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Short Note

Ecological Impact of Forest Fires and Subsequent Restoration in Chile

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Abstract: This note analyzes the effects forest fires in Chile have on vegetation and subsequent ecological restoration. We analyze why forest fires have been a main factor that affects the environment and causes the ecosystem to deteriorate, leading to loss of native forests, species extinction, damage to the urban population, and others. The data examined are derived from fire hotspots in Chile's central and central-south zones (33°00′ S–41°57′ S) between 1985 and 2017. We also analyze some key aspects for restoration priorities such as studying affected areas and posterior consequences. Finally, we evaluate actions the country has already taken, and propose further appropriate preventive and restoration measures.

Keywords: forest fires; native woods; ecological restoration; forest resources; Chile

1. Introduction

Fire has been one of the principal agents that affect the global ecosystem, damaging recovery cycles and altering the atmosphere [1]. The fire-ecosystem relationship is reflected in the response of ecosystems to natural fire episodes. Some ecosystems, where species have adapted to fire, have become dependent on it for maintaining their structure, composition and functionality. Yet, some of these ecosystems remain highly sensitive to fire generated by humans, whereas others in, for example, extremely dry or wet climates are less affected by such activity (resilience) [2,3].

For decades, ecosystems have also been influenced or dominated by humans, which has often led to the degradation of natural zones. In addition to natural wildfires, human-induced forest fires have been a key cause of ecological damage. Particularly, in mid 19th century Chile fire served to clear lands for farming, so vast swaths of native forests have been burned. These farm lands turned out highly useful for producing beneficial goods and services for humans (global hectares) [4]. In addition, these lands have served to create infrastructure and to spur economic growth. But all these practices also rendered recovery of many soils difficult, inflicting permanent erosion and loss of fertility [5].

While it is true that fire is a key agent that affects any ecosystem, damages cycles and alters the atmospheric composition, it is also true that fire and ecosystems have established relationships. Such relationship is called fire regime. It is reflected in ecosystem's responses to forest fire episodes and is related to intensity, damage, and stationary ignition sources (attributes). Depending on the fire regime, ecosystems are classified as dependent or independent. The former depend on fire to keep their structure, composition and functionality, as species have adapted to fire events. The latter, independent ones are more sensible to human-generated fire (tropical vegetation) and are characterized by extreme, dry or humid climates that prevent burning [3]. Modification of fire regimes (predestined cycles) that occurs with fire episodes damages ecosystems, affecting their structure and composition (loss of ecosystem functionality). Higher intensity and frequency of forest fires can lead to higher damage [6].

Forest fires cause tremendous damage to vulnerable ecosystems' structure and composition, leading to their collapse. Increasing intensity and frequency of fires only compound the damage. Steps for ecological restoration can vary depending on, for example, time and burned surface, environmental adaptations, meteorological conditions, vegetation and available resources. However, in some cases where extensive areas covered by native species were eliminated, restoration proved impossible.

As Camarero and Rozas [6] observe, Chile has some institutions that confront fire events. One of them is the Corporación Nacional Forestal (CONAF, National Forestry Corporation), responsible for the strategic management aimed at fire prevention and control. CONAF is a private and autonomous institution that depends on the Ministry of Agriculture, which handles Chilean forest policy, promotes the development of the sector, fights forest fires and manages national parks and national forestry resources [7]. For each fire, CONAF registers time, magnitude (national level, large or normal size) and surface burned (hectares). CONAF also provides conservatories for vegetal species, erosion control, re-forestation and monitoring of vegetation after forest fires. Other activities include revegetation and ecological restoration. However, these initiatives do not ensure the long-term restoration of integrity, health, and sustainability of affected ecosystems.

In this note, some effects forest fires have on Chilean territory are analyzed. We attempt to explain the main causes of fires that lead to ecosystem deterioration, causing native forest loss, species extinction, damage to urban populations, and others. In addition, we consider aspects to define restoration priorities such as studies of affected areas and their results. We also analyze some measures that are already in place. Finally, we propose appropriate prevention and restoration measures for implementation in Chile.

The area of study is restricted to fire hotspots in the central and central-south zones of Chile (33°00′ S–41°57′ S), from Valparaíso to Los Lagos regions (see Figure 1) between 1985 and 2017. Data come from CONAF, which quantifies and reports affected areas, and fire causes.

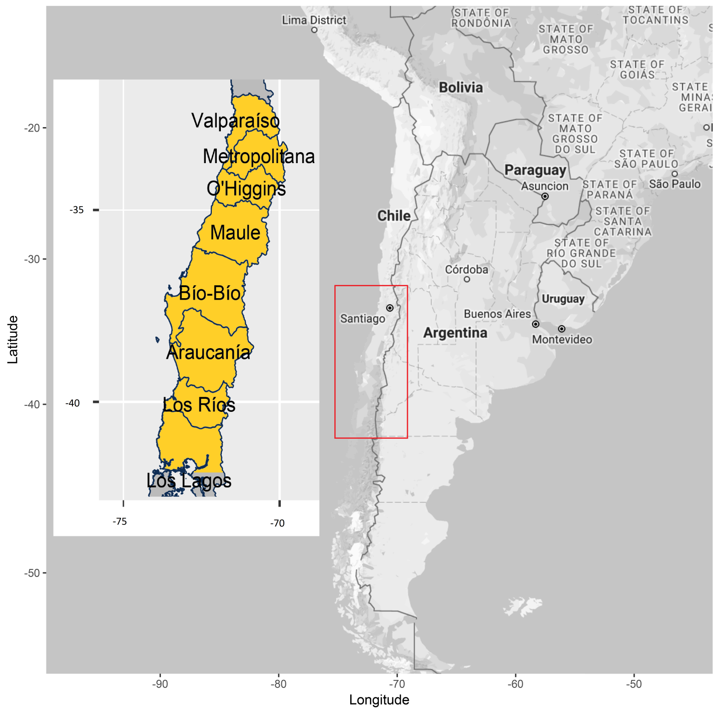

Figure 1. Study area restricted in Chile (33°00′ S–41°57′ S).

2. Forest Fires Factors

Chilean forests cover 17.3 million hectares (22.9%) of the country's surface. Around 18.4% of national forests correspond to native forest (13.6 million hectares), specifically 68% to radiata pine (*Pinus radiata*), 23% to eucalypts (*Eucalyptus*) and 9% to Mediterranean saltbush (*Atriplex halimus*), tamarugo (*Prosopis tamarugo*), Douglas fir (*Pseudotsuga menziesii*) and others [7]. Chilean species such as Chilean pine (*Araucaria araucana*), Chilean wine palm (*Jubaea chilensis*) and patagonian cypress (*Fitzroya cupressoides*) have developed fire resistant barks over time [8].

Fire hotspots in Chile concentrate mainly between Valparaíso (33°00′ S) and Los Lagos (41°57′ S) regions (see Figure 1). Toward the north, vegetation is scarce or inexistent, while toward the south humidity is high and population density low (<0.7 inhabitants per km^2), so millennial native forests are more protected against fires [8]. Nonetheless, according to the national registry 5972 forest fires occur on average per season, damaging more than 55,000 hectares per year, of which more than the 70% correspond to native vegetation [3]. Figure 2 replicates this picture, highlighting the summer season (December to March) and time of day from 3 pm to 6 pm, i.e., during strong solar activity (Figure 3).

An important factor is climate. For instance, during holiday season, high temperatures and zero rainfall facilitate the spread of fire in addition to its domestic misuse [9]. In the central and central-south zones, vegetation is highly susceptible to fires, due to a long, dry summer, high temperatures, strong winds and low relative humidity. Compared to other Mediterranean ecosystems (Mediterranean Europe, California, Australia), Chile's central zone does not suffer fires produced by storms, because they typically arise in summer season [3]. All of these factors are added to human activity [10].

Almost all fires originate from human actions, specifically agricultural activity, increased population, closer urban-rural links and more people in rural territories during holiday season [9]. See Figure 1 for hotspots in Valparaíso, Maule and Bíobío regions and Figure 2 for monthly distribution of forest fires.

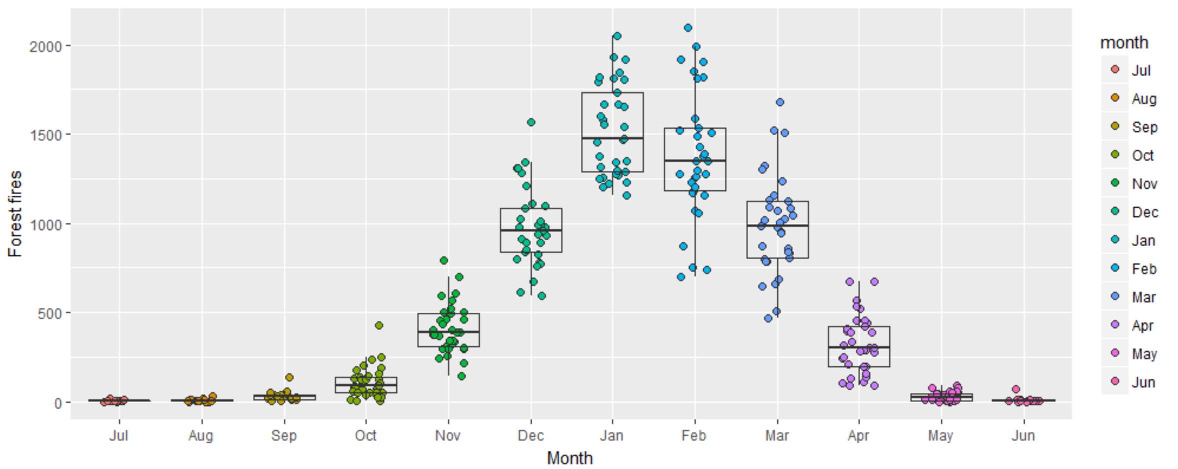

Figure 2. Distribution of monthly forest fires. The distribution corresponds to fire hotspots in the central and central-south zones of Chile (33°00′ S–41°57′ S) between 1985 and 2017.

Urbanization of forest zones complicates the matter further, because territorial ordering policies are lacking that regulate households, hotels, stores, entertainment, roads and transmission lines. This increases the risk of fires started either by negligence or intent. Table 1 indicates the principal causes of fires concentrated between Valparaíso and Los Lagos regions, with accidental and intentional causes being most frequent. Analyzing by region (Table 2), we observe that intentional causes appear most frequently in Bíobío and Araucanía regions, due to arson as a weapon in ethnic conflicts. Inversely, accidental causes are more frequent in the other regions.

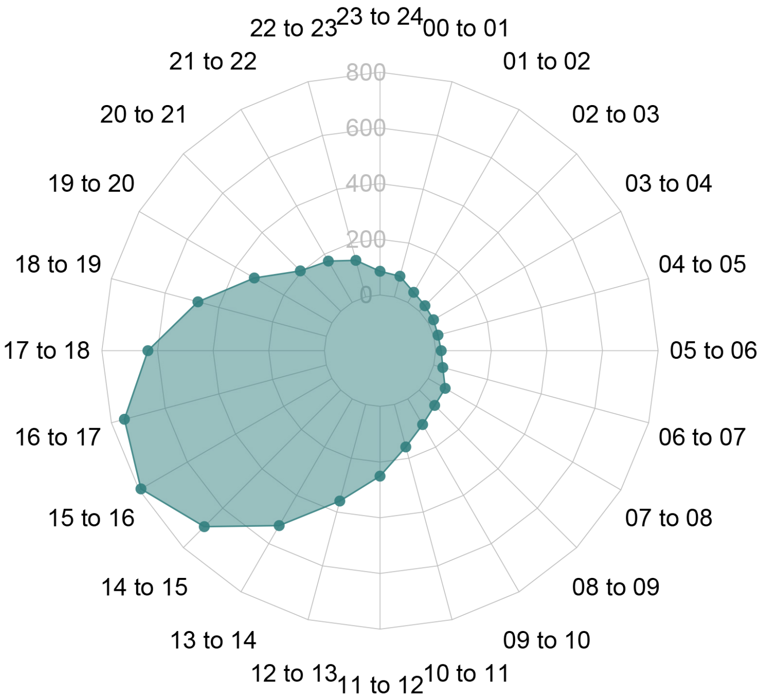

Figure 3. Distribution of occurrence of hourly forest fires. The distribution corresponds to fire hotspots in the central and central-south zones of Chile (33°00′ S–41°57′ S) between 1985 and 2017.

Table 1. Principal causes of fires concentrated between Valparaíso and Los Lagos regions. Data correspond to fire hotspots in the central and central-south zones (33°00′ S–41°57′ S) between 1985 and 2017. Intentional causes include arson, cigarette butts, incendiary attacks as part of ethnic conflict, power-line arcs, sparks from technical equipment, land burned for farming, and building of structures or recreational parks. Unknown causes are either investigated with origins impossible to determine, or are not investigated at all. Natural causes include lightning, sparks from falling rocks, spontaneous combustion or volcanic eruption.

Causes	**%**
1. Accidental	56.55%
1.1. Transit of people, vehicles or aircraft	31.14%
1.2. Recreational activities	7.65%
1.3. Farming and livestock farms	4.13%
1.4. Forest labors	4.05%
1.5. Burning of waste	3.87%
1.6. Electrical accidents	2.02%
1.7. Other activities	1.18%
1.8. Preparation and or extraction of secondary forest products	1.07%
1.9. Activities extinction of forest fires, structural fires or other	1.06%
1.10. Operations on railways	0.39%
2. Intentional	33.35%
3. Unknown	9.80%
4. Natural	0.31%
Total	100.00%

Table 2. Principal causes of fires (in percentage) concentrated by region (Valparaíso to Los Lagos) between 1985 and 2017. See description in Table 1.

Causes	Valparaíso	Metropolitana	O'Higgins	Maule	Bíobío	Araucanía	Los Ríos	Los Lagos
Accidental	75.74	84.13	83.60	83.15	38.02	46.32	77.38	85.33
Intentional	22.53	15.27	12.99	12.31	43.74	48.29	12.56	4.15
Unknown	1.66	0.54	3.25	4.11	17.94	4.80	9.79	10.15
Natural	0.07	0.06	0.15	0.44	0.31	0.59	0.27	0.37
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

3. Consequences of Forest Fires

A benefit of fire in ecosystems is their adaptation to fire for control of species diseases, reduction of weed diversity, release nutrients, and even seed germination. Therefore, fire play an important role for health and diversity of ecosystems. However, altering fire regimes by non-natural factors can have negative effects on the conservation of the ecosystem's diversity.

The effects of fire will depend on certain factors such as magnitude, environmental conditions and forest residues functioning as fuel [11]. Organisms in the ecosystem will be affected and probability of diseases and fungus increases as do bacteria and insect attacks. In addition to erosion and destruction of physical and chemical properties [12], fires also alter the vegetation physiologically, inhibit regeneration and increase risk of illness and plagues [13]. Additional, indirect effects on vegetation include habitat and biodiversity loss, deteriorating air quality, altered ph-values, modified hydrological cycles and vegetal cover loss.

Another consequence of fires is the degradation of soil [14], understood as damage to the soils' capacity to produce goods and services for the ecosystem. This damage begins with vegetation removal, leads to erosion, the excess of salts, pollution, and physical, biological and chemical degradation follows [15]. Furthermore, forest fires release carbon dioxide contained in trees which stays in the atmosphere if vegetation does not recover [1,16].

Yet, studies have found that no correlation between the occurrence of forest fires and burned surface exists (Figure 4). This is good news since a great magnitude of fire does not necessarily damage a lot of surface.

At the beginning of 2017, a series of forest fires in multiple hotspots between the central and southern zones of Chile occurred. Maule and Bíobío regions were most affected. Figure 5 shows the amount of surface burned from 1985 to 2017, including appreciation of seasonal variations. An upward trend in area burned occurs, as 2017 stands out as an extraordinary year (outlier) in the forest fire time series. During the 2017 season, 5178 forest fires occurred, affecting a total of 569,846 (Ha); specifically, 281,274 (Ha) of plantations, 256,336 (Ha) of natural vegetation, and 32,236 (Ha) of other areas. The principal cause of fires are related to unfavorable climate conditions, erosion by water due to intense agriculture, and changes of soil use in the zone [15]. Based on this problematic trend, the importance of recovering damaged soils has increased according to multiple international organizations [17]. As habitat loss rates have gone up as a significant amount of species have become extinct [18], recovery of degraded soils has become critical for biological conservation [19].

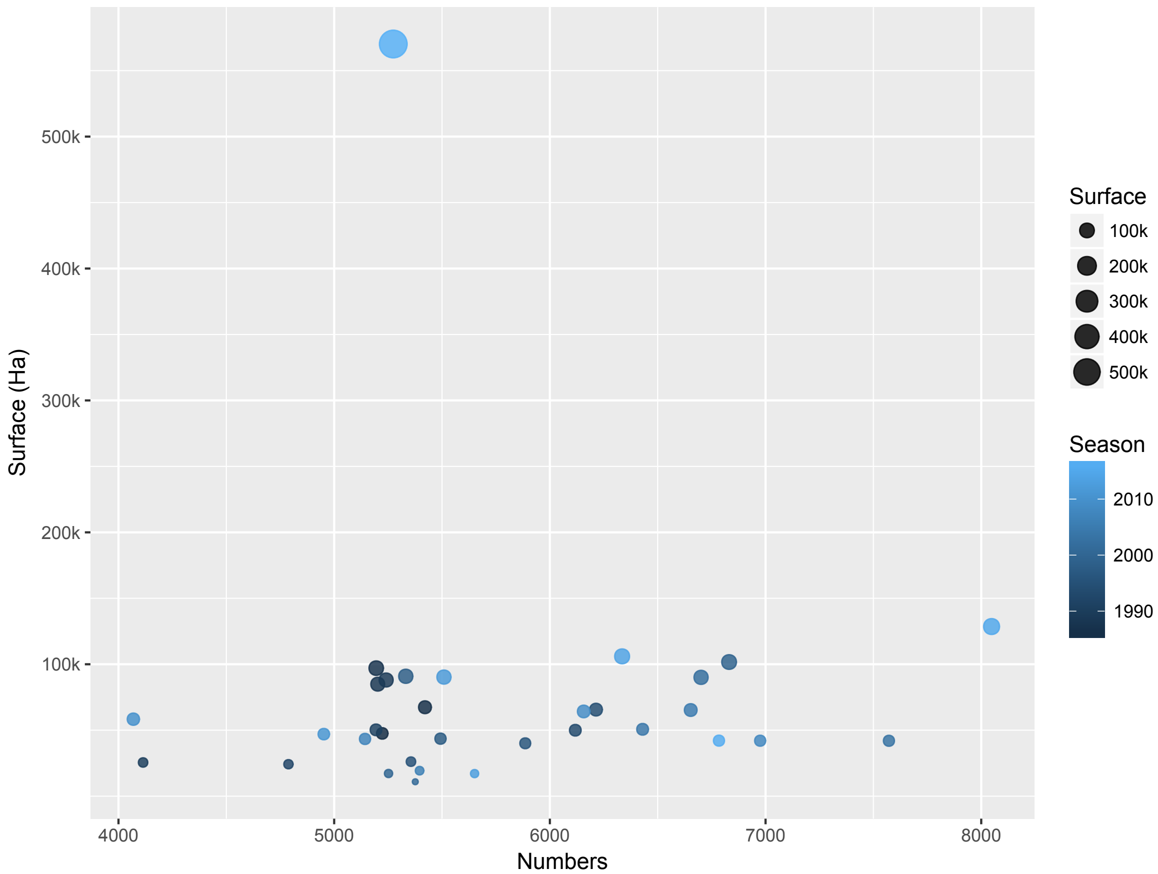

Figure 4. Number of forest fires by surface burned in hectares (Ha). Data corresponds to fire hotspots in the central and central-south zones of Chile (33°00′ S–41°57′ S) between 1985 and 2017.

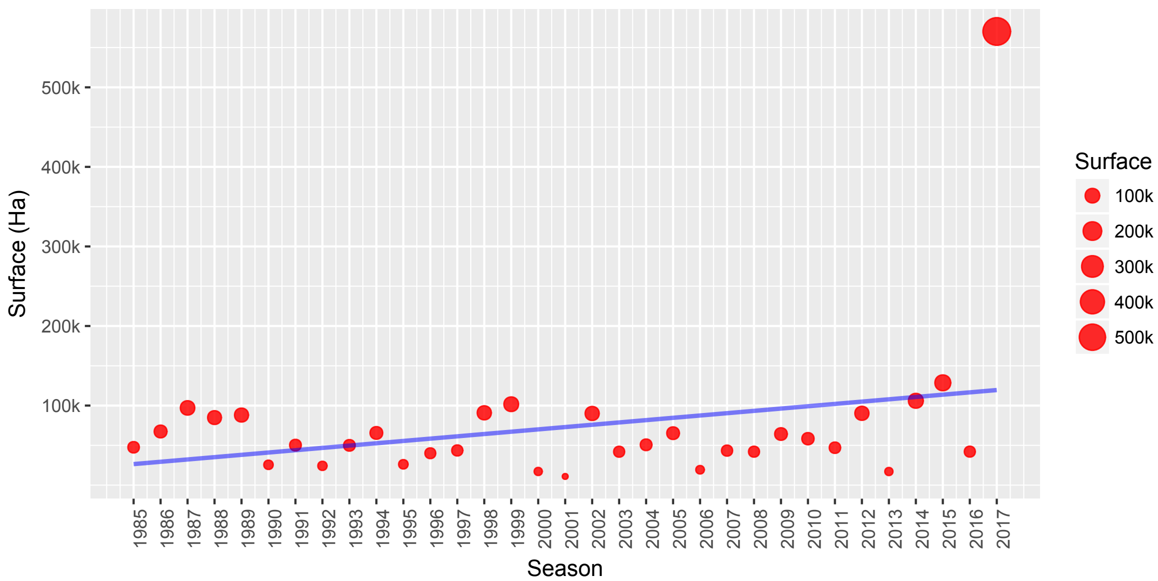

Figure 5. Surface burned by forests fires in hectares (Ha) per year. Data corresponds to fire hotspots in the central and central-south zones of Chile (33°00′ S–41°57′ S) between 1985 and 2017. The blue line corresponds to trend of surface burned between 1985 and 2017.

4. Restoration Strategies

4.1. Environmental Policies

Early in 2017 the government began to boost spending on forest fire control, in relation to affected areas and time variables. These costs increase with control efforts, thus decreasing benefits. But this mechanism can be controlled by using efficient operational resources.

In Chile, the Comisión Nacional del Medio Ambiente (CONAMA, National Commission for the Environment) [20] is the national institution that implements norms to decrease impacts of economic development on environmental and human health. However, environmental policies have remained ineffective, because their implementation requires economic resources, scientific and technical personnel and political will. Indeed, ecological restoration has been ignored.

Environmental policies can be explicit or implicit. Explicit ones are documented, officially accepted by a state organism and focus on environmental protection. Implicit policies relate to decisions in productive zones that influence environmental alteration [3]. Overall, these policies highlight issues such as the inclusion of specific goals for development and implementation of ecological restoration in Chile. Therefore, it is necessary to count with an institutional framework that supports ecological development [21], including research, training and formation of personnel, and infrastructure and resources for implementation.

4.2. Ecological Restoration

To counter negative effects after a fire, the first aspect to be considered is the immediate rehabilitation of the affected area. Among appropriate strategies count sowing, fertilization and application of hydro-seeding, which allows rapid germination.

The next step is restoration to recuperate the functionality and structure of the ecosystem. Restoration begins with a tour of the altered local ecosystem and then moves on to the expected state of recovery. It involves canceling or modifying an alteration to confront negative ecological processes [22]. Several strategies to that end include mechanisms against species invasion (including plant species), seed banks to regenerate communities, and others [23].

The stabilization of a recovered zone includes constant visits to check if water availability leads to mortality in species. Indeed, it is necessary to resort to herbivory (plant's predators) control, regulation of invasive plant species and monitoring performance.

The respective process is divided into three stages:

1. **Planning.** Restoration processes are conceived and vary depending on length and duration of conditions, opportunities and current limitations [24]. This should involve the shared structure, species and the establishment of ecological processes to recover soils and species [3]. This stage begins by defining existing problems to then establish benchmarks with the help of scientists and technicians from the natural or social sciences, politics or technology.
2. **Implementation.** Once the causes of a disaster are analyzed, detection of biotic and abiotic factors for the integration of new communities begins. This involves conducting studies on soil, topography, hydrology, nearby plant communities, potential disturbances, and climate and microclimate [25]. After species determination, analysis of the most suitable restoration mechanisms should follow. The introduction of species in the form of seed is the most common due to being economical and easy to distribute. However, seeds also tend to be depleted and require certain conditions for germination [8]. On the other hand, although the use of seedlings is more expensive, they also recuperate more quickly. Ideally, both strategies could be implemented. Sources of information include ecological descriptions, site maps, list of species, historical and current photographs, biological studies and paleoecology [26].

   For the case of fire-independent ecosystems (resilience), where under natural conditions fires occur with low frequency, fires become a problem to the degree they alter the ecosystem. Such alterations may relate to changing land use, climate change or invasion of alien species, which forms the foundation of this study.

3. **Monitoring.** This stage commences after performance evaluations and monthly inspections. These assessments can be evaluated along three strategies: trajectory analysis, analysis of attributes, and direct comparison. Trajectory analysis is used to interpret and compare data, and chart regularly collected data of the site to establish trends and determine whether restoration is on track [27]. According to analysis of attributes, achievements should be judged based on quantitative data from a scheduled monitoring. Finally, in direct comparison reference parameters according to restoration sites are determined.

Another important factor is the ability to regenerate the vegetation cover of the terrain. Vegetation is already affected by the development of buds, living in deeper soil not affected by fire, which serve as protection for the vegetation cover [13]. There are also other mechanisms such as germinating and reproducing seeds that have survived the fire, often found in shrubs or trees. Others include the stimulation of flowering [28], ecological indicators of whether a forest is harvested faster than it is growing [4], or determining levels of atmospheric carbon dioxide which influences timber growth [1,29]. All of these measures can be applied to various species.

As the intensity and frequency of fires grows, the need to recover soils becomes more urgent [23]. To reverse the impacts of fire, ecological restoration should be considered, i.e., fostering ecological processes that accelerate the recovery of the ecosystem to achieve sustainability [30].

5. Conclusions

This work emerged as a result of the problem of forest fires in Chile, as the country's climate and vegetation render it prone to such disasters. Taken together, weather conditions, fuel (load and vegetation characteristics), topography and human activities are key factors. Altering the natural fire regime (pre-established cycles) in an irresponsible way, has consequences on regional and global scales, as a damaged environment has repercussions for the human population. This way, bad effects of fire integrate into a circle that contains several cause-effect phenomena. Clearly, this is a complex problem since subsequent destruction of forests impacts soils for agricultural production, causes erosion, contamination and alteration of the cycle of water production.

Furthermore, fighting fires has great financial impact, demanding major resources for disaster prevention and control. As these disasters strike more frequently and more intense, they are harder to fight. This should be addressed from a national as well as a global perspective, including defense and protection policies. Furthermore, fire disasters have acquired a social dimension, as they occur inevitably ever closer to human presence.

Finally, fires affect mostly soils and vegetation that constitute the livelihood of many Chilean families. Therefore, fire management must be ecologically and socially tractable. Also, prevention, training and research as preventive measures become important for recovering the valuable vegetation heritage Chile offers. Implementation of forecasting methods [31,32], combined with different tools for trend breaks in time series [33], requires further work. Moreover, to gain better understanding of the spatio-temporal dynamics [34] of forest fires in the area considered here, spatial analysis is necessary over the long term.

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