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Forest Wildfires in Chile: Effects on Soil Degradation and Damage Mitigation

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Forest Wildfires in Chile: Effects on Soil Degradation and Damage Mitigation

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Abstract: The 2022-2023 Chilean summer showed increased temperatures and similar burned area, compared to the 2016-2017 season, where more than 500,000 hectares were compromised, mainly in the rural areas. After a brief review, it is revealed that the effects of forest fires on soil and hydrological properties are barely debated in Chile. Here, we showed a climatological analysis where temperature records in the 2016-2017 season were unusual, as well as another unexpected increase in the summer of 2022-2023, resulting in high-severity fires known as 'mega-fires' or "storm-fires". Mega-fires affect forest plantations and native forests mainly from 33º S (Maule Region) to 39º S (Los Ríos Region) and they are expected to become frequent due to climate change, moving from the north to the south. We present an overview of the influence of wildfires on soil components in the most affected areas (inland, Coastal and Andes ranges), their hydrological impacts, and potential erosion risk due to high winter precipitation. We propose several management practices that could help to prevent or mitigate these events, including pre-and post-fire interventions, such as afforestation and seeding, selective logging, mulching, erosion barriers, soil preparation, and dam monitoring. We argue that any effective plan in fire-prone and affected areas should include a combination of actions taken at the hillslope scale at integral ecosystem management, whose effectiveness should be monitored and verified regionally at the watershed scale.

Keywords: soil erosion; fire severity; ecosystem recovery; flooding risk; Chilean mega-fires

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1. Introduction

The total affected area in Chile due to wildfires during the 2022-2023 season exceeds 433.960 hectares [1], very close to 547,174 hectares burned in 2017 [2]. Fires have historically played an important role in the composition and distribution of terrestrial ecosystems [3,4]. However, these events have also represented an important pressure that has induced land degradation worldwide, and Chile is not an exception [5]. The impact of forest fires depends mainly on their severity, affecting individual flora, fauna, and other components of nature, air, soil, and water, but also affecting the relationship among these constituents compromising the functionality of the whole ecosystem [6,7] (Figure 1).

Figure 1. Successful sampling of forest soils and forest plantations after extreme fires in the Araucanía foothills (Anillo Project, https://proyectofiring.cl).

Wildfires can be classified as low, medium, and high-severity fires [8]. Fire severity depends on various environmental factors, such as weather patterns (temperature, humidity, and wind, [9], topography, fire history recurrence, accumulated biomass or fuel, type of vegetation and proximity to populated areas [10]. Here, we present a brief overview of the influence of wildfires on soil components, their impact in local hydrology, and the erosion risk induced by moderate and high-severity wildfires.

2. Surface damaged by wildfire

In Chile, various severe fires have been registered from 1985 to 2022. On average more than 124,600 hectares were affected, and from this total 39% have been forest plantation (*Pinus* spp and *Eucalyptus* spp), and 52% natural vegetation (grasses, native forest, and their understory brushes, shrubs) (Table 1).

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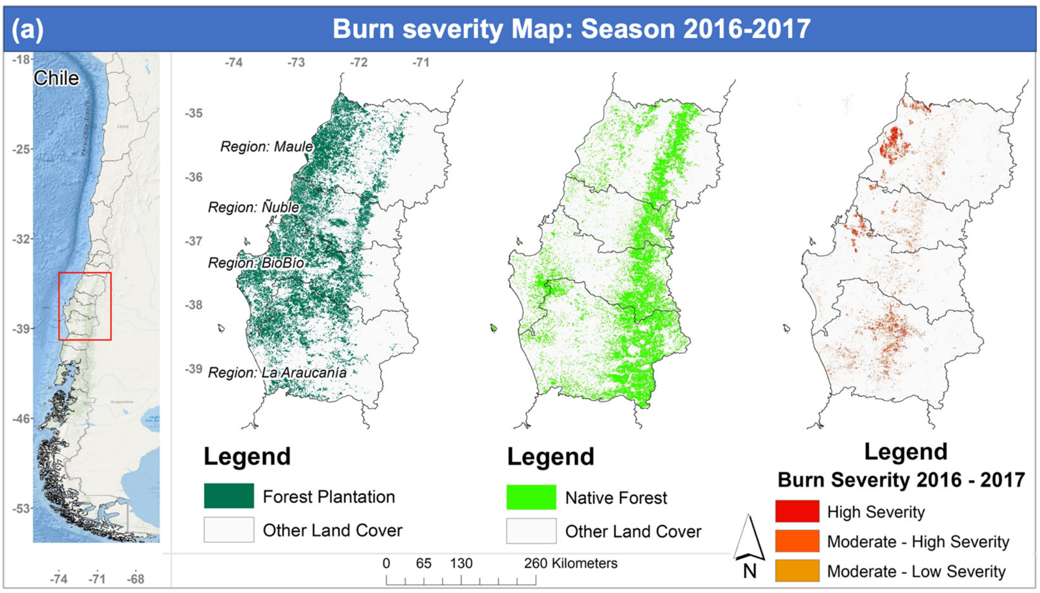
Table 1. Surface average of land use affected by wildfire between 1985 and 2022 (CONAF [1]).

Land use	Surface (ha)	Percentage of total (%)
Forest plantation		
Pinus spp.	34,518.07	27.68
Eucalyptus spp.	12,876.37	10.33
Other spp.	774.85	0.62
Subtotal	48,169.29	38.63
Natural vegetation		
Forest	20,300.08	16.28
Understory and shrubs	28,086.81	22.53
Grasses	16,910.84	13.56
Subtotal	65,297.73	52.37
Agriculture, Forest debris	11,218.28	9.00
Total	124,685.30	100.00

3. Climate and high severity wildfires

Massive wildfires have occurred between December and February of 2016-2017 and for years later in 2022-2023 seasons; the so-called `mega-fires' or 'storm-fires' mainly in bioclimatic Mediterranean and Temperate Regions in the Coastal range where the exotic plantation dominate the landscape, compared to endemic forests remaining in the Andes range (Figure 2). Mega-fires temporarily matched the maximum recorded air temperatures in central-south Chile, corresponding to Mediterranean and Temperate Regions (Figure 2).



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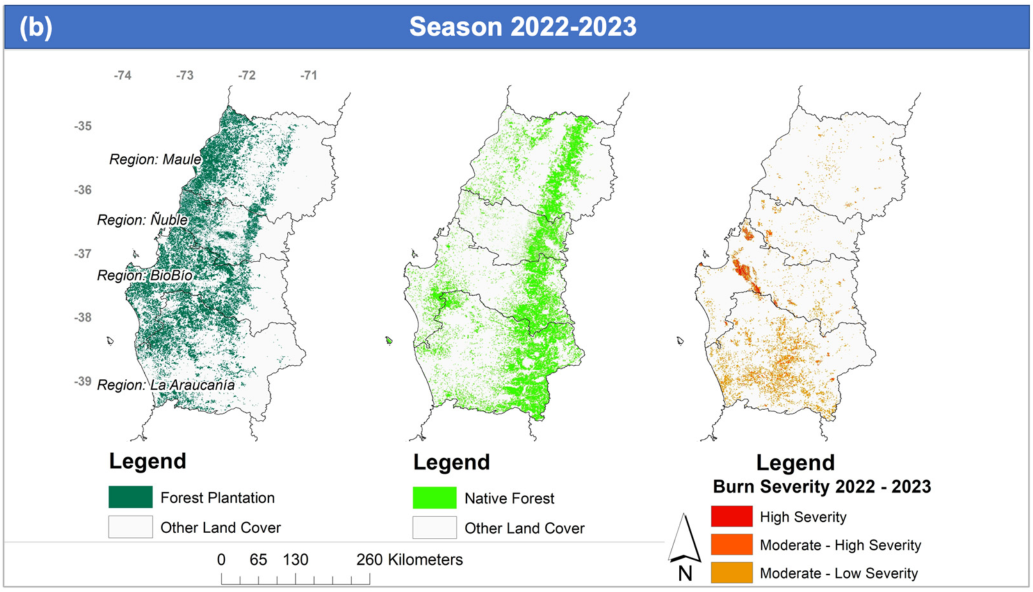

Figure 2. Burn severity maps from the main bioclimatic zones: Southern Mediterranean and Cold Temperate plantations, and native forests affected by wildfires from (a) summer season December 2016 to February 2017 and (b) December 2022 to February 2023. Map built using Sentinel images, not yet validated by the National Forestry Corporation (CONAF [1]).

In general, from the Central Mediterranean bioclimatic zone (33º S) to the Southern Temperate Transition zone (39º S), the maximum temperatures have been increasing during the last 23 years (Ñuble, BiBio and La Araucanía) Regions of Chile, including the Coastal south of Valdivia (Table 2). Non-parametric slope obtained by Mann-Kendall regression shows that the increase of maximum temperatures from 1977 to 2023 overall were highly significant. In the last season 2022-2023, the maximum and minimum temperatures sharply increased, so the differences between these extremes were smaller compared with the average of previous seasons (Figure 3).

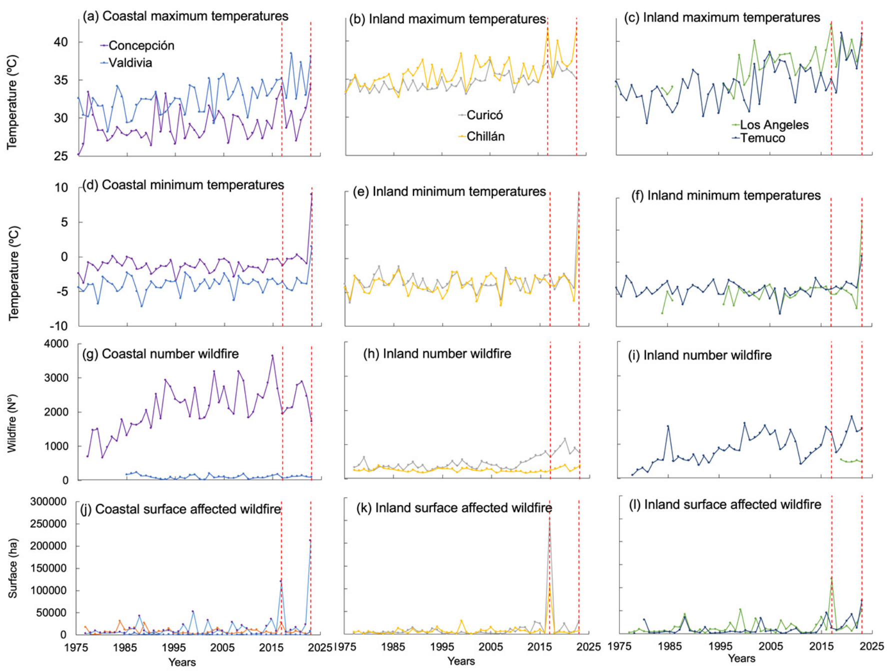

Figure 3. Maximum and minimum temperatures, number of wildfire and affected area (hectares) in the coastal (a, d, g, j) and inland (b-c, e-f, h-i, k-l) regions ([1,11] DMC). Dashed red lines indicate mega-fires in 2017 and 2023.

Table 2. Bidecadal records of annual maximum air temperature of non-parametric regression slope Mann-Kendall 1946)[1] [12] and (DMC [11]).

Region	City	Latitude (S)	Longitude (S)	Mann-Kendall slope 1977-1999	2000-2023	1977-2023	*p*-value 1977-1999	2000-2023	1977-2023
				----------------(ºC year^{-1})----------------					
Coastal									
Valparaíso	Valparaíso	33º03′55″	71º33′23″	-0.02±0.14	**0.13±0.09**	**0.04±0.04**	0.871	0.024	0.037
BibBio	Concepción	36º46′42″	73º03′45″	0.04±0.09	0.08±0.13	**0.06±0.04**	0.454	0.253	0.016
Los Ríos	Valdivia	39º39′02″	73º04′51″	0.11±0.16	0.16±0.16	**0.10±0.05**	0.111	0.091	0.000
Inland									
Maule	Curicó	34º57′59″	71º13′00″	0.045±0.05	0.07±0.07	**0.06±0.02**	0.097	0.059	0.000
Nuble	Chillán	36º35′14″	72º02′24″	**0.13±0.10**	0.10±0.13	**0.07±0.04**	0.044	0.106	0.001
BioBio	Los Angeles	37º18′55″	72º25′39″	0.13±0.83	**0.14±0.11**	**0.10±0.05**	0.764	0.020	0.000
La Araucanía	Temuco	38º50′16″	72º04′40″	0.10±0.16	0.13±0.19	**0.12±0.06**	0.112	0.180	0.000
Average				0.07±0.20	0.11±0.12	**0.07±0.04**	0.406	0.094	0.007

[1]Non-parametric test suggested by the World Meteorological Organization to estimate climatological time series trends ([12,13] slope based on Kendall's Tau coefficient (τ) and Pettitt test [14,15]. The statistical analysis was performed with the R program (R package version 4.2.3. at https://cran.r-project. org/package-trend [16,17] (Last accessed March, 2023) In bold, significative values.

Storm-fires desolated landscapes with vast strips of decimated forest crossing from the central valleys to the coastal Region with almost no vegetation cover (37º-38º S). The lack of vegetation can potentially intensify multiple soil degradation processes (i.e., increased erosion, organic matter depletion, loss of biodiversity), which could exacerbate alterations caused by other global change drivers. Studies combining warming, wildfire severity, and land degradation processes are lacking in Chile, yet substantial warming has been observed in the region. For example, for the Maule River watershed (34º S), a 0.6 °C temperature increases has been reported for the last 14 years, which is well above the world average [5]. This condition matches the regional trends of increased maximum temperature slope for Maule Region and other locations (Table 2). Moreover, a large part of the soils of the most affected area by wildfires have been historically affected by erosion and land degradation processes. In fact, in the Maule Region, more than 51% of the land is eroded [5]. Further south, in BioBio Region (Coastal Cordillera, 37 ºS), severe wildfire has induced heavy soil losses and sediment mobility in forested hillslope ([18]. In this study the highest potential soil loss was recorded for a 1-year-old plantation (*Pinus radiata* D Don), reaching 88.9±9.3 Mg per hectare, while in natural forest (*Nothofagus* spp.), the soil loss was 21.4±3.1 Mg per hectare . Earlier studies in similar granitic soils found that soil losses during the first year of fire occurrence were significantly greater in burned soils (2.13 Mg per hectare) than in undisturbed native forest soil (48 kg per hectare) soils [19].

4. Impact of wildfires on soil properties, erosion, and hydrological stability

The effect of wildfires on soil properties are well recognized, and they strictly depend on the intensity (heating release) and severity of fires (Figure 1). Negative effects of severe wildfires not only include the vegetation cover and soil losses but also comprise an increase in hydrophobicity, due to the alteration of fatty acid compounds following fires, deterioration of soil structure and porosity, along with soil organic matter (SOM) losses ([20–22]. All these conditions affect water infiltration, retention, and sediment transport in affected soils.

In Chile, despite the recurrence of extreme wildfires (e.g., Mataix-Solera *et al*. [22], Úbeda and Sarricolea [10]), there is still very limited research focused on the impact of land burning on soil properties and biodiversity ([8,22–28]. Direct effects of fires shift soil microorganism's community structure (see below), reducing vegetation cover and altering soil's chemical and physical properties [20]. Undirect effects of fires, such as ashes left behind following fires are considered a critical indicator of the magnitude of the changes in the soil properties and their hydrological effect on vegetation recovery. Although beneficial for soil nutrients (non-volatile), they can be detrimental due to soil pores sealing, enhancing surface water flow, and forming crusts that reduce infiltration and increase the

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risk of flooding or erosion. Therefore, the impacts on soil hydrology after severe fires can be extremely negative [7](Figure 4).

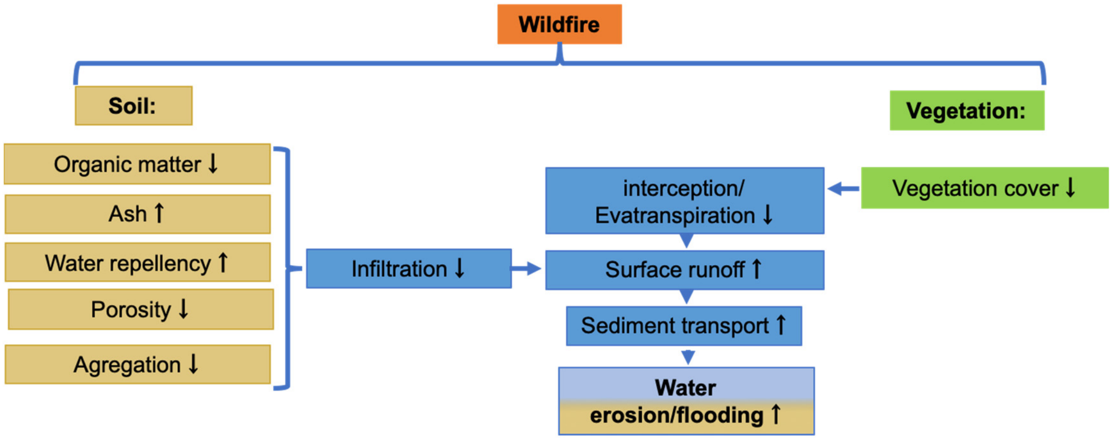

Figure 4. Effect of forest fires on water erosion due to the lack of protection of the soil due to the loss of vegetation. The factors that determine the erosion and degradation of the soil and the physical, chemical and biological changes post-fire are shown. The arrows next to each factor indicate a decrease (↓) or an increase (↑) in the intensity of the factor (Modified from Zema [7]).

The loss of vegetation (trees, shrubs, and herbaceous species) following fires alters SOM equilibrium, not only due to combustion, but also due to a temporal reduction in biomass inputs (i.e., leaf and root litter and roots exudates) [29,30]. Direct loss of SOM due to burning and decomposition are expected to be greater than the amount of biomass incorporated into the soil during the first years following soil burning [8]. Therefore, the SOM dynamics under these conditions are altered, resulting in an ecosystem impoverished in water retention capacity, nutrient availability, and soil carbon sequestration. Thus, a fast recovery of vegetation litter and exudates is the cornerstone for rebuilding SOM stocks in burned sites.

In addition to fire effects on soil physical and chemical properties, the greater sensitivity of soil biological properties to disturbances (compared to soil physico-chemical properties) is also well-established [21]. The effect of fires on soil biotic conditions are intrinsically related to the intensity and duration of these events, and in some cases, can last even for decades due to crown fires (root fire occurring underground) ([31]. Fires can directly affect soil biotic conditions by reducing the number of species, changing the abundances of key functional groups or altering the proportion between fungi and bacteria (e.g., Ferrenberg *et al*. [32], Hart *et al*. [33] Larchevêque *et al*. [34]). These changes can affect plant nutrition and carbon sequestration in the short and medium term [24]. In Mediterranean forest ecosystem of central Chile, even low-severity fires have altered soil microbial diversity and carbon storage capacity [23,35]. The effect of fire in soil communities has been reported. Legacy of land burning was still shaping soil microbial activity (i.e., microbial respiration) eight months after the fire, which was also reflected in lower carbon contents in burned soils [35]. Moreover, land burning still clearly shape soil prokaryotic community structure during the first three years after fire occurrence [23].

5. Restoration and prevention strategies

Vegetation and soil recovery of burned ecosystems to previous conditions can be achieved after a period that varies from a few months to several years ([37]. This is due to the changes induced by high-severity wildfires, such as soil biology, hydrology, and physical-chemical properties of the soil that affect forest ecosystem services [38]. This includes the availability of nutrients, water resources and the quality of water bodies, erosion control, floods and the maintenance of biodiversity [7]. The magnitude of these changes varies according to environmental conditions and human actions before and after the fire. Vegetation loss following high-severity fires not only affects soil properties, but

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also increases the risk of soil erosion, which in turn affects watershed hydrological features. Such high-severity fires have been reported to render the greatest erosion rates [18,19], resulting in high sediment loads downstream. Accordingly, fires can produce geomorphological changes (landscape changes) due to the transport of these materials and the rapid damming of rivers that can extend beyond the affected area. For example, in Chile, increases in the risk of flooding and the contamination of water bodies due to sediments have been registered in extensive surface areas, affecting surfaces well beyond the burned lands [5]. Negatives effects are devastating and can lead to the loss of the productivity of an ecosystem, that is, its ability to produce or regenerate the original biomass [39]. Moreover, in high-severity fires, such as those occurring in Chile during the 2011-20212 in Tolhauaca National Park (Andes Cordillera 38º S) and 2016-2017 and 2022-2023 (Coastal range, 33º-39º S), the charred wood which is not completely burned ([8,28] is very susceptible to new fires, especially when crown fires still active.

On the other hand, low-severity fires may have a minor incidence in flat soils, particularly in areas where landscape conditions and rapid growth of vegetation limit erosion. In such circumstances, soil heating is reduced, and the impact on the vegetation is minimal; therefore, surface flow and soil erosion are small compared to high-severity forest wildfires that can reach temperatures between 600 and 800 ºC and are usually short-lived and limited to the upper layer (a few centimeters from the surface) [7].

5.1. Control measures

Prevention activities strategies, and landscape management and ordering landscape policies are priority tasks to prevent and reduce the damage in socioeconomic and environmental losses derived from fire events [40,41]. The restoration of the ecosystems after a fire must be comprehensive, that is, the recovery of ecological functions and the management of fuel biomass to mitigate future risks of forest fires. The need to mitigate the effects of fire on ecosystems in general and on the soil has increased the use of post-fire treatments, which have been widely experienced in the United States, Australia, and Europe. The management practices before and after fire not only prevent fire reoccurrence but also mitigate and reduce the risk of floods caused by increased overland flow and the erosion of sediments coming from high-severity burned soils, a topic that is also rarely debated in Chile.

Severe wildfire effects may impair fast land coverage increasing risks of soil loss. In such situations, soil treatments can be practiced both on slopes and in riverbeds, for example, through reforestation, planting crops, selective logging commercial wood from moderates fires, distribution of forest debris to generate erosion barriers, soil covers (i.e., mulching or hydro-mulching), protection of human settlements with catchment ditches and soil preparation for the rapid restoration of native species for vegetation cover. After the mega-fires in 2022-2023, Conaf [42] allowed removing dead biomass from plantations under a regulation called ´Management standard for felling and reforestation of plantations affected by forest fires and multipurpose reforestation`, including a technical prescription for harvesting, thinning, and reforestation. The regulation also includes protection of soil, water, flora, and fauna for native forest and plantation managements. These measures are considered late but appropriate as they reduce the incidence of new fires, but we believe that these measures should be mandatory in areas affected by high severity fires, also preventing deliberate fire attacks. Other measurements, such as extraction of damaged trees and rapid removal of fine residual biomass must be carried out in the first two years after a fire to recover the understory and reduce the risk of fire in the same place. In general terms, selecting burned wood for harvest after a moderate fire in plantations could impact the soil since it is conducted with heavy machinery. The impact of this practices could be minimized by concentrating traffic during summer months and using lighter logging equipment to avoid soil compaction. In addition, it is necessary reduces the surface flow and sediment production by reducing runoff and increasing infiltration with the construction of wattles, check dams or infiltration ditches. All this, to reduce soil erosion and the risk downstream flooding in micro-basins with pronounced slope [43].

The literature has long discussed the benefit of salvage logging wildly practiced in burned natural areas and forest plantations. It is now clear that salvage logging can inhibit natural regeneration,

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help spread invasive species, distribute sediments into streams, alter plant species composition, and damage a suite of fire-associated animal species [44–47]. These effects may be even stronger than conventional logging because, after a major disturbance, forest stands and soils are particularly vulnerable to cumulative effects [44]. The removal of 'biological legacies', including above-ground and below-ground decomposing biomass, ash, standing snags, and other natural structures that create special microhabitats, can have very long-lasting impacts (hundreds of years). Postfire logging reduces regeneration due to soil disturbance and physical burial of seeds by woody material during logging operations. Thus, postfire logging could result in no net gain in the early establishment [44]. In addition, postfire salvage logging significantly increases both fine and coarse unmerchantable material (e.g., branches), which is notably incongruent with fuel reduction goals [44].

5.2. Monitoring

Follow-up and monitoring programs for the prevention of forest fires, considering the impact of soil type vulnerability by wildfire severity and subsequent recovery of ecosystems, is essential. The Chilean soils of the Coastal range in the central-southern zone derive from granitic and metamorphic rocks with high clay and relatively low organic matter contents. Many of these soils are highly eroded, and are prone to hydrophobicity [48], with limited infiltration capacity. Contrastingly most soils of the Piedmont and hillside of the Andes come from recent volcanic ash, and they have lower degrees of soil erosion with higher infiltration capacity and higher organic matter contents. Yet, Andisol have the highest resistance to wetting, which tend to increase by heating at low temperatures [49]. It is important to note that the soil properties and typical responses depicted above are only general, and are expected to vary broadly across these mountainous landscapes. Unfortunately, detailed soil information in mountainous regions in Chile is lacking, which makes difficult to predict how these soils may behave. In our opinion, there is an urgent need of mapping soil resources in these areas with a special focus on delivering soil indexes of fire degradation susceptibility. Monitoring the recovery of soil indicators is essential for an adequate assessment of ecosystem recovery after restauration practices have been implemented [27,50]. Any future government regulation considering mechanisms or subsidies for reforestation of burned forests, should include mandatory monitoring plans of soil and ecosystem recovery. Moreover, it is also important to create detailed maps of fire severity in areas where native forests and plantations are concentrated, and specially in catchments surrounding urban and rural centers to support decision-making and prioritize the mitigation and adaptation to forest fires.

6. Conclusions

Progress must be made in the coordination of actions to assess, prevent and more holistically mitigate the effect of forest fires in natural and managed ecosystem. Soils are a critical component of ecosystems that perform a multitude of functions that are generally overlooked by land managers and planners. We emphasized the need to improve soil conservation plans in fire affected areas, a non-renewable resource, since it takes thousands of years to develop. We celebrate the recently introduced regulations for managing harvest of plantations and reforestation in areas affected by wildfires, which is a relevant progress. Yet, Chile requires more comprehensive regulations that could deal with the multiple aspects and complex socioenvironmental consequences of wildfires and help build more fire resilient socioecosystems. Future regulations should consider mechanisms for continuous management practices and long-term monitoring of ecosystem recovery indicator to ensure the functional recovery of soils, flora and fauna in burned forests. Detailed soil information in forestlands is critical to better assess the impact and susceptibility of soils to degradation after wildfires. We believe that territorial planning of heterogeneous landscapes should be carried at the catchment scale to assess fire risk and better design mitigation and adaptation plans under an scenario of increasing extreme climatic events like droughts and heat waves due to climate change.

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and interpretation, AS discussion and interpretation, FN discussion and interpretation, JD discussion and interpretation, LMS Climatic data regressions.

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