Global and Planetary Change 146 (2016) 152–161

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Wildfires in Chile: A review

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ARTICLE INFO

Article history:
Received 3 June 2016
Received in revised form 3 October 2016
Accepted 5 October 2016
Available online 6 October 2016

Keywords:
Vegetation
Soils
Wildland urban interface (WUI)
Fire risk
Fire prevention

ABSTRACT

This paper reviews the literature examining the wildfire phenomenon in Chile. Since ancient times, Chile's wildfires have shaped the country's landscape, but today, as in many other parts of the world, the fire regime – pattern, frequency and intensity – has grown at an alarming rate. In 2014, >8000 fires were responsible for burning c. 130,000 ha, making it the worst year in Chile's recent history. The reasons for this increase appear to be the increment in the area planted with flammable species; the rejection of these landscape modifications on the part of local communities that target these plantations in arson attacks; and, the adoption of intensive forest management practices resulting in the accumulation of a high fuel load. These trends have left many native species in a precarious situation and forest plantation companies under considerable financial pressure. An additional problem is posed by fires at the wildland urban interface (WUI), threatening those inhabitants that live in Chile's most heavily populated cities. The prevalence of natural fires in Chile; the relationship between certain plant species and fire in terms of seed germination strategies and plant adaptation; the relationship between fire and invasive species; and, the need for fire prevention systems and territorial plans that include fire risk assessments are some of the key aspects discussed in this article. Several of the questions raised will require further research, including just how fire-dependent the ecosystems in Chile are, how the forest at the WUI can be better managed to prevent human and material damage, and how best to address the social controversy that pits the Mapuche population against the timber companies.

Contents

1. Wildfires as a worldwide phenomenon

There is evidence that wildfires appeared concomitant with the origin of terrestrial plants and that they have played an important role throughout history (Pausas and Keeley, 2009). Indeed, fire is ubiquitous and can occur across almost every biome, be it in zones of Mediterranean, boreal or tropical climates, and in all kinds of vegetation zones (Archibald et al., 2013).

In many parts of the world, wildfires have shaped the landscape, acting as an ecosystem agent (Mataix-Solera and Cerdà, 2009), even though many such fires are caused by humans, either deliberately or accidentally as a result of negligence. Yet, it has been shown that fire plays a role in sustaining biodiversity and ecosystem health (North et al., 2015) and, as such, we have learned to live with this phenomenon (Belcher, 2013).

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http://dx.doi.org/10.1016/j.gloplacha.2016.10.004
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It might be that the current conception of fire as an accelerating problem (in terms of number of fires and burnt hectares) is a question of human perception and not a statistical reality. Studies show that there is insufficient data to conclude that fire intensity has increased over the last century and that it is far from clear that economic losses are higher today than those recorded three decades ago (Doerr and Santín, 2016).

The initial effects of fires can be direct: killing animals, burning vegetation and disturbing soil horizons, the strength and duration of these effects having been shown to depend on the intensity of the fire (Úbeda and Sala, 1998). Moreover, the degree of degradation of both vegetation and soil tends to be especially great when fires are recurrent in the same area (Cerdà, 2011). Subsequent effects are indirect, ranging from soil erosion and water pollution to the silting up of dams and landslides (Stoof, 2011).

Although fire is a natural factor (Costa et al., 2011), wildfires may constitute an environmental problem – resulting in the loss and degradation of the biosphere, and a significant social problem – resulting in human losses, the pollution of aquifers, landslides in inhabited areas, and the degradation of crops.

The media play an important role in our perception of wildfires. Fires that break out in more densely populated regions tend to receive more media coverage than fires in uninhabited areas. This is perhaps only logical given that thousands of people's lives might be at risk from these fires and often they have to be evicted from their homes. These fires at the wildland urban interface (WUI) are known as fires of the fifth generation, that is, "fires of a high intensity occurring in inaccessible sites, with people and infrastructure that must be saved before attempting to extinguish the fire itself" (Costa et al., 2011).

Chile, a country with large areas under forests and woodland plantations, is no stranger to wildfires, which occur not only in the country's Mediterranean climate zone, but also in the more humid and temperate climate zones of its vast territory. According to Castillo (2015), in Chile the increase in the number of fires over the last 15 years has tended towards equilibrium in terms of the hectares burnt in rural areas, but has varied considerably in relation to interface fires, due among other reasons to authorised building practices on land unsuited for urban use.

These issues are addressed in detail in this paper which reviews documentary sources, from both the scientific and technical literature, that examine wildfires in Chile from ecological, social and planning perspectives. As such, this paper represents a new contribution to the knowledge of the fire community.

2. Chile: general trends

The South American country of Chile occupies a surface area of 756,102 km^2. Given its location between parallels 17°S and 56°S, Chile has markedly distinct climate types (Fig. 1a) and a geomorphology that is characterized broadly by the Andes Mountain Range and its corresponding volcanic activity (Fig. 1b). Chile has a population of 17,819,054 inhabitants (2014) with a density of 23.57 people/km^2. Fig. 1c shows the geographical distribution of this population. These general features are critical for understanding the distribution of vegetation, forests, and the main fire activity in the country.

According to the National Forest Corporation of Chile (CONAF, 2015), around 40 million hectares of national territory (equivalent to 50% of the land area) has an agro-grazing-forestry land use. In 2013, 17.3 million ha were dedicated to forests (22.9% of the country), of these, 14.18 million (18.7% of national territory) corresponded to native forest and 2.96 million ha to plantations. Within the native forests, the Lenga Forest type (*Nothofagus pumilio)* is the most abundant (3,642,695 ha), followed by Evergreen Forest type (*Nothofagus dombeyi*,

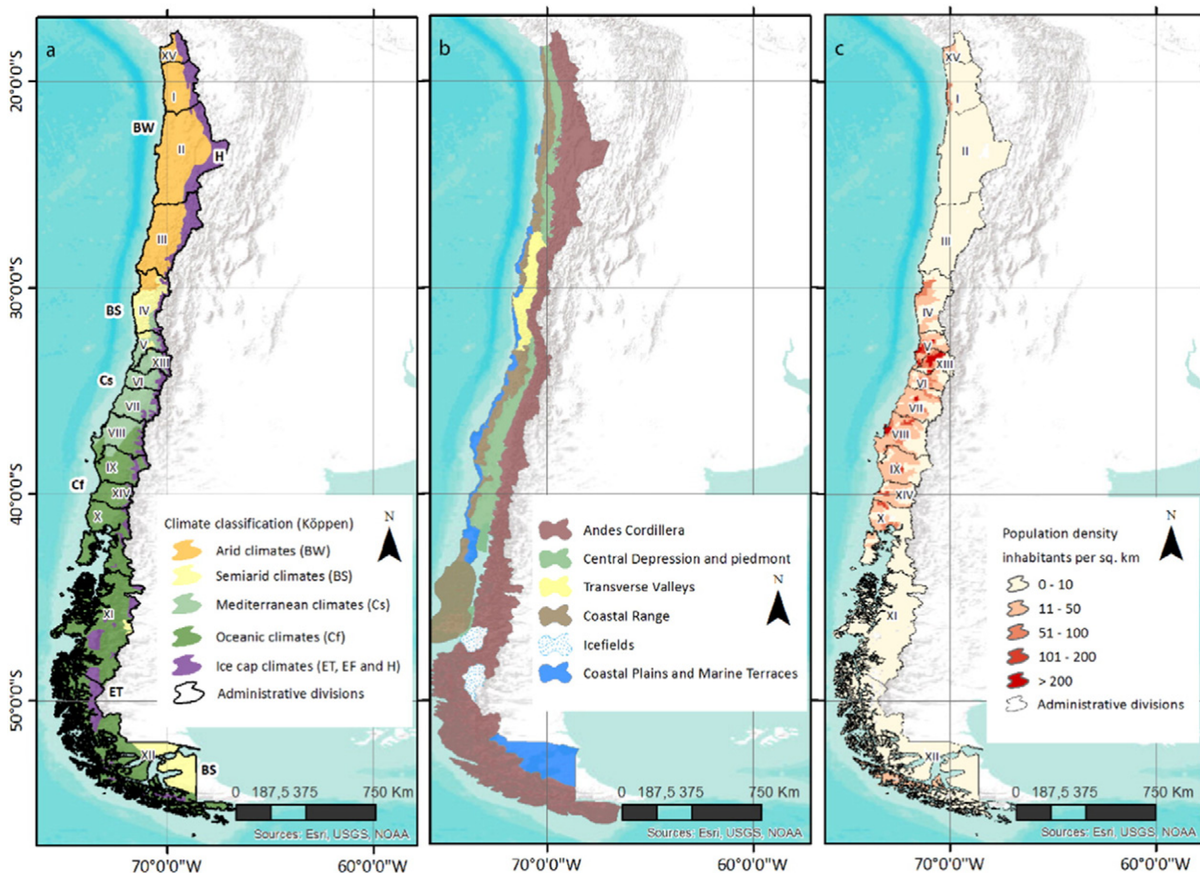

Fig. 1. a) Climate classifications; b) Great geomorphologic features; c) Population density.
(Source: 1a) www.rulamahue.cl/mapoteca 2a) http://www.rulamahue.cl/ 3a) http://sedac.ciesin.columbia.edu/)

Eucryphia cordifolia, *Weimmannia trichosperma*, *Laurelia philippiana*, and others) (3,514,644 ha), Coihue Magellanic (*Nothofagus betuloides*) (2,003,481 ha), and Oak - Raulí - Coihue (*Nothofagus alpine*) (1,528,028 ha). Less frequent are the Chilean palm forest (*Jubaea chilensis*) (15,085 ha) and Cordilleran Cypress (56,459 ha). Ninety-seven per cent of wood production originates from the plantations, primarily those of Eucalyptus (*Eucalyptus globulus* and *Eucalyptus nitens*) and Pine (*Pinus radiata*) (68% of the total pine plantations are of this species).

According to the CONAF (2015) definition, a wildfire is "A fire that, regardless of its origin and size, spreads unchecked in forest/rural lands and rural-urban interfaces, through woody shrubs and herbaceous vegetation, living or dead".

Fig. 2 shows the number of fires and burnt hectares in Chile since 1960 (but note that reliable records only really became available in 1984–1985). As can be seen, some years recorded a greater number of fires (the case of 2003 and 2008) and some recorded a greater number of burnt hectares (the case of 1999 and 2014). Applying the Mann-Kendall test, it can be concluded that the number of fires has increased significantly at the national level (p-value < 0.05) (1984–2016). In the area of highest incidence (regions V-IX – see, Fig. 1 for the location of the regions – the increase is significant between the VII (p-value < 0.01) and IX regions (p-value < 0.001), while decreasing in the V and VI regions (p-value < 0.05). In contrast, the size of the burnt area does not present any statistically significant changes in the period 1984–2016, even when we divide the series. According to Peña and Valenzuela (2008), the increase in the number of fires is closely related to the increase in the area planted with highly flammable species (Pines and Eucalyptus), the rejection of these modifications on the part of some local communities who subject these plantations to arson attacks; and, the application of intensive forest management practices resulting in the accumulation of a high fuel load. Moreover, the authors document the difficulties in reaching many areas of native vegetation due to the topography, which hinders the rapid extinguishing of wildfires in mountainous areas. Additionally, in recent years, there has been an increase in the number of wildfires at the WUI (Garfias et al., 2012).

Fig. 3a highlights the regions experiencing the largest number of fires: namely, V (Valparaíso), XIII (Metropolitan), and VIII (Bio Bio). Fig. 3b shows the number of hectares burnt in each of the regions. Region XI (Aisén) appears as a heavily burnt region, though here a small number of fires were responsible for considerable areal damage. Fig. 3c indicates which vegetation type burned more in each region – plantations or native forest. Here, it can be seen that in regions VIII (Bio Bio) and IX (Araucanía) the largest part of the burnt areas correspond to plantations (Eucalyptus and Pines).

These maps are critical for interpreting and locating the different aspects of wildfires described in the rest of this paper.

Many reports and articles have been published discussing the causes of wildfires in Chile and most conclude that almost all are of anthropogenic origin. According to CONAF (2015), the main causes of fire in Chile in 2011 were accidents and negligence (58.2%), intentional fires (24%), unknown (17.6%), and natural causes (0.2%). As such, natural ignitions, that is, thunderstorms and volcanic fires, appear to constitute < 1%. One reason for the small number of thunderstorms in Chile is that the formation of these electrical storms is impeded by the Andean Cordillera, while along the country's Coastal Cordillera these phenomena are not frequent (Keely et al., 2012). In Chile, the country's television and media have made acts of human negligence one of the most widely known causes of wildfires, especially those attributable to foreign tourists in the Torres del Paine National Park (in southern Chilean Patagonia). Chileans are especially proud of this park, and news of this kind quickly reaches the majority of the population. The media also give wide coverage to the apparently intentional fires resulting from the land ownership conflicts between the Mapuche indigenous populations and the new forestry companies in regions VIII and IX (Bio Bio and Araucanía).

Yet, some studies claim a number of fires are, in fact, started by natural causes (such as storms), but this remains a controversial hypothesis. Indeed, González (2005) notes that a 2002 fire in Araucanía which is listed as being attributable to human causes was started by lightning. Several other authors believe lightning storms to be crucial and, in this regard, they point out that many mid-latitude tree and shrub species

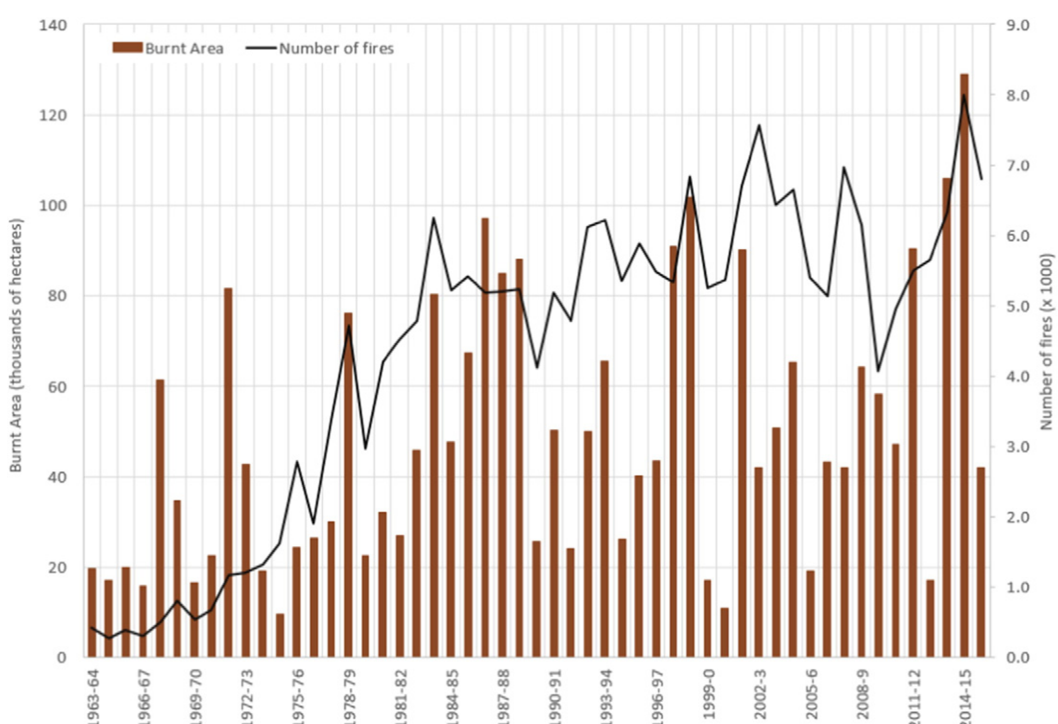

Fig. 2. Number of wildfires and burnt hectares since 1960 in Chile.
(Source: CONAF (2015).)

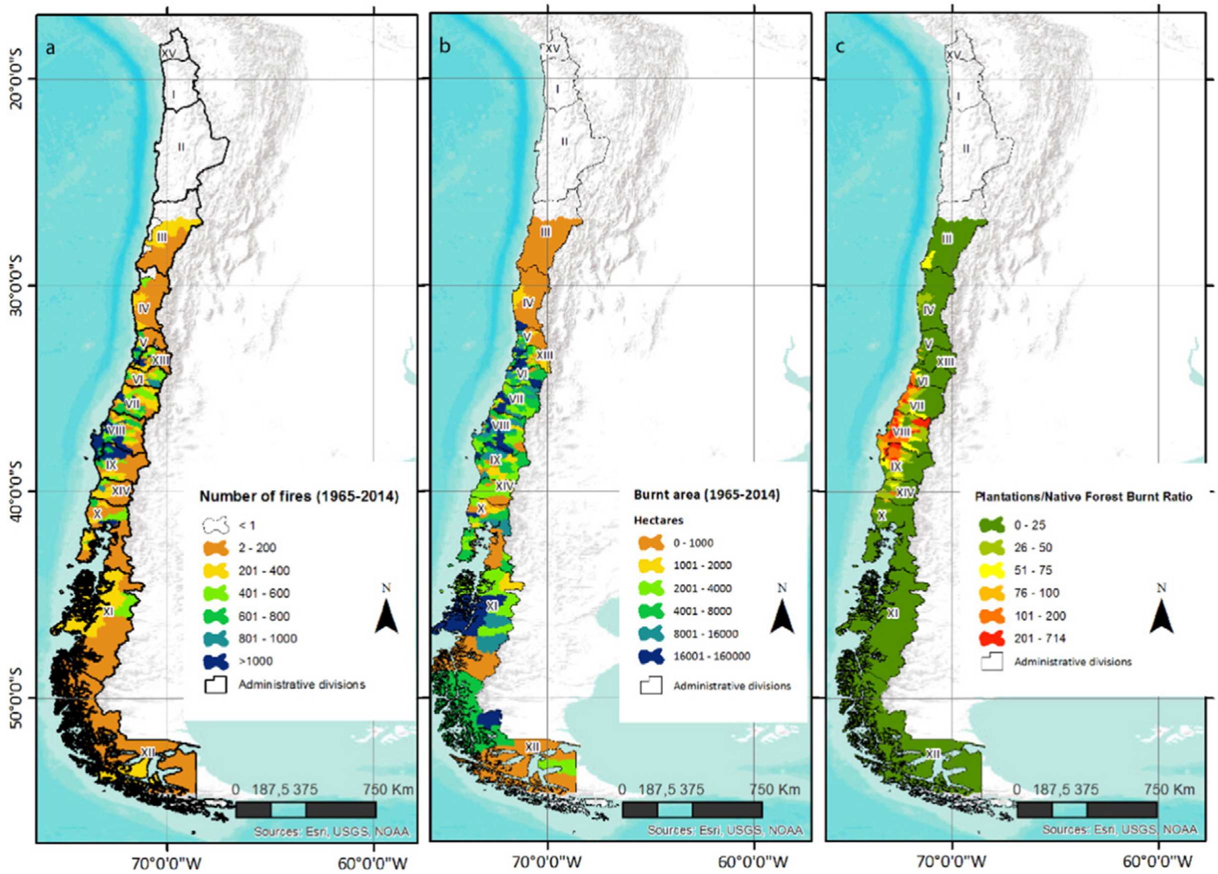

Fig. 3. a) Number of fires (1965–2014); b) Burnt hectares (1965–2014); c) Ratio between fires in plantation vs. native forests. (Source: CONAF (2015).)

of the southern Andes are well adapted to resist, or recover after fires. A good example is the araucaria which resprouts from buds at the base of the trunk, on lateral roots, and on the branches (Veblen et al., 1995).

The problem in Chile is that while thunderstorms might cause few fires, they often destroy many hectares of forest, because, in common with many Mediterranean countries, between 0.6 and 0.9% of all fires are responsible for >60% of the burned area (CONAF, 2015). This fact obviously needs to be taken into consideration, since the actual cause of the fire may not be as important as why the fire takes hold, why it acquires proportions that make extinguishing it extremely difficult, and why it propagates at such a high rate. Understanding all these aspects is clearly essential for effective prevention.

Another subject addressed in recent research is climate change and its influence on wildfires. González et al. (2011) indicate that climate change is evident in Chile and it has the potential to influence fire activity in south-central Chile (33° - 42° S), making the introduction of adaptation measures necessary to cope with the emerging problem. Numerous studies concur that the main effects of climate change in this area will be associated with a decrease in precipitation (CONAMA, 2006), which would result in an increment in the frequency of wildfires and the surface area affected (González et al., 2011). In this regard, recent international initiatives, such as New Generation Plantations and early certification as defined by the Forest Stewardship Council (FSC), aim to promote and regulate the proper management and sustainability of forests and plantations. In Chile, according to González et al. (2011), policies are needed to promote the territorial planning of rural landscapes and, in particular, the diversification of the forestry sector so that it can meet the challenges posed by climate change and promote healthier forests, in terms of their long-term productivity, diversity, and resilience.

3. Ancient fires

Today, the number and destructive capacity of wildfires in Chile are greatest in central regions, due primarily to climate conditions and problems of human pressure. However, there is clear evidence that southern parts of the country suffered fires as early as 17,000 yr BP (Huber et al., 2004; Whitlock et al., 2007). Pollen, charcoal, plant macrofossils and sediments all help in the reconstruction of past environments in terms of vegetation types and fire evidence (de Porras et al., 2012). Sediment characteristics, the absence of diatoms, and the scarcity of pollen suggest that before 18,000 cal yr BP, local glaciers attained their maximum extension, which would rule out the possible presence of fires (Markgraf et al., 2007). Nevertheless, while the interactions between climate and fire remain poorly understood, it is clear that during the Pleistocene-Holocene in Patagonia-Tierra de Fuego (49°S to 55°S), there were fires.

Huber et al. (2004) suggest that these wildfires would have been ignited either by human activity or by lightning. The first theory is concomitant with the fact that the earliest evidence of human occupation in Tierra del Fuego-Patagonia has been securely dated to ca 11 ^{14}C ka BP (ca 13 ka BP) (Borrero and McEwan, 1997). Indeed, Holz and Veblen (2011) conclude that the indigenous population was the most likely source of these early fires and, likewise, they document an increase in wildfire activity following the colonization and permanent settlement of the region by Euro-Chileans. However, the authors report that regional climate conditions would have inhibited the spread and extent of most fire events.

Lago Condorito (41°45′S, 73°07′W) is a location where North Patagonian rainforest taxa predominated between about 13,000 and 12,200 ^{14}C yr BP in the lowlands of southern Chile, near the present-day city of Puerto Montt. The subsequent period, between 12,200 and 9900 ^{14}C yr BP, was characterized by the expansion and persistence of the conifer *Podocarpus nubigena*. There is evidence that this vegetation was exposed to wildfires, but the dating of these events is too early for them to be related to the volcanic eruption dated at around 9000 ^{14}C yr BP. Thanks to evidence from neighbouring archaeological sites, it seems likely that these fires could have been caused by human activity (Moreno, 2000) and, moreover, the new post-fire scenario led to the expansion of opportunistic species favoured by this disturbance, replacing the closed-canopy vegetation typical of the rainforest (Moreno, 2000).

However, ultimately, it was the climate conditions (above all, the moisture content) that were responsible for the ignition and spread of fires. This has been documented by Pesce and Moreno (2014) in Chiloé (43°S), where low lake levels and enhanced fire activity between 800 and 2000, 4000–4300, ~8000–11,000, and 16,100–17,800 cal yr BP suggest lower rates of precipitation in north-western Patagonia. Markgraf and Huber (2010) stress the importance of wet and dry periods in association with fluctuating evidence of fire events.

The absence of fires after 9000 cal yr BP was apparently a response to a further increase in precipitation to present-day levels, while moisture variability was no longer a critical factor (Markgraf and Huber, 2010). The changes in fire regimes were clearly marked by prevailing climate conditions which also facilitated the development of a certain type of vegetation in northern Patagonia. This was the case of the mixed *Nothofagus dombeyi–A. chilensis* forests, which appeared after 3000 cal yr BP, and which were subject to frequent wildfires (Markgraf et al. 2013).

There is also evidence of fires in the northernmost part of the Aisén Province, in southern Chile (45°S). The maximum fire activity took place between 11,000 and 7500 cal yr BP, with several large local events. *Nothofagus* steppe–woodland developed and precipitation must have increased, but it is likely that summers were drier than today, with a high frequency of convective storms (Markgraf et al., 2007).

Climate was also decisive in the emergence of different tree-types, which burned when exposed to wildfires. In the post-glacial period (16,000–12,000 BP) and early Holocene (12,000–6000 BP), there was a rapid forest expansion from glacial refugia, a result due of climatic warming (Armesto et al., 2010).

Later, in Lake Shaman (44°S, 71°W) between 5 and 3 cal ka BP, evidence points to the retraction of the forest-steppe ecotone, accompanied by a marked variability in the pollen record and increased fire activity associated with greater climatic variability (de Porras et al., 2012). The same authors found an increase in the variability of plant species in the Late Holocene, which is a common regional pattern throughout Central Chilean Patagonia. It is interesting to note how de Porras et al. (2012) forward two potential explanations for this record variability, relating it to low magnitude south-westerly changes associated with ENSO (El Niño Southern Oscillation) and/or SAM (Southern Annual Mode) – a possibility also documented in Abarzúa and Moreno (2008), or to the complex relationships between vegetation, fire, and human occupations during this period. Fletcher and Moreno (2012) conclude that ENSO has been the main driver of growing seasonal moisture in south-central Chile over the last 1500 years, a phenomenon that has been significant in the increase/decrease in the occurrence of fire. Both de Porras et al. (2012) and Moreno (2000) stress the importance of fire in shaping the landscape, and the fact that it was doing so even in ancient periods.

Similarly, González (2005) used dendrochronological techniques to document the fundamental role played by fire in the ecology of *Araucaria-Nothofagus* forests. The author concludes that fire does not represent a problem for the *Araucaria-Nothofagus* forest; what is a problem is the change in the fire regime due to human pressure which causes more intense and more frequent fires that can damage the forest. However, interestingly, González (2005) is critical of the fact that the authorities (and even some researchers) fail to recognize that some fires, in all periods, could be caused by natural ignitions, such as by lightning storms, as was the case of the fires in 2001–2002 in several of Chile's Natural Parks. According to González (2005), it is important to recognize fire as a shaper of the *Araucaria-Nothofagus* forest, and he proposes investigating whether present-day fire regimes differ from historical regimes and, based on this knowledge, implementing forest management programs that benefit the Araucaria landscape.

4. Effects of fire on vegetation and soils in Chile

Several studies examine the relationship between vegetation (native species and plantations) and wildfires, focusing on the evolution in the relationship and on the quantity and location of fires. Castillo et al. (2012) analyse the last 35 years in the relationship between native vegetation and large wildfires in the central regions of Chile (Valparaíso, Metropolitana, Libertador Bernardo O'Higgins, and Maule), covering an area of 7,836,288 ha. According to references cited therein, between 1800 and 1950, more than half the native forests were devastated by the fires used in opening up areas for agriculture. One of the consequences of this process was the emergence of post-fire invasive species. Later, 1984 and 1999 were the two worst years in terms of the total number of hectares (>25,000 in both) burnt in these four regions (CONAF, 2015).

In Chile, as mentioned above, the majority of forests are native: 14.18 million ha of native forest vs. 2.96 million ha of plantations. Peña and Valenzuela (2008) carried out an in-depth analysis of wildfires in both scenarios. One of the conclusions they draw is that the number of fires has increased in parallel with the growth in the size of areas under forest plantations. Since 1975, the mean growth rate recorded by plantations stands at 70,000 ha per year, with regions VIII and IX presenting the largest areas dominated by the species of *Pinus radiate*, *Eucalyptus globulus* and, to a lesser extent, *Pseudotsuga menssiezii*. Crown fires are especially common in these plantations given the dominant tree species, their highly inflammable leaves, plantation homogeneity and continuity, and the high levels of forest residues on the soil surface.

Region IX (Fig. 1) also has a large area under native forest, most of it protected as national parks and reserves. These include Tolhuaca, Nahuelbuta Los Pangues, Villarrica, Lautaro, and Huerquehue. The vegetation is dominated by *Araucaria araucana*, *Nothofagus dombery*, *Nothofagus oblicua,* and *Nothofagus pumilio*, among others. According to Peña and Valenzuela (2008), the impact of fire in such forests is more severe than in the plantations given the quantity of flora and fauna that is at risk from wildfires. The authors also stress that the location of these native forests in the Andes Cordillera complicates firefighting tasks owing to the steep topography and difficulty of access.

One of the many native species of botanic value is the Chilean palm (*Jubaea chilensis* Mol. Baillon), the world's southernmost palm tree. It is found primarily in region V which is very densely populated. The tree has been the focus of a study by Castillo (2010), following a wildfire in February 2004 in Valparaiso. The author concludes that the palm is seriously threatened in this region, not only by fire but also by human pressure (road construction, collection of specimens and increase in rodents). Castillo (2008) and Quintanilla and Castillo (2008) also report that, although this species has adapted to moderate fires, some recent fires, such as that of 2004, are more intense than their bark can withstand. Quintanilla and Castillo (2009) (as reiterated six years later by CONAF, 2015), show that the recurrence of wildfires in these areas has increased since the mid-80s and continues unabated. This has interrupted the population dynamics of the Chilean palm in the adult phase, as wildfires prevent the species reaching a stage at which it can reproduce. Additionally, the species is confined to places with steep slopes, making plant development difficult. According to Castillo et al. (2009), if no special protection is proposed for the Chilean palm, it runs the risk of disappearing.

One of the controversies regarding the relationship between vegetation and fire in Chile is whether or not fire-dependent ecosystems can be said to exist. According to Montenegro et al. (2004), fire frequency in the past was apparently not high enough to cause evolutionary pressures in the Chilean species and, indeed, some species can even survive fire. High intensity fires, as are common at present, can destroy the tree completely. Moreover, the author argues that Chilean species are not serotinous plants. CONAF (2015) claims that while in many other parts of the world there are ecosystems that are fire-dependent and which require fire for their life cycles, this is not the case in Chile. In the south, in Torres del Paine (51° S) in region XII, that of Magallanes, Vidal (2012) reports that fire does not form part of the ecosystem in this National Park. Moreover, the lack of resilience to wildfire means the forest here does not grow back, rather patches of the Patagonian steppe are left exposed and susceptible to invasive species. Some fauna may also be affected by wildfires in the Park, including many bird species, such as the one-and-a-half foot tall *Magellanic* woodpecker.

However, as mentioned above, some researchers (Veblen, 1982; Godoy et al., 1994) claim that forests such as the Andean *Araucaria araucana* are adapted to fire. Fires caused by relatively infrequent storms produce natural fires, but climate change and humans have significantly influenced the frequency and magnitude of these episodes (González and Veblen, 2007). Veblen (2007) states that although lightning storms are rare in Chile, the infrequent occurrence of lightning-ignited fires is of major ecological importance in these forests. Even in the humid Fitzroya forests (*F. cupressoides*) of coastal Chile, where there are thousands of square kilometres of forest, lightning-ignited fires may only occur a few times in a century, but the effects on forest structure last for centuries (Veblen, 2007).

An extensive study was carried out by Villaseñor and Saiz (1990) in region V, analysing 52 Chilean Mediterranean species after a very intense fire in 1984 (one of the worst years on record in Chile as far as burnt hectares are concerned). The species included *Lithraea caustica* (litre), *Cryptocarya alba* (peumo), *Quillaja saponaria* (quillay), *Azara celastrina* (lilén), *Colliguaja odorifera* (colliguay), *Podanthus mitiqui* (mitique), *Schinus polygamus* (huingán), *Adesmia arborea* (espinillo), *Ephedra andina* (pingo-pingo), *Puya violacea* (puya), *Echinopsis chiloensis* (quisco), *Eriosyce curvispina* (quisquito colorado), and *Jubaea chilensis* (palma chilena). Villaseñor and Saiz (1990) concluded that the regrowth of these Mediterranean species following fires is generally irregular. Woody species can often withstand a fire and recover, but typical post-fire herbaceous species compete with woody species for moisture and light, and this fierce competition hinders normal development. Four years after a fire, the tree forest physiognomy changes to scrubland because some of the tree species regrow as shrubs.

In a Government report carried out in conjunction with the Pontificia Universidad Católica de Chile (Fernández et al. 2010), it was concluded that there was a need for more studies addressing the fire response of plant species in Chile. While various studies consider certain Mediterranean species, none examine plant formations. Moreover, no study of any kind was found at the landscape level, assessing the distribution of biotic and abiotic components and attempting to link them with fire dynamics. Promoting further research is essential in order to implement ecological restoration after wildfires.

Another line in the literature brings together studies of fire and vegetation by focusing on the effect of fire on soil temperature and invasive species in Central Chile. García et al. (2010) study how one invasive species (*Teline monspessulana*) thrives after fires. According to the authors, the problem with this, and other invasive species, is that they are better adapted to fire than the native species of the same area. An additional problem is that after a fire, the growth of this Mediterranean shrub is rapid but it is highly flammable given its small branches (García et al. 2007). These authors also recommend not carrying out controlled fires on burnt crop residues in plantations of *Pinus radiata* because their experiments show that the seeds can germinate after low intensity fires. Rivas et al. (2006) indicate that this may also occur with other invasive species such as *Ulex europaeus* L. and *Cytisus scoparius* L.

However, Figueroa et al. (2009), in a study conducted in the Metropolitan region (33°, 10′S) with both native (*Lithrea caustica*, *Baccharis spp.*, and *Colliguaja odorifera*) and exotic shrubs (*Anthriscus caucalis* and *Erodium spp.*) found that the fire temperature did not increase the emergence of the latter at the expense of the native species. Moreover, they report evidence of the fact that heat shock can increase the occurrence of such native herbs as *Bromus berteroanus* and *Oxalis micrantha*.

Another important finding that needs to be taken into account is that Chilean evergreen shrubland can germinate as a result of fire-induced heat. However, many seeds of Chilean species die during wildfires (Muñoz and Fuentes, 1989) and various laboratory tests designed to provoke the germination of seeds report a different behaviour to that found in the forest. Likewise, a number of studies report that the smoke produced during wildfires does not stimulate seed germination of dominant species in the Chilean Mediterranean shrubland (Gómez-González et al., 2008; Figueroa et al., 2009).

In comparison with the literature on vegetation, few studies examine the relationship between fire and Chilean soils. Litton and Santelices (2003), in a study of *Nothofagus glauca* forest soils, after a high-intensity surface/crown fire that took place in 1997, in region VIII (Bio-Bio, 35°–36° S), found that the changes observed in the organic matter content of the soils and the availability of nutrients to plants and soil microorganisms have short-term implications for the post-fire development of the *Nothofagus* forests in central Chile, as well as long-term implications for their productivity and sustainable management. The authors carried out their analysis after collecting samples 2, 9, 14, and 21 months after the fire, and concluded that more long-term studies are needed to better understand the role that fire plays as a natural disturbance in these native forest soils.

Rivas et al. (2012) studied the effect of a fire event that extended from December 2001 until February 2002 on Andisol topsoils in Araucaria-Nothofagus spp. forest and agricultural sites (38° 20′S). Three years after the fire, the results indicated that the black carbon content of agricultural soil was unaffected by stubble burning, even though such burnings had been performed over the preceding 17 years. In forest soils, by contrast, carbon content increased with fire severity from 0.5% at an unburned site up to 7% in a topsoil severely affected by wildfire. According to the authors, therefore, fire can increase the total amount of organic matter in the soil by around 5% at agriculture sites and by 7% in forest soils.

Escudey et al. (2015), in laboratory work conducted on southern Andisol and Ultisol soils (40°S approx.) from five sites, studied the way in which ash produced from native species (*Nothofagus dombeyi*, *Nothofagus obliqua*, *Nothofagus pumilio*, *Laurelia Sempervirens*) and from the trees in the most common plantations (*P, Pinus radiata* D. Don and *E, Eucalyptus globules*) increases soil pH, primarily within the first top 10 cm of the soil layer. The authors found ash incorporation to be mostly positive because of increased K and Ca availability and increased soil retention capacity for P and Zn, essential inputs for boosting the productivity of volcanic soils that are naturally low in fertility. The same authors have also shown that the availability of P in burnt volcanic soils depends on the origin of the ashes (native forest, pine or eucalyptus) (Escudey et al., 2010). In terms of organic matter, Escudey et al. (2015) and Molina et al. (2007) found that in Andisols, the loss of organic carbon due to the dissolution of the organic matter under the effect of an alkaline pH was minimal.

Chile has a highly mountainous terrain, including that of the Andes Cordillera and the Cordillera de la Costa, with slopes of 30–50% (Francke, 2002). A major problem associated with wildfires is the soil erosion rates recorded after the event. One of the tasks that has been carried out by CONAF since the 1990s is that of watershed restoration following a wildfire (Francke, 2002). Such management projects are undertaken in watersheds at high risk of erosion due to the steepness of their slopes. A good example of this work is that undertaken after the Sierra Bellavista forest fire (region VI, O'Higgins). This fire took place in 1999 and burned a total of 10,000 ha. The fire caused damage to an urban settlement (second residences in the forest), destroying 11 homes and injuring 56 people. In addition, there was considerable danger of landslides and the contamination of the reservoir downstream (Pantano de Rapel). This "pantano" due to the steepness of the slopes and the erosion after the fire, a lot of ashes and sediment filled the reservoir (Francke, 2002). The restoration work undertaken included the construction of gabions, checkdams, and fences on the slopes and reforestation using native species. CONAF has accumulated many internal reports on the effects of fire on soil properties. These have proved especially useful in the restoration of areas affected by fires since the 90s; however, not all these reports are accessible to the general reader, though CONAF do make the information available on request.

A number of interesting studies have also been published about forest restoration in the Mediterranean and temperate regions of Chile (Armesto et al., 2009). A good knowledge of fire regimes and fire recurrence is essential to understand the post-fire regeneration of these vegetation types. In this respect, changes in fire regime as well as fire intensity are the most important threats to ecosystem recovery. In a scenario of an increasing occurrence of wildfires which hinder natural recovery, restoration strategies are essential, although at the same time the authors stress that fire prevention, detection and community education are also important in ensuring the success of the natural regeneration of the vegetation. Armesto et al. (2009) report detailed research of the fire history of each of the most important Chilean species and the most suitable restoration strategies, according to whether they should be passive or active, and depending on the extent to which the vegetation and soil have been affected.

5. Fire risk evaluation and wildfire prevention in Chile

Wildfires have been considered a serious risk in Chile for many years, however, it was not until 1985 that homogenous, reliable statistics about wildfires in Chile became available (Castillo et al. 2012) and the relationship between fires and meteorological trends could be determined more accurately.

In 1993, Chile developed a Wildfire Forecast System based on scientific records and data from the previous 30 years. The system, known as KITRAL (meaning 'fire' in the Mapuche language) was funded by the Chilean National Scientific and Technological Research Commission (Julio et al., 1995). The objective was to implement more suitable control strategies with regards to the recurrence, spread, and damage of wildfires specifically in Chile, but which might also be applied in other Mediterranean countries (Castillo et al. 2015). KITRAL has been refined and modified over time and remains operational. Indeed, Castillo and Garfias (2010) show that the model provides results that tend to be more reliable, especially for larger areas.

The most densely populated areas of Chile with a Mediterranean-type climate and vegetation are at greatest risk from wildfires, as typified, for example, by the Valparaíso region. Castillo (2012) has presented a fuzzy methodology for the identification of the areas at greatest risk in this, and other, regions. The author combines multiple analyses of different variables with GIS (Geographical Information System) cartography to identify 'hot spots', i.e., where fires are most likely to break out. He then uses this information to undertake future territorial planning (Castillo et al., 2013), including the concentration of forest management resources in these spots. Forest management entails a huge cost outlay and so this new methodology can help control the expense (Castillo, 2012).

As discussed, the wildland urban interface – sometimes referred to as the rural-urban interface or the urban-forest interface (terms used in the literature with similar, if not identical, meanings) – constitutes one of the main problems facing forest managers in these critical areas (Castillo et al., 2009; Castillo et al., 2011). Indeed, the characterization of fire risk in these interface areas has become one of the main objectives in the development of forecast systems (not only in Chile, but in many other countries affected by similar problems of dense land occupation). Since its introduction, KITRAL has had to be modified in line with the dynamics of population growth (Castillo et al., 2013).

In a review of the risks associated with wildfires in Chile, Castillo et al. (2015) claim that the development of technologies that can forecast and simulate fire spread has the additional objective of reducing fire-fighting costs, improving the efficiency of fire-fighters, and minimizing resources for the forestry companies when extinguishing wildfires in plantations.

A review of the history of wildfires in Chile combined with the analysis of fire risk using computer models allows areas of population and infrastructure at greatest risk to be identified. This preliminary work is essential for action to be implemented on the ground, as illustrated by Castillo et al. (2012) in the case of Valparaíso and Viña del Mar. (32°S). The authors, in collaboration with CONAF, developed different strategies to manage these critical areas, based above all on the recognition of the problem posed by the accumulation of fuel at the WUI. Pruning, clearing, and building firebreaks are some of the actions that have been implemented to reduce the amount of combustible material, facilitating greatly the firefighting task in areas of highly irregular topography. The wildfire at the WUI in Valparaíso in February 2014 demonstrated the continuing need for these actions as the effects would have been much worse if they had not been implemented. The authors also conclude that the participation of the population at risk is essential in order to minimize the effects of wildfires.

The inhabitants of areas at risk in the Valparaíso region have expressed grave concerns that wildfires may once again threaten their homes. Neighbourhood associations have responded by adopting basic protocols in the face of such emergencies. Yet, people are slow to change their way of living (Fig. 4), despite a growing awareness that their homes are at the WUI (Garfias et al., 2012). Interestingly, the authors report that those with high incomes adopt more management and protection measures against possible fires.

MODIS (Moderate Resolution Imaging Spectroradiometer) is a technique for evaluating the risk that people and infrastructure are at from wildfires. It is suitable for mapping the damage caused by medium and large fires (affecting >200 ha), and can be downloaded for free (Molina et al., 2014). In this respect, Castillo et al. (2009) distinguish between direct and indirect damage, where the former includes all tangible goods with a market price and the latter involves the environmental and social impact suffered by intangible goods. Such studies show that the investing in prevention measures, if well implemented, is a more economical strategy than bearing the losses or instigating post-fire actions.

The risk models developed with GIS also help establish parameters for building the minimum number of wildfire detection towers. Tapia and Castillo (2014), for example, report that they are able to cover at least 75% of the territory in the Metropolitan Region (33°S). Such towers have existed for years, but were often built without taking visibility or fire risk into consideration. However, the high cost of this infrastructure means it is essential to conduct prior studies incorporating all the information acquired from implementing risk models (Tapia and Castillo, 2014).

In 2011 an awareness campaign was launched by CONAF and ONEMI (Ministry of the Interior and Public Health), entitled "*Depende de ti*" (It depends on you). The objective was to generate a preventive culture and consciousness among citizens so as to reduce the number of wildfires, but it remains unclear whether such campaigns are successful, despite being disseminated across the country. Urzúa and Cáceres (2011) conclude that prevention campaigns of this kind incur high costs and their success must be seen in a long-term perspective to determine if they are able to influence perceptions of wildfires among the population.

The majority of studies examining fire risk and fire prevention have been conducted in the Central Region of Valparaíso and Metropolitana (33° and 34°S). History shows that these areas have suffered the most damage in both human and infrastructure terms and that their high population density leaves them especially vulnerable. Indeed, this research leads to the conclusion that wildfires should be classed more as a social than as an environmental problem.

Fig. 4. A neighbourhood in Valparaíso, an example of a wildland urban interface (2011). Photo by Pablo Sarricolea.

Risk models of this type can be implemented in regions with other types of climate and land use after adjusting the variables to local conditions and focusing on areas where fast, on-going agricultural expansion is more likely to increase the occurrence of fire (Di Bella et al. 2006). In a similar vein, studies such as Altamirano et al. (2013) conclude that models need to take a more applied approach and not just consider the typical variables of temperature, precipitation, seasonality, and distance from cities. They argue for the need to incorporate more ecological variables, such as the relationship between the ecological processes in wildfires or states in successional forests in order to provide an adequate basis for protection priorities.

6. Land use planning and management

A growing number of researchers in Chile are of the opinion that, independent of the origin of the fire, damage could be reduced through more appropriate landscape management, based on a scientific understanding of the function of the ecosystems to be managed. It is, therefore, also the responsibility of public policy, the authorities, landowners, and forestry companies to progress in the regulation of productive activities, making them more environmentally and socially sustainable. Appropriate measure include, for example, more stringent controls on agricultural burning, creating more frequent and more numerous firebreaks in forest plantations, restoring urban corridors with walls of less flammable native species, and cleaning watersheds and river edges. In this way, it should be possible to design landscapes that can protect communities from fire, erosion, and drought, reducing the environmental and socio-economic costs generated by wildfires, and most importantly, saving lives (Gómez, 2014).

Independent of the cause of ignition, a better understanding is needed of the factors that favour the spread of fires. Correa (2014), from CONAF, concluded that the factors that led to the fire in Valparaiso in 2014 were: 1. Weaknesses in the instruments of territorial planning, which failed to consider fire as a risk factor; 2. Land occupation without any organizational structure and charge potential (services and infrastructure); 3. Poor quality housing; 4. Special topographical conditions in the Valparaiso interface; and 5. Environmental conditions of extreme dryness in the summer of 2014 (Fig. 4). The authorities, he stresses, need to think in these terms in order to fight wildfires and their consequences effectively. A call has gone out in Chile for the need to train more professional firefighters, but to date fire brigades remain amateur in status.

Chile is by no means an isolated case in considering the risk of wildfire as an element to be incorporated within its broader spatial planning. Along with such countries as the United States and Spain, the controversy as to whether fire should be seen as another element of landscape ecology has been overcome, and, consequently, governments have stopped thinking about forest policies in terms of fire suppression strategies, and rather have gradually come to prioritise the prevention of high intensity fires.

However, risk management policies have yet to be fully developed in any of these countries, despite the fact that the lack of management is considered a risk by those that inhabit their forest and woodland areas (Rodríguez-Carreras et al., 2014). In Chile, wildfire risk management policies (WRMP) have no place in the territorial plans. Even today, in the majority of countries, WRMP are limited to measures of conventional prevention (firewalls, forest cleaning, the location of water points), and are not concerned with creating links between the forestry and agricultural uses, territorial planning and fire risk management (Plana, 2011).

One factor that greatly complicates planning measures that incorporate fire risk is the unlawful use made of the territory. In many countries of the Mediterranean basin, but especially in Spain, France and Greece, this situation has led to the construction of urban settlements for second homes in forest areas. In Chile, as in other countries, the lax nature of regulations in the past saw the building of very low quality constructions with a poor provision of infrastructure in these forest areas. Originally, many of the residents of these houses would have used the forest's resources as an energy source for their homes, but today this practice has been replaced by more modern sources of energy. This means that fuel has been allowed to accumulate at the WUI, creating a highly flammable scenario in locations of high-density human occupation. To complicate matters further, these houses are typically located on slopes, making firefighting particularly difficult (Castillo, 2015).

A further question that needs to be addressed in relation to WRMP is determining who has ultimate responsibility in this transversal area. Which government department is responsible for wildfire risk management? Typically, the departments of territorial planning, the environment and agriculture all have some expertise in risk management, given that the degree of risk is determined by nature, productive actions, forest management, and firefighting and fire prevention methods. Coordination is not always straightforward, but the need for it becomes readily apparent when a catastrophic event occurs (Plana, 2011). In Chile, responsible for firefighting is CONAF, which is a private corporation under the Ministry of Agriculture. In fires in the WUI also the urban firefighters, which are voluntary, help in the extinction and in this case they act under the orders of CONAF.

Wildfires are not the only phenomenon that have to be considered by those responsible for land and risk management. In Chile, and in other countries, risk plans have to be drawn up for inhabited areas at risk from floods, earthquakes, tsunamis, and landslides, among other potential hazards. In the case of a flood or earthquake nobody doubts its natural cause, but in the case of fire, it should be perceived as an unavoidable phenomenon (one that will happen sooner or later, a natural event or human induced, regardless of the temperature regime).

In Chile, as in other countries (including Spain, Portugal and Greece) that face considerable human pressure on their forests, citizens tend not to be very well informed about the services offered by the government in terms of management practices aimed at avoiding the risks of wildfire. According to Rodríguez-Carreras et al. (2014) in a study conducted in a forested area of Spain, this is because the term “management” is not always understood in the same way by all parties. Thus, management can be perceived as a “protectionist policy” or as a way to obtain a “more productive forest”, among others. Owners of woodland areas tend to be suspicious of the former as they often include laws that prohibit certain forest activities that they have been undertaking for years. However, according to the World Bank Cl (2013), Chile is noted for its adaptability and willingness to innovate in terms of expressing an interest in learning about new services offered by the authorities. This is perhaps because, in order to mitigate the fire risk, recent projects include programs whose objectives are to reduce the risk while boosting the productive sector.

In Chile, according to government reports (CONAF, 2015), almost 100% of fires are considered to have an anthropogenic origin. It is, therefore, assumed that by addressing the causes, the problem can be solved: “the problem is the wildfire, we must prevent outbreaks of wildfire”. However, the problem is not so easily eradicated. Yet, increasingly, in common with many other countries, prevention measures are being introduced in Chile. This approach is broad in its perspective and includes environmental education, perception studies, management policies as well as the participation of different actors in interdisciplinary studies.

To protect the country's biodiversity and its ecosystems, Chile currently adheres to the guidelines established by the 2003 National Biodiversity Strategy, implemented by the Ministry of the Environment. As part of this and of its regional strategies, the Ministry has identified over 300 priority areas for conservation throughout the country, including the ecosystems of the Valdivian rainforests of southern Chile and the Mediterranean forests of central Chile, the two areas with the most recurrent wildfires in the country. Currently, this management project is being overseen by CONAF.

7. Conclusions

Since 1985, the number of wildfires in Chile has risen sharply; however, the number of hectares burnt since that year has remained fairly stable.

Chile's wildfires affect the country on various fronts, generating three main types of problem:

1.- **Environmental problems.** Large wildfires are frequent in the south, typified by the recurrent fires of Torres del Paine (1985, 2005, 2012, each destroying approximately 150 km^2). These have given rise to an environmental problem in one of the country's most important and best-known Natural Parks.

2.- **Social problems**. Fires are becoming more frequent in the densely populated areas at the WUI resulting in major social problems, including the loss of human lives, as occurred for example in February 2014 and March 2015 in Valparaíso. Other fires constitute a social/natural problem. This was the case for example of the Sierra Bellavista fire in 1999, when homes were burnt and the Rapel reservoir was affected by sediment accumulation and contaminated runoff water from the slopes. A broader social problem also appears to underpin the fires attributable to the conflicts between the indigenous inhabitants of the country and the new forestry landowners.

3.- **Economic problems.** Forestry companies are affected economically when extensive areas of their pine or eucalyptus plantations are burnt.

Any review of the literature about wildfires in Chile has to confront the controversial question as to whether any fire-dependent ecosystems can be said to exist in the country. Clearly, there are species that have in the course of history developed fire adaptation strategies; however, it has yet to be proved whether species have acquired reproductive strategies in post-fire conditions.

Finally, the actual importance of natural fires (caused primarily by lightning storms) is unclear. According to some experts, they are more common than government statistics indicate. What is clear, however, is that the small number of natural fires are of major ecological importance, being responsible for a disproportionately large burnt area.

Acknowledgments

The first author of this paper would like to thank the University of Barcelona for the permission to collaborate with the University of Chile for three months and also the Department of Geography at the University of Chile for the invitation. Grateful to the project CGL2013-47862-C2-2-R of the Ministerio de Economía y Competitividad of Spain. The second author would like to thank the project FONDECYT 11130629. We thank Daniel Mast and Iain Robinson for the revision of the English language of the paper. We also want to thank the anonymous reviewers their task to improve the final version of the paper.

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