Tamm review: Does salvage logging mitigate subsequent forest disturbances?

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Abstract

After natural forest disturbances such as wildfires, windstorms and insect outbreaks, salvage logging is commonly applied to reduce economic losses and mitigate subsequent disturbance risk. However, this practice is controversial due to its potential ecological impacts, and its capacity to mitigate or increase the risk of subsequent disturbances remains unclear. Salvage logging removes and alters the legacies remaining after natural disturbances, and it produces additional management legacies. Consequently, salvage logging has the potential to alter the functional connection between natural disturbances and also produce new functional connections to additional disturbances. We reviewed the efficacy of salvage logging in mitigating the risk of subsequent wildfire, insect outbreaks, hydrologic disturbances, mass movements, windthrow, browsing, and microclimatic stress. We asked: (1) *Does salvage logging modify resistance to subsequent disturbances?* (2) *Through what mechanisms do such effects operate?* Based on 96 publications, salvage logging can reduce total ecosystem fuels but increase small ground fuels and produce drier fuels in the short term, reduce bark beetle host trees and beetle-tree connectivity (though with little evidence for outbreak mitigation), magnify erosion and flood impacts of disturbance but with uncertain watershed-scale implications, increase susceptibility to windthrow at artificially created stand edges, remove the protective function of deadwood in preventing rockfall and avalanches, alter browsing pressure by modifying forage availability and hiding cover for herbivores and predators, and increase microclimatic stress due to greater radiation and temperature fluctuations. We propose a decision-making framework to evaluate the suitability of salvage logging to manage subsequent disturbances. It contemplates the likelihood and impacts of both salvage logging and the subsequent disturbances. In summary, salvage logging does not necessarily prevent subsequent disturbances, and sometimes it may increase disturbance likelihood and magnitude. Forecasting the suitability of salvage logging for management goals requires assessing the mechanisms through which salvage logging effects operate under local conditions, balanced with its impacts as a disturbance itself. Managing to foster the highest-priority functions and services –such as biodiversity conservation, pest mitigation or economic return– across different parts of disturbed forest landscapes based on decision-making procedures such as the one proposed may constitute the best response to uncertain subsequent disturbances.

Keywords: beetle outbreak, compound disturbance, disturbance interaction, fire prevention, linked disturbance, pest control, post-disturbance management, salvage harvest, sanitation logging

1. Introduction

Wildfires, insect outbreaks, windthrows, and other disturbances occur under natural conditions in the world's forests (White and Pickett, 1985). However, climate change, disturbance suppression, and changes in land use and management are modifying the characteristics of natural disturbances, often making them more frequent (Seidl et al., 2017). Further, disturbance events can trigger or buffer other disturbances, modifying their effects through complex disturbance interactions (Buma, 2015; Foster et al., 2016). Such interactions may have positive outcomes or produce unforeseen, negative ecological consequences, so it is important to evaluate whether post-disturbance management can modify ecological resistance to subsequent disturbances.

An initial disturbance can affect ecological resistance (defined here as a reduced vulnerability to disturbance given some forcing) to subsequent disturbances (Buma and Wessman, 2011). Reduced resistance can trigger an interaction chain as subsequent disturbances become more likely, extensive, or intense (Foster *et al.* 2016, Burton et al. 2020). For instance, spruce trees weakened by windthrow are generally more susceptible to subsequent infestation by bark beetles (Seidl et al., 2016). Additionally, an initial disturbance can modify resilience (defined as a system's ability to recover given some disturbance) and thereby produce an interaction modification (Foster et al., 2016). Interaction modifications and interaction chains are driven by the legacies left behind by disturbances (Buma, 2015), such as surviving trees, snags and litter, and management that alters these legacies can affect the functional connection between multiple disturbances (Fig. 1).

Salvage logging consists of the removal of the trees affected by previous natural disturbances (Lindenmayer et al., 2008). While such management usually follows economic objectives, it also often professes to reduce the risk of subsequent disturbances (Müller et al., 2019). Salvage logging can alter the functional connection between disturbances by removing, modifying, and redistributing the biological legacies left by the initial disturbance. For example, logging after windthrow often aims to reduce beetle infestations by removing host material that can trigger population booms (Dobor et al., 2019), and post-beetle logging is often undertaken to reduce fuel loads and avoid subsequent wildfires (Donato et al., 2013).

Despite the above, several studies have questioned the actual efficacy of salvage logging in reducing the risk of subsequent disturbances, such as wildfire (Donato *et al.* 2006) and insect outbreaks (Grodzki *et al.* 2006). Other studies indicate that salvage logging may trigger other interaction chains, including a higher risk of erosion (Wagenbrenner et al., 2016), avalanches (Wohlgemuth et al., 2017), herbivory (Castro, 2013), and windthrow (Dobor et al., 2019). Several mechanisms may influence the risk of various subsequent disturbances depending on how, and over what timeframes, the logging intervention affects disturbance legacies and forest recovery. Further, broad-scale salvage logging contributes to a disturbance interaction chain itself (Leverkus et al., 2018a) and can impact ecosystem regeneration and functions (Lindenmayer et al., 2008). It is thus essential to understand the outcomes of post-disturbance logging in the context of interacting disturbances, but a comprehensive review on this topic is currently missing.

Here, we review whether salvage logging modifies the likelihood and characteristics of subsequent disturbances. The questions addressed are: (1) *Does salvage logging modify resistance to subsequent disturbances?* (2) *Through what mechanisms do such effects operate?* This paper is structured around each subsequent disturbance type (including wildfire, insect outbreaks, flooding and major erosional events, mass movement disturbances, windthrow, browsing, and microclimatic stress), which are individually addressed in the following section. For each subsequent disturbance, we address the mechanisms through which salvage logging may interfere in the functional connection between the initial disturbance and the specified subsequent disturbance, or produce a functional connection mediated through salvage logging itself. After reviewing the effects of salvage logging on the likelihood and magnitude of subsequent disturbances, we briefly address the mechanisms through which the resilience to those disturbances could also be affected. We end by developing a management decision-making framework that includes several considerations for managing the risk of subsequent disturbances. Our review encompasses Mediterranean, temperate, and boreal forests, in which most of the relevant literature is concentrated (Leverkus et al., 2018b; Thorn et al., 2018).

2. Salvage logging effects on subsequent disturbances

In this section, we briefly indicate how initial disturbance by wildfire, insect outbreak or windthrow is functionally connected to the risk of each of several possible subsequent disturbances (each addressed in one subsection). We then address the mechanisms through which salvage logging can interfere in this connection or produce new mechanisms of functional connection (Fig. 1; illustrated in Figs. 2 & 3). We specify those cases where the mechanisms are specific to particular initial disturbances. Note that, as highlighted previously (Leverkus et al., 2018b; Thorn et al., 2018), most of the publications on salvage logging have measured effects over less than five years. Whereas this limits our ability to understand the dynamics of subsequent disturbance risk, we highlight the temporal patterns that have been described.

2.1 Wildfire

Natural disturbances such as windthrow and insect outbreaks alter the conditions for subsequent wildfires by moving some fraction of the standing live biomass pool to the dead pool on the ground (Fig. 2a). This also occurs after wildfires, as trees tend not to burn completely and fuel gradually accumulates on the ground as they collapse (Molinas-González et al., 2017). The dense collections of fine, dead fuels after initial disturbances are potentially more flammable than the more dispersed, live fuels in an intact canopy (Cannon et al., 2017), and they can produce longer and more intense burns for some time (Buma and Wessman 2011). Thus, salvage logging often focuses on fuel removal.

Salvage logging reduces the amount of standing live and dead fuels, and of downed coarse deadwood after windthrow, thereby reducing total ecosystem fuels and the risk and severity of crown fire in the short term (Fraver et al., 2011). But it can also alter fire risk via fuel geometry (vertical/horizontal orientation), fuel status (live/dead), microclimate, and altered fuel trajectories (Fig. 2b). A large-scale assessment across the northwestern USA (Peterson et al., 2015) and a global meta-analysis (Leverkus et al.,

2020) highlight that salvage logging effects on surface fuels depend on an interaction between fuel type and time, explained as follows. With the exception of windthrows, downed coarse fuels are initially unaffected by salvage logging, as the delay in snag collapse in naturally-disturbed sites and the removal of trunks from salvaged sites yield an initial absence of downed deadwood in both scenarios (Leverkus et al., 2020). The gradual collapse of dead trees progressively increases coarse fuels in unlogged areas (Peterson et al., 2015), thereby potentially increasing the severity of subsequent fire (Buma and Wessman, 2011). But whereas coarse fuels can increase the ground-level impact of fire (Monsanto & Agee 2008, Buma and Wessman 2011), it is fine fuels that primarily drive key fire characteristics such as rate of spread and flame length (Dunn and Bailey, 2015).

After windthrow, salvage logging can reduce the amount of fine fuels through intensive, whole-tree removal approaches (Johnson et al., 2013), but it may also increase fine fuels via mechanical abrasion during tree removal and the accumulation of slash (branches, tops and bark) during initial on-site log processing (Donato et al., 2006; Gilmore et al., 2003). This can increase fire risk compared to unsalvaged scenarios. Fine surface fuels may remain constant for decades after beetle outbreaks or fire –thereby suppressing fire likelihood for at least a decade (Buma et al., 2020)– while they immediately increase after salvage logging for up to 4-5 years (Fig. 4a; Peterson, Dodson & Harrod 2015; Leverkus *et al.* 2020). At later stages, the effect of logging is a reduction in small fuels due to faster decay in salvaged stands and the addition of dead branches from the canopy to the surface in unsalvaged stands (Fig. 4b; Peterson, Dodson & Harrod 2015).

Shrub and tree regeneration can outweigh dead fuels and drive fire risk as the stand develops. Salvage logging can affect vegetation, and ultimately alter flammability, through numerous mechanisms. The shrub layer can be impacted when operations kill the initial flush of regeneration (Donato et al., 2013), thereby reducing live fuel loads. But soil compaction due to mechanical action can also affect vegetation growth, thereby reducing biomass. Contrarily, highly flammable, early seral species can be favoured by salvage logging (Campbell et al., 2016). Collins *et al.* (2012) modelled that after a mountain pine beetle (*Dendroctonus ponderosae*) outbreak, enhanced spruce regeneration in unsalvaged stands would increase the likelihood of active crown fire as the stand matured. Similar conclusions were reached after the Summit Fire in Oregon, where a reburn was similarly severe across treatments because regeneration outbalanced logging-induced increases in fine fuels and eliminated any effects of salvage logging (McIver and Ottmar, 2018). However, greater flammability and fire severity can also be driven by actions associated with salvage logging, such the establishment of densely stocked conifer plantations (Fig. 3, 4c; Thompson, Spies & Ganio 2007).

Low fuel moisture can explain higher combustion of large fuels and quicker fire spread after salvage logging (Dunn and Bailey, 2015). Salvage logging may reduce shading after fire and beetle outbreaks and thus increase ground temperature (Griffin et al., 2013; Lindenmayer et al., 2009), ultimately producing drier fuels and greater potential fire spread and intensity (Hood et al., 2017). By drying the ground, exposing mineral soil to the heat, and compacting litter, salvage logging can lead to hotter smoldering and ultimately to higher fire severity at the ground level (Fraver et al., 2011). But such effects, while potentially locally important, are likely to be outweighed by those of weather (Fernandes et al., 2014) and influenced by how salvage logging modifies fuel connectivity across the landscape –topics that have received less attention than stand-scale effects in the reviewed literature.

In sum, the efficacy of salvage logging in altering fire risk depends on how it affects the temporal trajectory of the fuel bed after disturbance. Coarse surface fuels are generally reduced immediately after logging of windthrows, yet salvaging of fire- and insect-affected stands increases small fuels in the early years and reduces large fuels at later stages. Salvage logging can increase fire intensity by producing drier fuels and if accompanied by reforestation. Thus, salvage logging alters the composition of fuels which can affect fire behaviour and impact, but rarely appears justified as a way to reduce fire likelihood.

2.2 Insect outbreaks

Insect outbreaks –among which we address those produced by bark beetles (Coleoptera, Curculionidae, Scolytinae)– are a common disturbance in many temperate and boreal forests. They are particularly common after other disturbances due to weakened or dead host trees (Seidl et al., 2016; Stadelmann et al., 2013). As a result, disturbed forest stands (Fig. 4d) are often salvage logged with the goal of preventing outbreaks. Salvage logging is expected to reduce insect impacts by reducing host density and reducing connectivity between host trees (Fettig *et al.* 2007). For instance, salvage logging reduced the mortality of surviving spruces by half in a post-windstorm study in Sweden (Schroeder and Lindelöw, 2002).

Once outbreaks reach an epidemic stage and expand to undisturbed forests, harvesting –sometimes termed sanitation logging – is still a generalised response to halt beetle expansion. Depending on particular logging methods, the mechanisms expected to stop outbreak progression involve downsizing beetle populations by removing their broods (Jönsson et al., 2012), reducing brood survival (Billings, 2011), and forcing insect dispersal to unfavourable seasons (Billings, 2011). Still, most existing indications on the mechanisms through which logging should prevent outbreaks at the stand scale are based on unsystematic observations from practice (reviewed in Fettig *et al.* 2007; Billings 2011; Six, Biber & Long 2014). Further, some studies show that stand edges generated by sanitation logging increase attractiveness for bark beetles (Fig. 3; Grodzki *et al.* 2006) and susceptibility to windthrow and insolation, which, again, favour the expansion of bark beetles as a *further* disturbance (beetles → salvage → increased windthrow → increased beetles; Modlinger & Novotný 2015).

At the scale of landscapes, logging aims to reduce the number of infestation spots (Gawalko, 2004) and the connectedness between host and beetle populations (Seidl et al., 2016). However, management of bark beetles at the stand scale was a poor predictor of outbreak progression in a 23-year time series in the Bavarian Forest National Park, Germany (Seidl et al., 2016). Similarly, tree mortality due to a bark beetle outbreak in the Tatra Mountains of Slovakia could not be reduced despite intensive pest management measures (Grodzki et al., 2006); the logging represented a significant disturbance at the scale of the landscape, and it was unfavourable weather that ultimately reduced the outbreak (Havašová et al., 2017). In a large-scale assessment of the European spruce bark beetle in Switzerland, Stadelmann *et al.* (2013) concluded that sanitation logging (i.e., of infested trees) reduced infestation spots, yet with an effect size that was an order of magnitude smaller than that of five variables that increased spot numbers. Intensive salvage logging of large windthrows reduced the number of infestation spots (as derived from a positive effect of unsalvaged spruce volume), but outbreaks still occurred after a severe storm regardless of management (Stadelmann et al., 2013).

The effectiveness of logging in mitigating beetle outbreaks appears to be non-linear. As found in a Swedish study, beetle populations may limit population growth at low beetle population sizes (with a threshold of 200 females m^{-2}), whereas under greater population densities the brood material is the limiting factor (Jönsson et al., 2012). In a large-scale modelling study in central Europe (Dobor et al., 2019), removing 100% of windthrown or infested spruce trees reduced the number of newly infested spruce trees (albeit with a greater risk of wind disturbance), yet if as little as 5% of trees were left, logging had no effect on bark beetle dynamics. In a subsequent model (Dobor et al., 2020), salvaging along roads acted as “beetle breaks” with the potential to avoid their spread. However, climate change minimised the effectiveness of salvage logging because warming temperatures increased beetle populations (Seidl et al., 2016).

In sum, the existing body of literature describing well-designed studies addressing the efficacy of salvage logging in preventing the explosive population growth of forest-damaging insects is sparse. This is, at least partially, caused by the inherent nature of bark beetle outbreaks and the fact that unlogged control areas are scarce due to legal mandate for salvage logging (Biedermann et al., 2019). Salvage and sanitation logging can reduce infestation rates, particularly with low beetle densities and if all infested trees are removed –an often unrealistic scenario after large disturbances. The efficacy of salvage logging is lower if outbreaks are widespread, and mostly determined by regional to landscape-scale factors such as weather.

2.3 Flooding and major erosional events

Initial disturbances that lessen canopy cover can increase the risk of hydrologically-related disturbance by reducing transpiration and increasing net precipitation and rainfall energy at the ground. Additionally, fire can substantially reduce soil infiltration capacity through changes in soil structure, infilling of pores by ash and clay, and increases in soil water repellency (Robichaud et al., 2010). Through these processes, initial disturbances can produce a shift from subsurface to overland flow, increase the sensitivity of hydrologic processes to extreme rainfall events, and increase the risk of soil erosion and the magnitude of peak flows (Schnorbus et al., 2010). Salvage logging, through mechanisms operating at different spatial scales, can mitigate or boost the risk and magnitude of floods and erosion (Fig. 2, 3).

Ground-based salvage equipment can compact soil, damage understory vegetation, and magnify erosion (Gerber et al., 2002; McIver and McNeil, 2006). Such effects, combined with increases in net precipitation after canopy removal, can reduce soil water holding capacity and increase soil saturation (Fig. 4e; Prats *et al.* 2019). After moderate-severity disturbances, such as insect outbreaks with partial canopy mortality, salvage logging further decreases transpiration and infiltration by killing remaining overstory and understory vegetation (Winkler et al., 2008). This may result in wetter ground, increased overland flow, greater propensity to soil disturbance (e.g., rut formation) by machinery, and ultimately increased surface runoff (Wagenbrenner et al., 2015).

Increased runoff is more likely to concentrate into rills, thereby increasing transport capacity and the connectivity between hillslopes and stream networks (Bryan, 2000). This hydrologic connectivity particularly increases when the skid trails and roads form highly connected networks. This occurs most often in burnt areas because of the large-scale consumption of the understory and litter layers (Sosa-Pérez and Macdonald, 2017). The increased connectivity would persist until the understory and organic forest floor recover, which, after severe fire, could be on the order of decades.

The amount of bare soil is a major control on erosion that management can influence (Fig. 4f; Robichaud, Ashmun & Sims 2010). Ground-based salvage logging typically increases bare soil by damaging vegetation and by displacing organic forest floor materials (Wagenbrenner et al., 2015). However, salvage logging can also mitigate post-fire erosion at small scales by increasing slash cover (Olsen, 2016) or creating irregular ground surfaces that reduce runoff speed (Collins and Dunne, 1988). The balance of different mechanisms can thus result in greater (Wagenbrenner et al., 2015) or equivalent erosion after salvage logging (Collins and Dunne, 1988), until vegetation regrowth outbalances initial and subsequent erosion effects.

Stream networks may receive greater sediment delivery through greater erosion and hydrologic connectivity. In streams where sediment loads are already high, this could lead to aggradation and loss of conveyance capacity, resulting in increased overbank flow and flooding. On the other hand, initial disturbances can increase wood delivery to stream channels (Jones and Daniels, 2008; Phillips and Park, 2009). Greater log recruitment can increase streambed stability, while it does not seem to increase flooding (Phillips and Park, 2009). Salvage logging reduces the supplies of coarse wood to small streams unless riparian zones are protected, and this can produce relatively long periods of channel degradation and instability (Jones and Daniels, 2008), with concomitant risks of flooding.

In regions where snow melt dominates hydrographs, openings created by initial disturbances, and amplified by salvage logging, increase the radiation that reaches the snowpack, turbulent heat transfer due to higher local wind speeds, and latent heat transfer due to condensation and freezing at the snowpack surface (Alila et al., 2009). The resulting faster snow accumulation and melt rates can lead to earlier and greater peak flows (Schnorbus, 2011), and hence to greater flood risk. In western Canada, salvage logging has magnified the hydrological effects of a recent, large-scale mountain pine beetle infestation (Schnorbus, 2011), with concomitant shifts toward a greater frequency of extreme flows. However, as catchments are usually not completely affected by the initial disturbance or salvage logging, cumulative impacts at larger spatial scales may not always be detectable (e.g., Wagenbrenner *et al.* 2015; James & Krumland 2018).

In summary, salvage logging can affect various processes that, in turn, are related to hydrologic disturbances. By compacting soil, reducing rain-intercepting deadwood, affecting advance and regenerating vegetation, altering snow-melt conditions, and amplifying rill networks, it can aggravate soil erosion, boost surface runoff, and increase the risk of flooding.

2.4 Mass movement disturbances

On steep mountain slopes, forests protect against avalanches by intercepting snow in the tree crowns, affecting snow stratigraphy, and reducing the formation of homogeneous snowpack layers (Fig. 2, 4g; Teich *et al.* 2019). Major disturbances simplify the vertical structure of the forest and reduce anchoring to the ground. However, disturbed forests can still play a protective function (Lingua et al., 2020). Standing dead and dying trees following bark beetle outbreaks or wildfires still intercept snow, produce heterogeneous snow stratigraphy, and buffer temperature fluctuations that weaken snow layers (Teich et al., 2019). Following windthrows, the ground is suddenly covered by uprooted trees and boles, whose protective effect may last for several decades (Schönenberger et al., 2005).

By removing deadwood after disturbances, salvage logging can trigger gravity-driven disturbances including avalanches, landslides, and rockfall (Fig. 2, 3; Lingua *et al.* 2020). The reduction of canopy cover and fallen deadwood leads to snow profile characteristics similar to those of unforested sites (Teich et al., 2019), including large, homogeneous snow packs and weaker layers resulting from wider temperature fluctuations, which are the main causes of slab avalanches (Frey and Thee, 2002). Clearing the windthrown areas also increases the risk of rockfall (Schönenberger et al., 2005), as snags and deadwood otherwise obstruct falling rocks (Fig. 4h; Lingua *et al.* 2020). Salvage logging in mountain forests thus increases the risk of gravity-driven disturbances during the decades preceding stand recovery, thereby prolonging the protection gap (Wohlgemuth et al., 2017).

2.5 Windthrow

By creating forest edges and leaving isolated surviving trees and tree patches, natural disturbances can increase susceptibility to windthrow. Salvage logging increases wind speed (Fig. 2) and the amount of unforested area across the landscape, and it can thereby increase forest fragmentation and the extent of new forest edges (Grodzki et al., 2006), which are more susceptible to being windthrown (Modlinger and Novotný, 2015). But such effects can also be mediated by interactions with other disturbances: where salvage logging effectively dampens beetle outbreaks, it increases the availability of trees at risk of wind disturbance at long temporal scales (Dobor et al., 2019). Salvage logging can thus directly and indirectly increase the risk of windthrow in remaining forest patches, yet such effects have received little scientific attention.

2.6 Browsing

Disturbances promote the growth of graminoids and resprouting shrubs, which in turn attract herbivores (particularly after fire; Foster *et al.* 2016). However, deadwood elements can act as physical impediments for large animals (Fig. 2), and thus as browsing refugia for regeneration (Castro, 2013). By opening space, salvage logging may increase browsing pressure and eventually reduce regeneration. However, different guilds of herbivores may be attracted to areas managed in different ways (Hagge et al., 2019; Leverkus et al., 2013). In some places, the top-down limitation imposed by carnivores is more relevant than food availability, as shown both for ungulates (Hebblewhite et al., 2009) and rodents (Leverkus et al., 2013). Hiding cover can reduce perceived predation risk, resulting in higher damage to regeneration in uncleared sites. In contrast, browsing by some species shows no association with areas with contrasting amounts of deadwood (e.g., Kupferschmid & Bugmann 2005). Browsing pressure may also be affected by qualitative factors such as stem thickness, differential palatability of stems and leaves as a function of shade, and the use of habitats for purposes other than browsing (Faison et al., 2016). The ways in which salvage logging affects browsing thus depend on how it changes predation risk and the availability and quality of food, and on the local herbivore densities. But understanding whether such changes affect the long-term process of forest succession is limited by the short-term nature of studies.

2.7 Microclimatic stress

Deadwood can ameliorate harsh microclimatic conditions and thereby improve the survival and growth of regeneration (Marzano et al., 2013). Dead-tree removal may increase near-surface daytime temperatures (Vlassova and Pérez-Cabello, 2016) and reduce nightly minimum temperatures (Fontaine et al., 2010), thus increasing diurnal soil temperature fluctuations. As microclimatic requirements for seedlings are usually more restrictive than for adult plant survival, the amplification of temperature ranges can be particularly detrimental for plants regenerating from seed. As a result, the few existing studies suggest that salvage logging can worsen the physiological performance of seedlings by increasing abiotic stress in semi-arid environments (Castro et al., 2011; Marañón-Jiménez et al., 2013; Marzano et al., 2013). Yet more research on interactions between natural disturbance, salvage logging, and subsequent drought is critically needed under a warming climate.

3. Salvage logging effects on resilience to subsequent disturbances

Above, we reviewed the effects of salvage logging on ecological resistance to subsequent disturbances. However, salvage logging may also affect resilience to subsequent disturbances, here defined as forest recovery capacity. Such effects may occur through changes in community functional composition (Taboada et al., 2018) and in the behaviour of the subsequent disturbance (Buma and Wessman, 2011). For instance, after blowdown by tornado in a hardwood-pine forest in Mississippi, salvage logging disfavoured resprouter species of low flammability, and therefore produced communities less resilient to subsequent disturbances such as wildfires (Cannon and Brewer, 2013). In a burnt pine stand in Spain, salvage logging reduced bird-mediated seed dispersal of a key resprouter tree species (Leverkus and Castro, 2017) and reduced plant diversity and the cover of post-fire seeder species (Leverkus et al., 2014), with likely implications for resilience to further fire. Conversely, species with long-range seed dispersal mechanisms are generally less impacted (Buma and Wessman, 2012). However, multiple different responses of vegetation to salvage logging have been reported (see reviews in Royo *et al.* 2016 and Taeroe *et al.* 2019), and in some cases the compositional differences induced by salvage logging can be erased by the occurrence of the subsequent disturbance (Rhoades et al., 2018; Taboada et al., 2018).

The effects of salvage logging on resilience via changes in subsequent-disturbance characteristics can also be mediated by species traits. In subalpine forests of the Rocky Mountains, severe blowdown increased coarse-fuel loadings and the extent of high-severity burn patches (Buma and Wessman, 2011). This reduced the regeneration of serotinous *Pinus contorta* – but not that of wind-dispersed trees – through greater seed mortality and through increased seed-dispersal distances (Buma and Wessman, 2012). Post-blowdown salvage logging, which occurred prior to the fire, mitigated this interaction through reductions in coarse fuels.

By modelling changes to subsequent-disturbance behaviour as a result of post-logging ecosystem alterations (e.g., Collins *et al.* 2012), and by combining that with knowledge of species-specific resilience mechanisms, one could anticipate the sometimes diverging effects of salvage logging on species and ecosystem resilience. This constitutes a key direction for further research and an important aspect for decision-making.

4. Management considerations

Based on our review, neither is salvage logging universally successful in preventing the subsequent disturbances addressed in sections 2.1–2.7, nor are subsequent disturbances guaranteed in its absence. Rather, salvage logging can affect particular mechanisms that modify the risk and intensity of particular disturbances. The effects of salvage logging on natural disturbances vary in space, time, and magnitude and thus its efficacy in preventing subsequent disturbance highly depends on local conditions. Further, managing to avoid subsequent disturbances via salvage logging involves applying one disturbance, namely logging, to avoid another. Thus, beyond solely attempting to reduce the risk that such disturbances occur, management decisions should also address the risks associated with the disturbance of management itself.

Our review – in accordance with most of the literature – simplified the effects of post-disturbance management by primarily considering the stand-scale effects of applying one treatment or another, whereas post-disturbance landscapes are generally more complex. The spatially intermingled combinations of different disturbance severities, slopes, aspects, proximities to riparian areas and roads, property ownerships, and other factors, generally result in heterogeneous risks associated with subsequent disturbances across the disturbed landscape, and in different management needs. The complexity of managing subsequent-disturbance risk is further exacerbated by the potential effects of the spatial configuration of salvage logging on landscape connectivity, as highlighted by some existing modelling studies (e.g., on the effect of the spatial configuration of salvage logging along roads or in large blocks on the progression of bark beetle outbreaks; Dobor et al., 2020). Management decisions require considering such complexity to prioritise different functions across the landscape.

Based on our review, and on some broader questions that deserve attention, we propose a management decision-making framework regarding subsequent disturbances (Fig. 5). The starting point for this framework is the occurrence of one natural disturbance, and the steps are as follows.

1. Evaluate whether, and how, the legacies of the initial disturbance modify the risk of subsequent disturbances (point 1 in Fig. 5). This requires mapping aspects such as deadwood, soil properties, and weakened trees across the area of the initial disturbance. Coupled with information on climate, slope, wind exposure, beetle populations, and other variables, the risk of particular subsequent disturbances across the landscape should be assessed prior to justifying the use of management to mitigate them. For instance, whereas fire severity can depend on the severity of previous disturbance (Buma and Wessman, 2011), in other cases such functional connection is inexistent (McIver and Ottmar, 2018).

2. In case of increased likelihood of subsequent disturbances, forecast their expected impacts (point 2 in Fig. 5). Whereas natural disturbances can produce some negative impacts (Thom and Seidl, 2016), there is increasing recognition of their role in maintaining biodiversity, landscape heterogeneity, and other ecosystem services (e.g., Pausas & Keeley 2019). Managers may sometimes allow disturbance chains to happen without necessarily compromising management goals (e.g., Beudert *et al.* 2015), particularly in conservation-dedicated areas (Müller et al., 2019). But if management goals are primarily economic, subsequent disturbances may reduce wood quality further and compromise management objectives.

3. If expected impacts from subsequent disturbances are negative, assess whether salvage logging can prevent or mitigate the functional connection between disturbances (point 3 in Fig. 5). The effects of salvage logging on the disturbance legacies that are functionally connected with subsequent disturbances, identified in point 1, can be

evaluated based on the results of our review (Figs. 2 & 3; Appendix S1). For instance, following small windthrows, quick salvage logging may effectively dampen subsequent beetle outbreaks. In other cases, the functional connection between natural disturbances may not be driven by deadwood legacies but by the subsequent regeneration (Thompson et al., 2007) or other mechanisms on which management may have little effect (Cannon *et al.* 2017). Furthermore, climatic drivers are sometimes more important than previous disturbance dynamics in defining the risk of fire (Fernandes et al., 2014; James et al., 2011), insect outbreaks (Dobor et al., 2020), and hydrologic disturbances (Gerber et al., 2002). This suggests that climatic drivers may become increasingly important in defining disturbance likelihood and extent as the climate changes, thereby overriding the effects of management (e.g., Dobor *et al.* 2020).

4. If salvage logging has the potential to mitigate subsequent disturbances, compare the risks (likelihood x impact) associated with those potential subsequent disturbances with the impacts of salvage logging (point 4 in Fig. 5). Salvage logging is itself a subsequent disturbance (Leverkus et al., 2018a), sometimes more intense than the initial disturbance (Modlinger and Novotný, 2015), and it can affect ecosystem functioning and biodiversity (Leverkus et al., 2020; Lindenmayer et al., 2008; Lindenmayer and Sato, 2018; Thorn et al., 2020; but see Royo *et al.* 2016). Such impacts would need to be compared with the risks from the subsequent disturbance, derived from points 1 and 2 above.

5. If salvage logging is not expected to have greater negative impacts than subsequent disturbances, assess whether salvaging produces new legacies that affect the

likelihood or characteristics of additional disturbances (point 5 in Fig. 5). Such legacies are included in this review (Figs. 2 & 3; Appendix S1), and they may include fine deadwood (logging slash) on the ground, compacted soil, skid trails, habitat for herbivores, etc. The new management legacies, plus the removal of natural-disturbance legacies, can produce additional feedbacks by favouring subsequent disturbances.

6. In case management legacies are connected with subsequent disturbances, define additional actions to mitigate them (point 6 in Fig. 5). Examples include mechanical treatments to reduce fuels such as whole-tree removal and slash burning (Gilmore et al., 2003), pre-emptive logging to remove host trees in advance of outbreaks (Fettig et al., 2007), bark scratching of downed trunks to reduce breeding substrate of bark beetles (Hagge et al., 2018), mulching to reduce bare soil and mitigate hydrologic impacts (Wagenbrenner et al., 2006), and planting in unsalvaged windthrow to speed up protection from avalanches (Wohlgemuth et al., 2017). Return to point 4 to contrast the combined effect of salvage logging plus mitigation actions with the forecasted impact of subsequent disturbances.

7. Following point 5, if disturbance plus management legacies are not functionally connected to further disturbances, additional decision-making criteria can be evaluated (point 7 in Fig. 5). Note that our framework allows to decide on the appropriateness of salvage logging to mitigate the impacts of subsequent disturbances, yet other legitimate aspects such as aesthetic, economic, and safety criteria (unrelated to subsequent disturbance) may also be relevant.

As the likelihood of occurrence and magnitude of subsequent disturbances tends to vary across disturbed landscapes, and as managing one disturbance can affect others in unknown ways (Dobor et al., 2019), we further suggest that, besides considering the framework of Fig. 5 to address resistance to subsequent disturbances, strategies be developed to enhance resilience, which would promote recovery after uncertain subsequent disturbances. This would increase the odds of reducing large-scale impacts of uncertain future events, and of management aimed at preventing them, in the world's forests experiencing shifting disturbance regimes.

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Figure captions

Figure 1. Conceptual diagram of salvage logging in the context of multiple disturbances. This review addresses how salvage logging can modify the likelihood and characteristics of subsequent disturbances, both by altering the functional connection between natural disturbances and by creating new pathways of functional connection with other disturbances.

Figure 2. Illustration of a forest stand affected by a) natural disturbance and b) natural disturbance and salvage logging. The effects of salvage logging (positive + or negative -) on the indicated elements and processes can increase (full symbol) or decrease (empty symbol) the likelihood, extent or magnitude of subsequent disturbances. Asterisks show particular controversy. For references, see Appendix S1.

Figure 3. Illustration of a forest landscape affected by a) natural disturbance and b) natural disturbance and salvage logging. The effects of salvage logging (positive + or negative -) on the indicated elements and processes can increase (full symbol) or decrease (empty symbol) the likelihood, extent or magnitude of subsequent disturbances. Asterisks show particular controversy. For a symbol legend see Figure 2. For references, see Appendix S1.

Figure 4. Ground fuel loads can greatly increase after post-fire logging (a), yet in the mid-term they increase more in unsalvaged areas (b) through snag fall. Actions associated with

salvage logging, such as planting, can produce additional effects on soils, flammability, and erosion risk (c). Recent windthrows are susceptible to bark beetle outbreaks (d). Salvage logging compacts soils and reduces infiltration (e), and it can increase erosion and sediment export risk (f). Standing dead trees reduce the risk of avalanches by preventing homogeneous snow layers (g) and of rockfall by halting downward movement (h).

Figure 5. Decision-making framework about salvage logging in relation to mitigating the risk of subsequent disturbances. Green boxes (with solid contour lines) indicate management assessments. The orange box (dotted contour line) indicates the ending point of the process, at which stage the needs and strategies to mitigate other impacts (from economic to biodiversity) need to be evaluated. This framework is best applied at scales small enough to encompass the spatial variation in disturbance legacies and risk of subsequent disturbances. SL = Salvage logging.

Figure 1

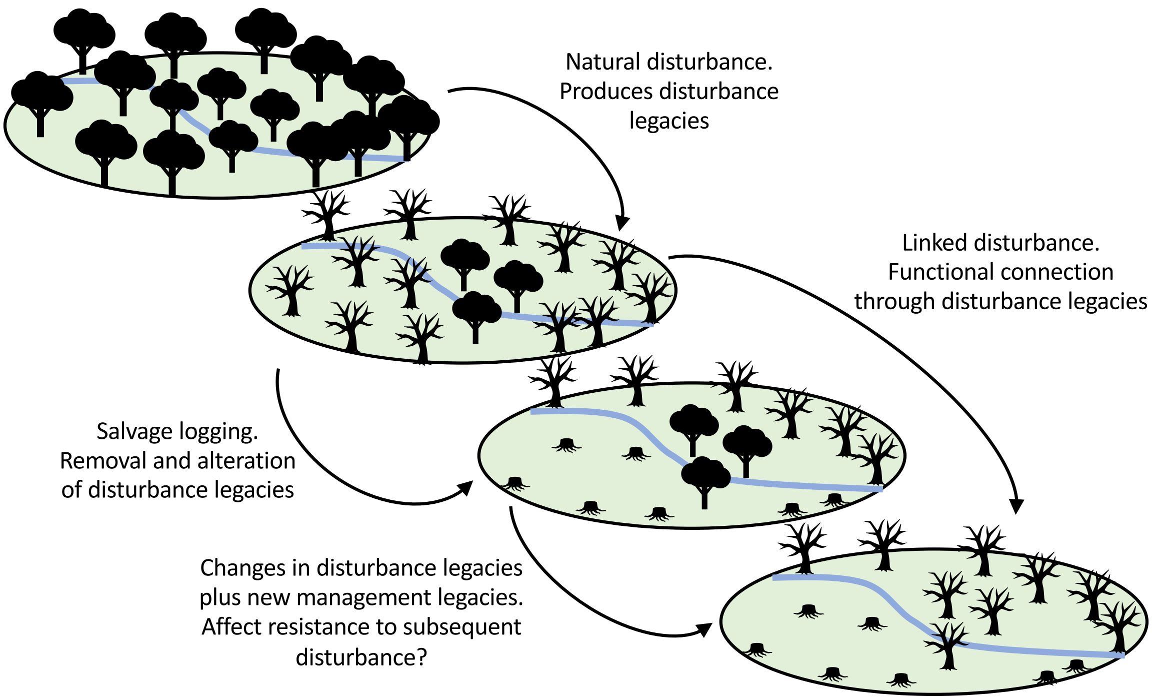
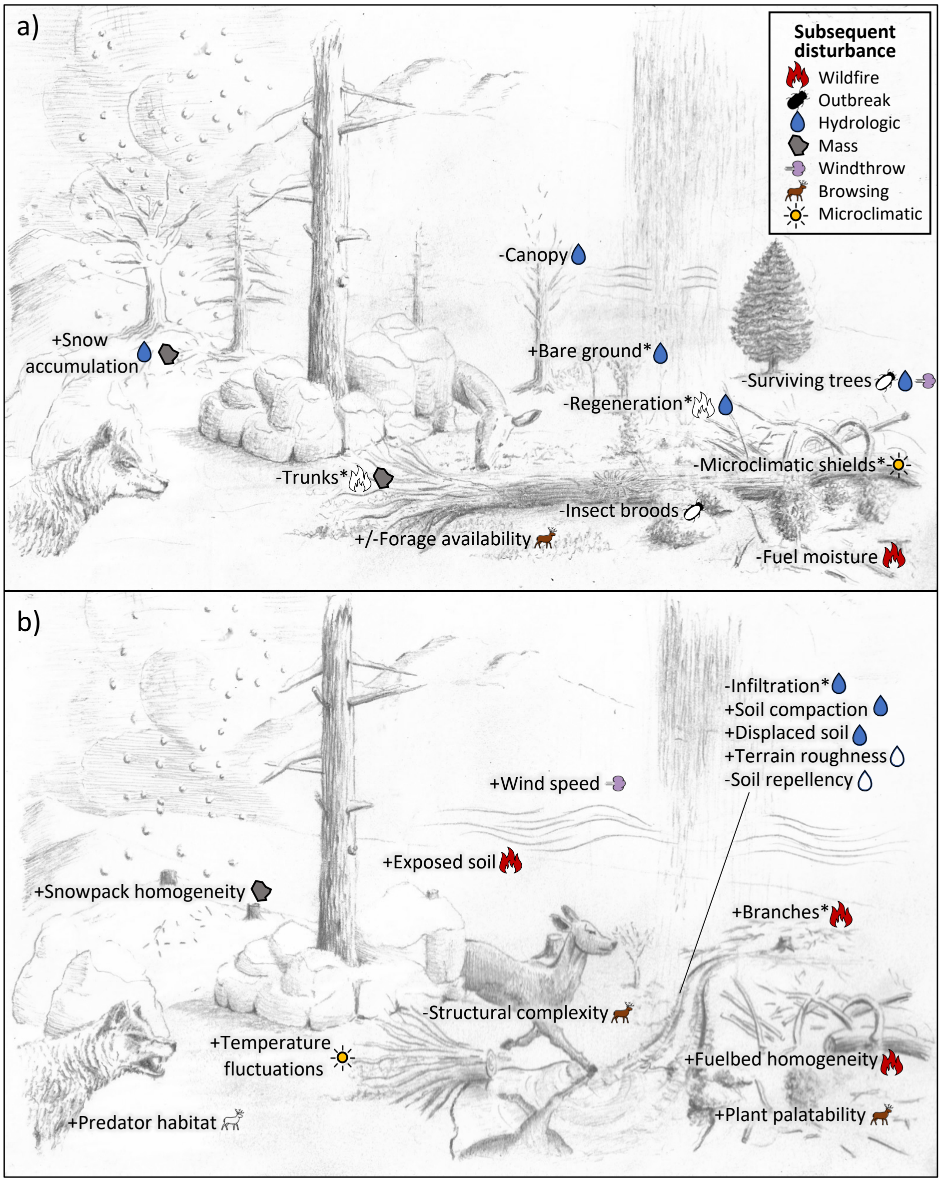

Natural disturbance.
Produces disturbance
legacies
Linked disturbance.
Functional connection
through disturbance legacies
Salvage logging.
Removal and alteration
of disturbance legacies
Changes in disturbance legacies
plus new management legacies.
Affect resistance to subsequent
disturbance?

Figure 2



a)
Subsequent disturbance
Wildfire
Outbreak
Hydrologic
Mass
Windthrow
Browsing
Microclimatic
-Canopy
+Snow accumulation
+Bare ground*
-Surviving trees
-Regeneration*
-Microclimatic shields*
-Trunks*
-Insect broods
+/-Forage availability
-Fuel moisture
b)
-Infiltration*
+Soil compaction
+Displaced soil
+Terrain roughness
-Soil repellency
+Wind speed
+Exposed soil
+Snowpack homogeneity
+Branches*
-Structural complexity
+Temperature fluctuations
+Fuelbed homogeneity
+Plant palatability
+Predator habitat

Figure 3

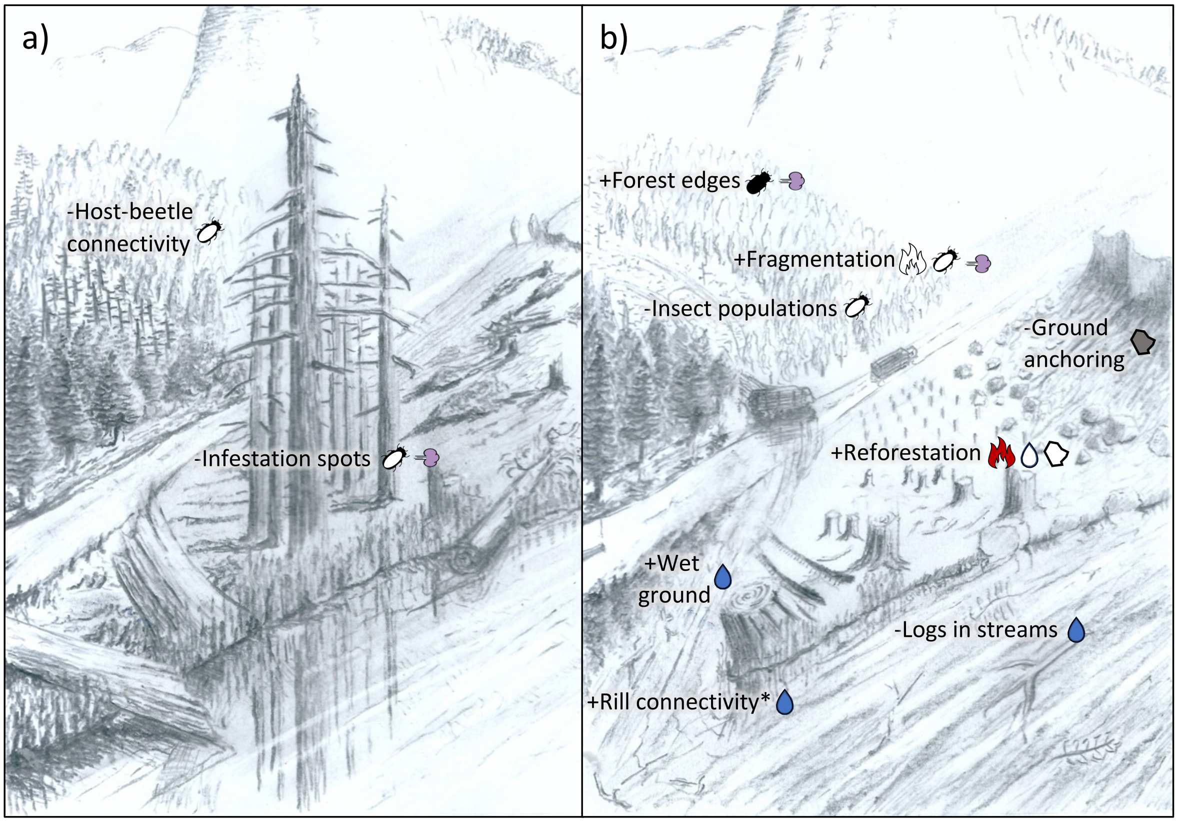

a)
-Host-beetle connectivity
-Infestation spots
b)
+Forest edges
+Fragmentation
-Insect populations
-Ground anchoring
+Reforestation
+Wet ground
-Logs in streams
+Rill connectivity*

Figure 4

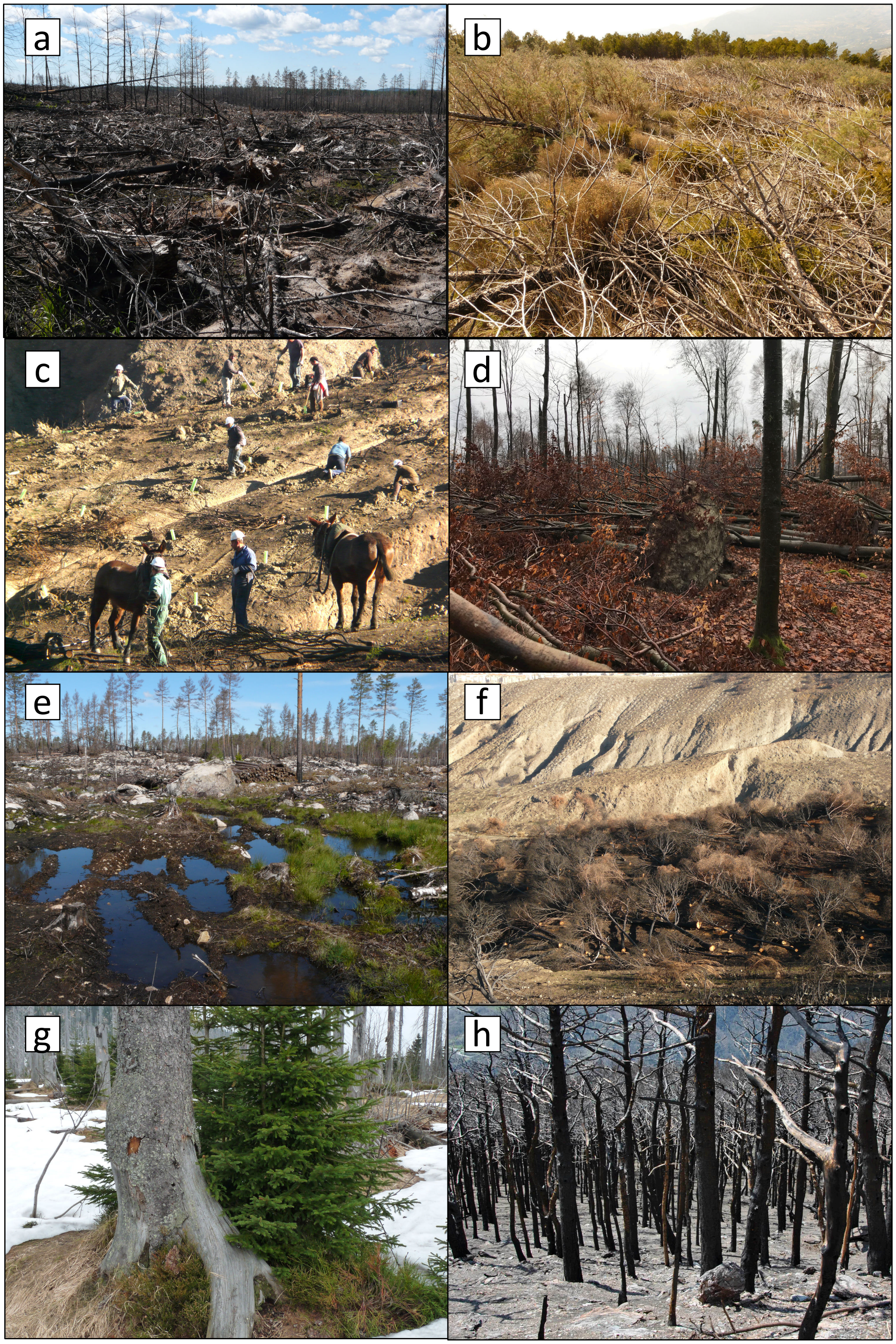
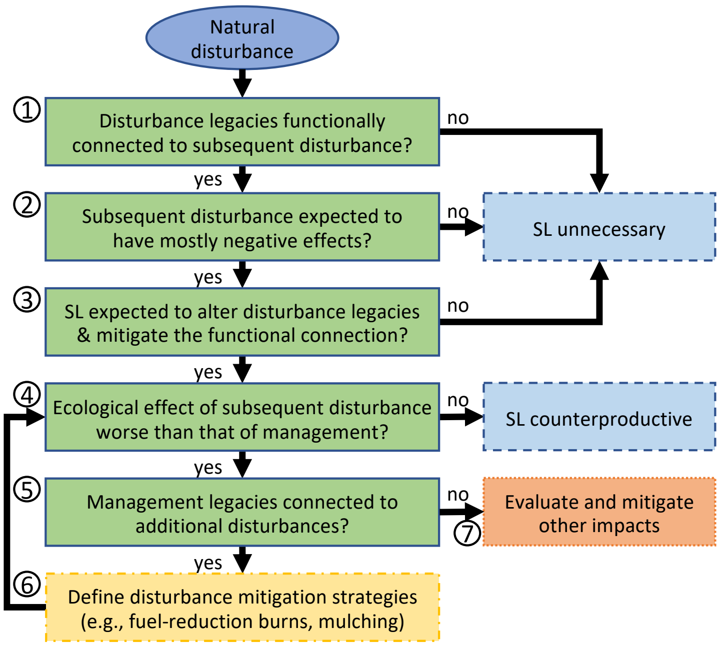


Figure 5


Natural disturbance
①
Disturbance legacies functionally connected to subsequent disturbance?
no
yes
②
Subsequent disturbance expected to have mostly negative effects?
no
SL unnecessary
yes
③
SL expected to alter disturbance legacies & mitigate the functional connection?
no
yes
④
Ecological effect of subsequent disturbance worse than that of management?
no
SL counterproductive
yes
⑤
Management legacies connected to additional disturbances?
no
⑦
Evaluate and mitigate other impacts
yes
⑥
Define disturbance mitigation strategies (e.g., fuel-reduction burns, mulching)