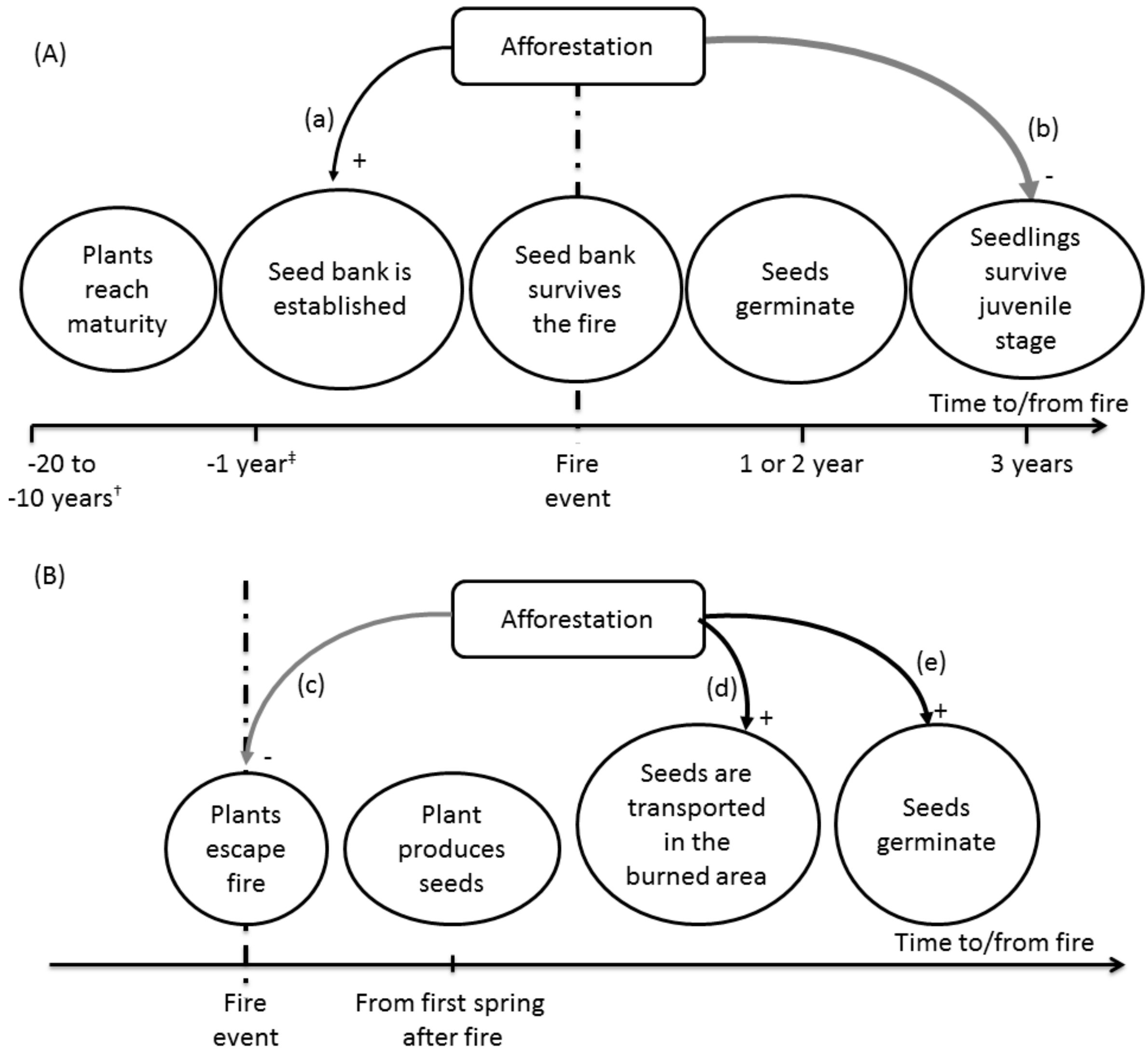


Figure 8: Impact of afforestation on the resilience of Mediterranean forest to fire: A) Impacts on RM 1; B) Impacts on RM2. The width of arrows indicates the relative importance of supporting (+) and hindering (-) interactions.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

Plants that use Regeneration mechanism 2 are not affected by fire frequency and are often shade-tolerant, so afforestation should have no negative impact on these resprouters as long as they are not killed during afforestation work. However, areas chosen for afforestation do not normally have a high tree presence, and even less of resprouting individuals. For this reason we cannot establish a direct link between afforestation with *Pinus halepensis* and Regeneration mechanism 2.

Planted trees tend to form a homogeneous, continuous canopy, reducing the chances of patches escaping a fire (ibid.) and potentially increasing the size of the burned area (c). However, increased soil moisture, nutrient content, and soil stability may promote post-fire recruitment (e). Moreover, the reported increase in animal diversity might lead to greater secondary dispersion (d).

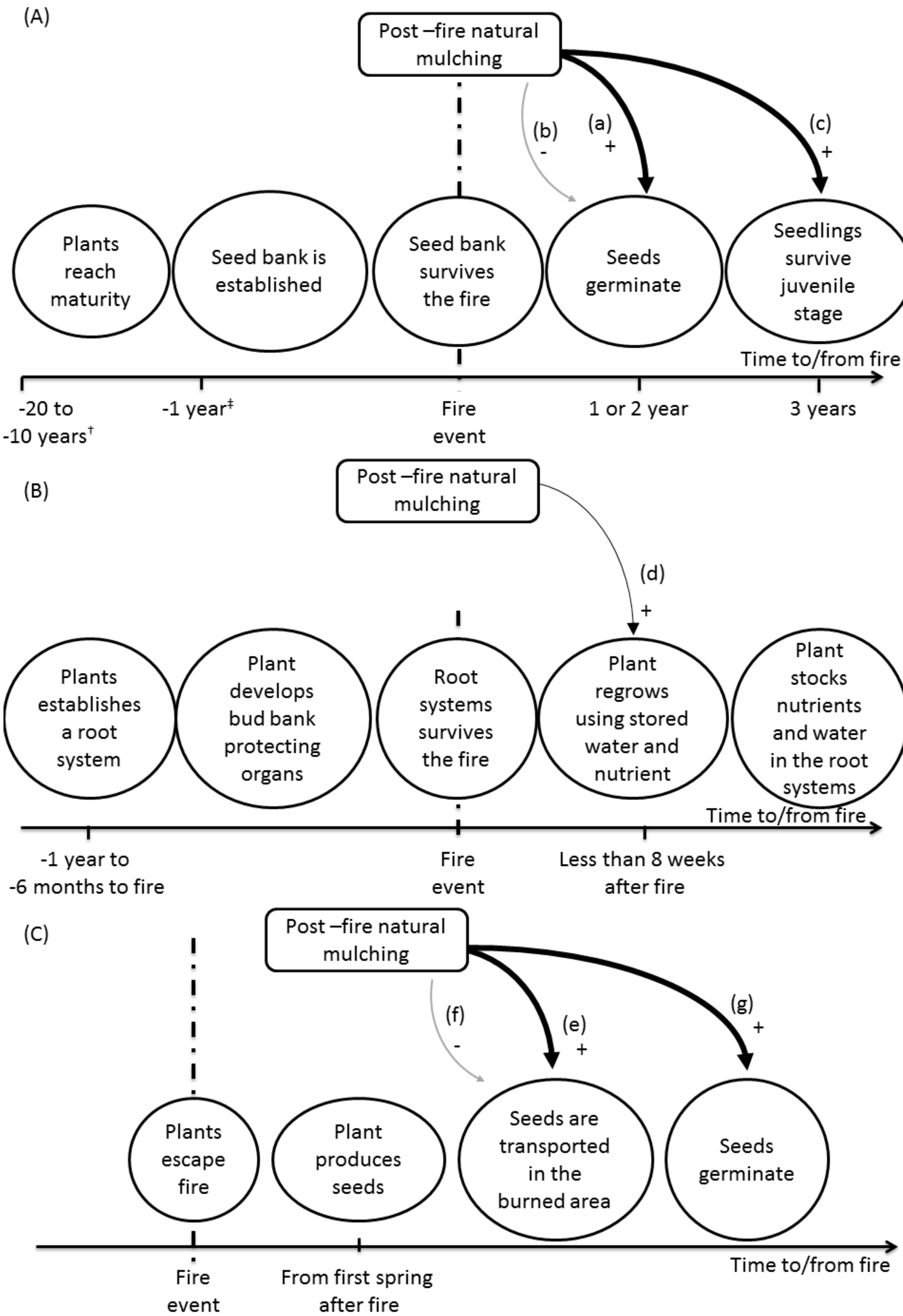
3.4.5 Post-fire mulching

Post-fire mulching consists of spreading chopped forest residues on slopes after a fire to increase the ground cover and reduce erosion and increase water infiltration (Figure 9). This greatly reduces post-fire degradation. Fires of high intensity will consume pre-fire litter; leaves and branches left over after the fire will not suffice to effectively protect the soil, leaving it exposed to weathering and erosion by water. Mulching is applied on steep slopes, where fire intensity tends to be high, and uphill from infrastructure or valuable areas. It is best carried out immediately after the fire, before the next rain. Relevant benefits of mulching include increased soil cover, reduced soil loss, reduced surface runoff, and decreased evaporation. No disadvantages were reported for this technology in the WOCAT assessment.

Figure 4: Spreading of natural mulch on a burned steep slope. Source: WOCAT T_POR003en, "Post-fire residue mulch", compiled by Sergio Prats.

Figure 10 gives an overview of the impacts of mulching on forest resilience to fire. As explained in Section 3.1.3., the presence of litter or covering material is crucial for seeds to survive until germination, as it reduces decay, erosion, and animal predation [48] (a). Furthermore, by helping to maintain soil humidity and soil organic matter content, it promotes the recovery of soil fauna and nutrient cycling after the fire. All these factors contribute to greater soil fertility, which in turn increases the germination rate and seedling survival [43] (c). Accordingly, mulching is clearly beneficial to Regeneration mechanism 1. However, if mulching is too thick, it can decrease the germination rate of obligate seeder species such as *Ulex parviflorus* or *Cistus sp.* (b).

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981



622 **Figure 5**: Impact of mulching on the resilience of Mediterranean forest to fire: A) Impacts on RM 1; B)
623 Impacts on RM2; C) Impacts on RM3. The width of arrows indicates the relative importance of
624 supporting (+) and hindering (-) interactions.

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

Post-fire soil conditions have no major impact on Regeneration mechanism 2, as resprouter plants maintain their own reserves of nutrients and water. However, greater soil humidity after a fire may promote resprouting, thereby increasing the speed of regeneration (d).

Seed survival and germination are important processes in Regeneration mechanism 3. Accordingly, the presence of continuous litter and stable, humid soil is important in enabling recruitment (e) and seedling survival (g). Germination could also be hindered by a thick layer of mulch (f).

4. Discussion and conclusion

4.1 Regeneration mechanisms

The concept of regeneration mechanisms elaborated in this paper bears similarity to concepts used by ecologists to study plant traits related to fire (e.g. concept of "regeneration paths" by Pausas & Keeley [10]). However, fire ecologists focus mainly on how fires affect plant evolution and morphology, as well as on how individual plants adapt to fire disturbances [11,22,49]. While these studies are fundamental to improving our understanding of the ecosystem, they rarely provide useful recommendations for management, as they do not take into account environmental factors that might influence a fire event and post-fire recovery, nor of the interactions that occur at a larger scale. Our review of the literature on forest ecology and post-fire forest regeneration reveals two important aspects of forest resilience: First, there are various processes that are important to post-fire regeneration that may take place before the fire event. Thus, efforts to increase forests' resilience to fire should be launched prior to fires, not only after the fact. Second, there are a number of processes that play a role in post-fire forest regeneration that are not directly related to the fire event itself. These processes are often poorly understood in light of their effects on post-fire regeneration. Moreover, there is a need for research on the relative significance of these processes and on important thresholds that can influence regeneration. Further, we lack quantitative indications regarding thresholds in the various processes constituting regeneration mechanisms.

4.2 Can we increase forest resilience through land management?

Mediterranean forests are composed of various species, and land managers cannot choose which of the three regeneration mechanism their system will follow. However, by examining its species composition and monitoring the hindering and supporting factors, they can understand which regeneration mechanism is most likely to fail or to function. Depending on their management practices, the fire regime, and other environmental factors, they can focus their attention on those processes that are at risk of failing.

Regeneration mechanism 1 – forest regeneration from seed banks – requires the longest interval between fires (see Section 3.1.2) and has the most hindering factors (Table 4). However, our analysis of the impact of management practices indicates that fuel breaks and fuel management might considerably increase the resilience of plants using this mechanism.

By contrast, Regeneration mechanism 2 – forest regeneration from resprouting individuals – appears to be the most stable of the three mechanisms, the quickest to foster recovery, and the least influenced by external factors (Table 4). It has to be noted, however, that the establishment of resprouter species is difficult, and can be hindered by many factors (see table 4, "Total"). The management practices analysed do not seem to have any relevant influence on it, with the exception of fuel management through selective clearing (see Section 4.3.).

Regeneration mechanism 3, contrary to the other processes, does not require any preparation period prior to the fire event, and is therefore independent of the frequency of fires. It is the slowest way for a forest to recover, and the one that is most likely to bring changes to the system. The impacts of management on this regeneration mechanism are the most uncertain, mainly due to the high number of processes involved and the paucity of scientific knowledge about it.

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

When comparing the management practices, fuel management appears to increase forest resilience the most. It is especially beneficial to pre-fire processes, which makes it a strategic option for prevention. Afforestation with *Pinus halepensis* seems the least promising of all management practices; this becomes even more so if we consider the high cost of implementation and the low success rate in terms of seedling survival and fire risk at the long term. Fuel management and afforestation can be implemented in very different ways, and the specific implementation technique strongly affects how these practices influence regeneration mechanisms.
The available literature on forest management [50,51] generally supports the information provided by the WOCAT database, as well as the conclusions drawn in this article. However, while most management practices have been studied for their effect on fire regimes, and some (e.g. fuel management and afforestation) also with regard to post-fire recovery, very few empirical studies have analysed the diverse impacts of management on soil erosion, seed bank establishment, and other factors involved in Mediterranean forests' resilience to fire. In light of these gaps, despite WOCAT's largely qualitative and somewhat general approach to assessing management practices, the WOCAT database represents an important tool for use in better understanding the role of forest management. Moreover, our literature review revealed a lack of articles providing a general method for assessing resilience, or offering evaluation of the impact of management practices on the resilience to fire of Mediterranean forests.

4.3 Other factors influencing forests' resilience to fire

Focussing on regeneration makes it possible to relate impacts of land management to forest resilience in a direct way. However, there are other factors that can increase the resilience of forests and improve the likelihood of post-fire regeneration: First, certain land uses, in particular grazing and wood gathering, reduce the amount of available fuel in forests, thus reducing the risk of repeated and intense fire. These activities were part of forest use for centuries, and their disappearance – owing to declining (perceived) economic returns – is an important factor in the changing of fire regimes of many Mediterranean countries. However, it also implied in some cases the removal of root systems, reducing or even eliminating completely the presence of keystone resprouting species. Second, the shape and diversity of landscape mosaics have direct effects on fire spreading, fire suppression, and post-fire regeneration (especially vis-à-vis regeneration mechanisms). The interplay between forest areas, open areas (e.g. pastures), and areas with low flammability (e.g. orchards, built areas) influences the size and occurrence of burned areas following a fire. In many forest stands of the Mediterranean Basin, land abandonment is radically changing the traditionally diverse and patchy landscapes, with clear effects on fire regimes and forest evolution. Third, the presence of certain plants or combinations of plants has beneficial impacts on soils and ecosystems in general. Increasing research on functional groups, and clear identification of the most important ones, will undoubtedly improve land managers' ability to enhance the resilience of forest stands.

Supplementary material

Supplementary material 1: Summary result sheet of the WOCAT assessment of land management practices available at: https://dl.dropboxusercontent.com/u/26249349/ResMechanisms-LMPractice.pdf

Acknowledgements

This paper was developed within the CASCADE project (Seventh Framework Programme FP7/2007–2013 grant agreement 283068). The authors acknowledge financial support from the CASCADE project and the European Cooperation in Science and Technology (COST). We also thank the contributors to the WOCAT database: Nina Lauterburg (CDE), Celeste Coelho and Sergio Prats (University of Aveiro, Portugal), and Velia de Paola (University of Basilicata, Italy). In addition, we would like to thank Jaime Baeza for their help in sharpening the concepts and their insights on fire ecology. Ultimately the authors thank Marlene Thibault (CDE) for the editing. Thanks also go to the editor and the anonymous reviewer for their comments and suggestions, which enabled significant improvements to the manuscript.

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

Author Contributions: Matteo Jucker Riva has framed the paper idea and wrote the paper, Hanspeter Liniger and Gudrun Schwilch have structured the analysis of the land management practice, Alejandro Valdecantos contributed to the analysis of the ecological literature.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results".

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

Appendix A: Matrix of interactions between ecological benefits and disadvantages of land management practices and factors hindering or supporting forest resilience. A1 Interactions between ecological benefits of land management and factors supporting or hindering land forest resilience

	Vegetation		Soil properties				Climate	Fire regime			Land use	Fauna		Vegetation		Soil properties			L u	Fau
Hindering factors	Old age of trees	Dense vegetation	Low water availability	Low nutrient availability	Soil erosion	Soil compaction	dry spells	Intense fires	Frequent	Fire during flowering	Logging / uprooting	Presence of wild animals	*Suppoting factors*	Big stem / root system	Tall trees	Presence of litter and	High water and nutrient	Deep soils		wild animals
Ecological Benefits																				
increased soil moisture			--														++			
reduced evaporation			--														++			
reduced surface runoff			-	-	--											+	+	+		
reduced hazard towards adverse							-		--	-										
improved soil cover			-		-											++	+	+		
increased biomass / above ground		++	-	-	-			+		+						+	+			-
increased nutrient cycling /			-	--	-												++			
increased soil organic matter / below ground C			-	--	-												++			
reduced soil loss			-	-	--									+		+	+	++		
reduced soil crusting/sealing			-	-		--											+			
reduced soil compaction				-		--											+			
reduced fire risk									++	+					+					
increased animal diversity												++								+
increased plant diversity																				
reduced invasive alien species		-																		
increased beneficial animal species (predators, earthworms)																				+
diversity																				-
Total interactions:	0	2	9	7	6	2	1	1	2	3	0	1		1	1	4	10	3		4

Legend: ++ Direct positive interaction, – Direct negative interaction, + indirect positive interaction, - indirect negative interaction

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

A2: Interactions between ecological disadvantages of land management and factors supporting or hindering land forest resilience

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Hindering factors	Vegetation		Soil properties				Climate	Fire regime			use	Fauna	*Supporting factors*	Vegetation		Soil properties			use	Fauna	Other
	Old age of trees	Dense vegetation	Low water availability	Low nutrient availability	Soil erosion	Soil compaction	dry spells	Intense fires	Frequent fires	Fire during flowering season	Logging / uprooting	Presence of wild animals		Big stem / root system	Tall trees	Presence of litter and veg. Cover	High water and nutrient content	Deep soils	Coppicing	Presence of wild animals	Landscape heterogeneity
Ecological negative impacts																					
decreased soil moisture			++	+				+									--				
increased surface water runoff			+	+	++											+	+	+			
decreased soil cover			+	+	+											--	-	-			
decreased soil organic matter			++	++	+	+								-			--				
increased soil erosion (locally)			+	+	++									-		-	-	--			
increased fire risk									++	+											
increased niches for pests												++								-	
increased habitat fragmentation												+									-
Total interactions:	2	1	7	6	5	2	2	3	2	2	2	4		4	1	5	6	4	2	3	3

Legend: ++ Direct positive interaction, – Direct negative interaction, + indirect positive interaction, - indirect negative interaction

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

All appendix sections must be cited in the main text. In the appendixes, Figures, Tables, *etc*. should be labeled starting with 'A', e.g., Figure A1, Figure A2, *etc*.

5.References

1. Pausas, J. G.; Llovet, J.; Rodrigo, A.; Vallejo, R. Are wildfires a disaster in the Mediterranean basin? – A review. *Int. J. Wildl. Fire* **2008**, *17*, 713.
2. Santana, V. M.; Alday, J. G.; Baeza, M. J. Effects of fire regime shift in Mediterranean Basin ecosystems: changes in soil seed bank composition among functional types. *Plant Ecol.* **2014**, *215*, 555–566.
3. Peterson, G.; Allen, C. R.; Holling, C. S. Ecological Resilience , Biodiversity , and Scale OF. **1998**, 6–18.
4. Buma, B.; Wessman, C. A. Disturbance interactions can impact resilience mechanisms of forests. *Ecosphere* **2011**, *2*, art64.
5. Reinhardt, E. D.; Keane, R. E.; Calkin, D. E.; Cohen, J. D. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *For. Ecol. Manage.* **2008**, *256*, 1997–2006.
6. Paula, S.; Arianoutsou, M.; Kazanis, D.; Tavsanoglu, Ç.; Lloret, F.; Buhk, C.; Ojeda, F.; Luna, B.; Moreno, J. M.; Rodrigo, A.; Espelta, J. M.; Palacio, S.; Fernández-Santos, B.; Fernandes, P. M.; Pausas, J. G. Fire-related traits for plant species of the Mediterranean Basin. *Ecology* **2009**, *90*, 1420.
7. Lavorel, S. Ecological diversity and resilience of Mediterranean vegetation to disturbance. *Divers. Distrib.* **1999**, *5*, 3–13.
8. Delitti, W.; Ferran, A.; Trabaud, L.; Vallejo, V. R. Effects of fire recurrence in Quercus coccifera L. shrublands of the Valencia Region (Spain): I. plant composition and productivity. *Plant Ecol.* **2005**, *177*, 57–70.
9. Liniger, H.; Schwilch, G. Enhanced Decision-Making Based on Local Knowledge. *Mt. Res. Dev.* **2002**, *22*, 14–18.
10. Pausas, J.; Keeley, J. Evolutionary ecology of resprouting and seeding in fire-prone ecosystems. *New Phytol.* **2014**, *204*, 55–65.
11. Buhk, C.; Meyn, A.; Jentsch, A. The challenge of plant regeneration after fire in the Mediterranean Basin: scientific gaps in our knowledge on plant strategies and evolution of traits. *Plant Ecol.* **2006**, *192*, 1–19.
12. Verdú, M. Ecological and evolutionary differences between Mediterranean seeders and resprouters. *J. Veg. Sci.* **2000**, *11*, 265–268.
13. Battisti, A.; Cantini, R.; Rouault, G.; Roques, A. Serotinous cones of Cupressus sempervirens provide viable seeds in spite of high seed predation. *Ann. For. …* **2003**, *60*, 781–787.
14. Spanos, I. a.; Daskalakou, E. N.; Thanos, C. a. Postfire, natural regeneration of Pinus brutia forests in Thasos island, Greece. *Acta Oecologica* **2000**, *21*, 13–20.
15. Hackett, W. P. Juvenility and Maturity. *For. Sci.* **1987**, *24-26*, 216–231.
16. Long, R. L.; Gorecki, M. J.; Renton, M.; Scott, J. K.; Colville, L.; Goggin, D. E.; Commander, L. E.; Westcott, D. a; Cherry, H.; Finch-Savage, W. E. The ecophysiology of seed persistence: a mechanistic view of the journey to germination or demise. *Biol. Rev. Camb. Philos. Soc.* **2014**.
17. Quintana, J.; Cruz, A.; Fernandez-Gonzales, F.; Moreno, J. Time of germination and establishment success after fire of three obligate seeders in a Mediterranean shrubland of central Spain. *J. Biogeogr.* **2004**, *31*, 241–249.
18. Hanley, M.; Fenner, M. Pre-germination temperature and the survivorship and onward growth of Mediterranean fire-following plant species. *Acta Oecologica* **1998**, *19*, 181–187.
19. Keeley, J. Fire intensity, fire severity and burn severity: a brief review and suggested usage. *Int. J. Wildl. Fire*

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

2009, *18*, 116–126.

20. Heras, J. De; Moya, D.; Vega, J. A.; Daskalakou, E.; Vallejo, R.; Grigoriadis, N.; Tsitsoni, T.; Baeza, J.; Valdecantos, A.; Fernández, C.; Espelta, J. *Post-Fire Management and Restoration of Southern European Forests*; Moreira, F.; Arianoutsou, M.; Corona, P.; De las Heras, J., Eds.; Managing Forest Ecosystems; Springer Netherlands: Dordrecht, 2012; Vol. 24.

21. Saracino, A.; D'Alessandro, C. M.; Borghetti, M. Seed colour and post-fire bird predation in a Mediterranean pine forest. *Acta Oecologica* **2004**, *26*, 191–196.

22. Bond, W.; Midgley, J. Ecology of sprouting in woody plants: the persistence niche. *Trends Ecol. Evol.* **2001**, *5347*, 45–51.

23. Rodrigo, A.; Retana, J.; Picó, F. X. Direct Regeneration Is Not the Only Response of Mediterranean Forests To Large Fires. *Ecology* **2004**, *85*, 716–729.

24. Romano, A.; Barros, S.; Martins-Loução, M. A. Micropropagation of the Mediterranean tree Ceratonia siliqua. *Plant Cell. Tissue Organ Cult.* **2002**, *68*, 35–41.

25. Ojeda, F.; Brun, F.; Vergara, J. Fire, rain and the selection of seeder and resprouter life-histories in fire-recruiting, woody plants. *New Phytol.* **2005**, *168*, 155–165.

26. Clarke, P.; Lawes, M.; Midgley, J. Resprouting as a key functional trait: how buds, protection and resources drive persistence after fire. *New …* **2013**, 19–35.

27. Hodgkinson, K. Sprouting success of shrubs after fire: height-dependent relationships for different strategies. *Oecologia* **1998**, 64–72.

28. Malanson, G.; Trabaud, L. Vigour of post-fire resprouting by Quercus coccifera L. *J. Ecol.* **1988**, *2*.

29. Canadell, J.; Lloret, F.; López-Soria, L. Resprouting Vigour of Two Mediterranean Shrub Species after Experimental Fire Treatments Resprouting experimental vigour of two mediterranean fire treatments shrub species after. *Vegetatio* **1991**, *95*, 119–126.

30. López-Soria, L.; Castell, C. Comparative genet survival after fire in woody Mediterranean species. *Oecologia* **1992**, *4*.

31. Barberis, A.; Dettori, S.; Filigheddu, M. . Management problems in Mediterranean cork oak forests: post-fire recovery. *J. Arid Environ.* **2003**, *54*, 565–569.

32. Tavşanoğlu, Ç.; Gürkan, B. Long-term post-fire dynamics of co-occurring woody species in Pinus brutia forests: the role of regeneration mode. *Plant Ecol.* **2014**, *215*, 355–365.

33. Román-Cuesta, R. M.; Gracia, M.; Retana, J. Factors influencing the formation of unburned forest islands within the perimeter of a large forest fire. *For. Ecol. Manage.* **2009**, *258*, 71–80.

34. Radford, I.; Andersen, A.; Graham, G.; Trauernicht, C. The Fire Refuge Value of Patches of a Fire-Sensitive Tree in Fire-prone Savannas: Callitris intratropica in Northern Australia. *Biotropica* **2013**, *45*, 594–601.

35. Nathan, R.; Muller-Landau, H. Spatial patterns of seed dispersal, their determinants and consequences for recruitment. *Trends Ecol. Evol.* **2000**, *5347*, 278–285.

36. Wall, S. Vander; Kuhn, K.; Beck, M. Seed removal, seed predation, and secondary dispersal. *Ecology* **2005**, *86*, 801–806.

37. WOCAT *Questionnaire on SLM technologies (Basic). A Framework for the evaluation of sustainable land management practices (revised)*; Bern, 2008.

38. Green, L. R. *Fuelbreaks and other fuel modification for wildland fire control*; 1977.

39. Finney, M. A. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *For. Sci.* **2001**, *47*, 219–228.

40. Baeza, M. J.; Raventós, J.; Escarré, A.; Vallejo, V. R. The effect of shrub clearing on the control of the fire-

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

prone species Ulex parviflorus. *For. Ecol. Manage.* **2003**, *186*, 47–59.

41. Merriam, K. E.; Keeley, J. E.; Beyers, J. L. Fuel Breaks Affect Nonnative Species Abundance In Californian Plant Communities. *Ecol. Appl.* **2006**, *16*, 515–527.

42. Fernandes, P. M.; Davies, G. M.; Ascoli, D.; Fernández, C.; Moreira, F.; Rigolot, E.; Stoof, C. R.; Vega, J. A.; Molina, D. Prescribed burning in southern Europe: developing fire management in a dynamic landscape. *Front. Ecol. Environ.* **2013**, *11*, e4–e14.

43. Bautista, S.; Bellot, J.; Vallejo, V. R. Mulching treatment for postfire soil conservation in a semiarid ecosystem. *Arid Soil Res. Rehabil.* **1996**, *10*, 235–242.

44. Khurana, E.; Singh, J. S. S. Ecology of seed and seedling growth for conservation and restoration of tropical dry forest : a review. *Environ. Conserv.* **2002**, *28*, 39–52.

45. Arévalo, J. R.; Fernández-lugo, S.; García-domínguez, C.; Naranjo-cigala, A.; Grillo, F.; Calvo, L. Prescribed Burning and Clear-Cutting Effects on Understory Vegetation in a Pinus canariensis Stand (Gran Canaria).

46. Vélez, R. Fire effects and fuel management in Mediterranean ecosystems in Spain. *Proc. Symp. Dyn. …* **1982**.

47. Maestre, F. T.; Cortina, J. Are Pinus halepensis plantations useful as a restoration tool in semiarid Mediterranean areas? *For. Ecol. Manage.* **2004**, *198*, 303–317.

48. Pérez-Ramos, I. M.; Marañón, T. Factors affecting post-dispersal seed predation in two coexisting oak species: Microhabitat, burial and exclusion of large herbivores. *For. Ecol. Manage.* **2008**, *255*, 3506–3514.

49. Herrera, C. Historical effects and sorting processes as explanations for contemporary ecological patterns: character syndromes in Mediterranean woody plants. *Am. Nat.* **1992**, *The Americ*.

50. Agee, J. K.; Skinner, C. N. Basic principles of forest fuel reduction treatments. *For. Ecol. Manage.* **2005**, *211*, 83–96.

51. Valdecantos, A.; Baeza, M. J.; Vallejo, V. R. Vegetation Management for Promoting Ecosystem Resilience in Fire-Prone Mediterranean Shrublands. *Restor. Ecol.* **2009**, *17*, 414–421.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2016 doi: 10.20944/preprints201607.0081.v1

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

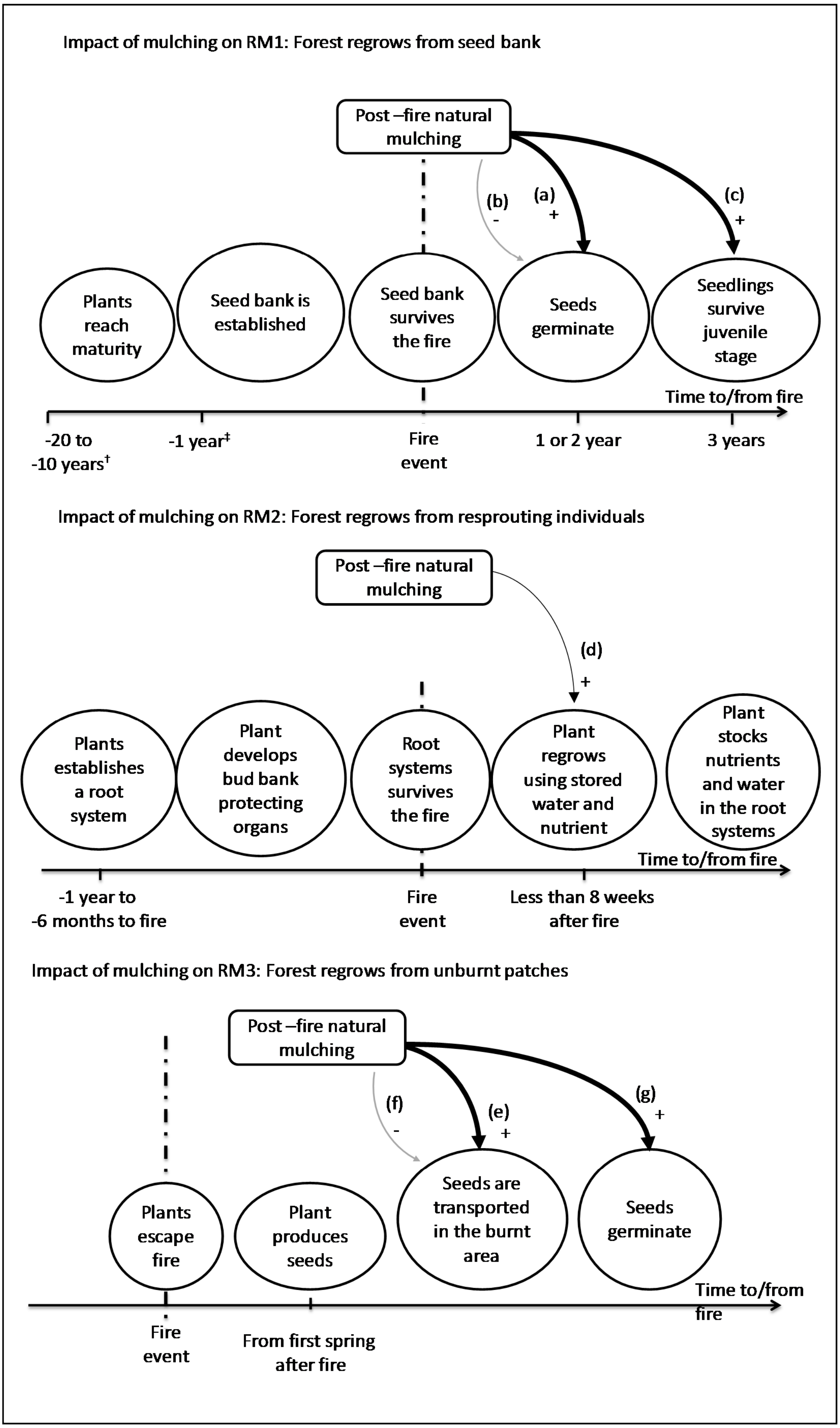


Figure 6: Impact of mulching on the resilience of Mediterranean forest to fire. The width of arrows indicates the relative importance of supporting (+) and hindering (-)

Peer-reviewed version available at Sustainability 2016, 8, 981; doi:10.3390/su8100981

interactions.

Figure 11 gives an overview of the impacts of mulching on forest resilience to fire. As explained in Section 3.1.3., the presence of litter or covering material is crucial for seeds to survive until germination, as it reduces decay, erosion, and animal predation (Perez-Ramos & Maranon, 2008) (a). Furthermore, by helping to maintain soil humidity and soil organic matter content, it promotes the recovery of soil fauna and nutrient cycling after the fire. All these factors contribute to greater soil fertility, which in turn increases the germination rate and seedling survival (Bautista et al., 1996) (c). Accordingly, mulching is clearly beneficial to Regeneration mechanism 1. However, if mulching is too thick, it can decrease the germination rate of obligate seeder species such as *Ulex parviflorus* or *Cistus sp.* (b).

Post-fire soil conditions have no major impact on Regeneration mechanism 2, as resprouter plants maintain their own reserves of nutrients and water. However, greater soil humidity after a fire may promote resprouting, thereby increasing the speed of regeneration (d).

Seed survival and germination are important processes in Regeneration mechanism 3. Accordingly, the presence of continuous litter and stable, humid soil is important in enabling recruitment (e) and seedling survival (f). Germination could also be hindered by a thick layer of mulch (f).

1. Discussion and conclusion

1.1. Regeneration mechanisms

The concept of regeneration mechanisms elaborated in this paper bears similarity to concepts used by ecologists to study plant traits related to fire (e.g. concept of “regeneration paths” by Pausas & Keeley, 2014). However, fire ecologists focus mainly on how fires affect plant evolution and morphology, as well as on how individual plants adapt to fire disturbances (Bond & Midgley, 2001; Herrera, 1992; Buhk et al., 2006). While these studies are fundamental to improving our understanding of the ecosystem, they rarely provide useful recommendations for management, as they do not take into account environmental factors that might influence a fire event and post-fire recovery, nor of the interactions that occur at a larger scale. Our review of the literature on forest ecology and post-fire forest regeneration reveals two important aspects of forest resilience: First, there are various processes that are important to post-fire regeneration that may take place before the fire event. Thus, efforts to increase forests’ resilience to fire should be launched prior to fires, not only after the fact. Second, there are a number of processes that play a role in post-fire forest regeneration that are not directly related to the fire event itself. These processes are often poorly understood in light of their effects on post-fire regeneration. Moreover, there is a need for research on the relative significance of these processes and on important thresholds that can influence regeneration. Further, we lack quantitative indications regarding thresholds in the various processes constituting regeneration mechanisms.

Peer-reviewed version available at *Sustainability* **2016**, *8*, 981; doi:10.3390/su8100981

1.2. Can we increase forest resilience through land management?

Mediterranean forests are composed of various species, and land managers cannot choose which of the three regeneration mechanism their system will follow. However, by examining its species composition and monitoring the hindering and supporting factors, they can understand which regeneration mechanism is most likely to fail or to function. Depending on their management practices, the fire regime, and other environmental factors, they can focus their attention on those processes that are at risk of failing.

Regeneration mechanism 1 – forest regeneration from seed banks – requires the longest interval between fires (see Section 3.1.2) and has the most hindering factors (Table 4). However, our analysis of the impact of management practices indicates that fuel breaks and fuel management might considerably increase the resilience of plants using this mechanism.

By contrast, Regeneration mechanism 2 – forest regeneration from resprouting individuals – appears to be the most stable of the three mechanisms, the quickest to foster recovery, and the least influenced by external factors (Table 4). It has to be noted, however, that the establishment of resprouter species is difficult, and can be hindered by many factors (see table 4, "Total"). The management practices analysed do not seem to have any relevant influence on it, with the exception of fuel management through selective clearing (see Section 4.3.).

Regeneration mechanism 3, contrary to the other processes, does not require any preparation period prior to the fire event, and is therefore independent of the frequency of fires. It is the slowest way for a forest to recover, and the one that is most likely to bring changes to the system. The impacts of management on this regeneration mechanism are the most uncertain, mainly due to the high number of processes involved and the paucity of scientific knowledge about it.

When comparing the management practices, fuel management appears to increase forest resilience the most. It is especially beneficial to pre-fire processes, which makes it a strategic option for prevention. Afforestation with *Pinus halepensis* seems the least promising of all management practices; this becomes even more so if we consider the high cost of implementation and the low success rate in terms of seedling survival and fire risk at the long term. Fuel management and afforestation can be implemented in very different ways, and the specific implementation technique strongly affects how these practices influence regeneration mechanisms.

The available literature on forest management (Agee & Skinner, 2005; Valdecantos et al., 2009) generally supports the information provided by the WOCAT database, as well as the conclusions drawn in this article. However, while most management practices have been studied for their effect on fire regimes, and some (e.g. fuel management and afforestation) also with regard to post-fire recovery, very few empirical studies have analysed the diverse impacts of management on soil erosion, seed bank establishment, and other factors involved in Mediterranean forests' resilience to fire. In light of these gaps, despite WOCAT's largely qualitative and somewhat general approach to assessing management practices, the WOCAT database represents an important tool for use in better understanding the role of forest management. Moreover, our literature review revealed a lack of articles providing a general method for assessing resilience, or offering evaluation of the impact of management practices on the resilience to fire of Mediterranean forests.

1.3. Other factors influencing forests' resilience to fire

Focussing on regeneration makes it possible to relate impacts of land management to forest resilience in a direct way. However, there are other factors that can increase the resilience of forests and improve the likelihood of post-fire regeneration: First, certain land uses, in particular grazing and wood gathering, reduce the amount of available fuel in forests, thus reducing the risk of repeated and intense fire. These activities were part of forest use for centuries, and their disappearance – owing to declining (perceived) economic returns – is an important factor in the changing of fire regimes of many Mediterranean countries. However, it also implied in some cases the removal of root systems, reducing or even eliminating completely the presence of keystone resprouting species. Second, the shape and diversity of landscape mosaics have direct effects on fire spreading, fire suppression, and post-fire regeneration (especially vis-à-vis regeneration mechanisms). The interplay between forest areas, open areas (e.g. pastures), and areas with low flammability (e.g. orchards, built areas) influences the size and occurrence of burned areas following a fire. In many forest stands of the Mediterranean Basin, land abandonment is radically changing the traditionally diverse and patchy landscapes, with clear effects on fire regimes and forest evolution. Third, the presence of certain plants or combinations of plants has beneficial impacts on soils and ecosystems in general. Increasing research on functional groups, and clear identification of the most important ones, will undoubtedly improve land managers' ability to enhance the resilience of forest stands.

Acknowledgements

This paper was developed within the CASCADE project (Seventh Framework Programme FP7/2007–2013 grant agreement 283068). The authors acknowledge financial support from the CASCADE project and the European Cooperation in Science and Technology (COST). We also thank the contributors to the WOCAT database: Nina Lauterburg (CDE), Celeste Coelho and Sergio Prats (University of Aveiro, Portugal), and Velia de Paola (University of Basilicata, Italy). In addition, we would like to thank Jaime Baeza for their help in sharpening the concepts and their insights on fire ecology. Ultimately the authors thank Marlene Thibault (CDE) for the editing. Thanks also go to the editor and the anonymous reviewer for their comments and suggestions, which enabled significant improvements to the manuscript.