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Maintaining the protective function of mountain forests under climate change by the concept of naturalness in tree species composition

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In Swiss mountain areas, the protective function of forests is the predominant ecosystem service having high cultural and economic significance. It is assumed that natural forests or close-to-natural forests, i.e., forests being in the equilibrium with environmental conditions are the most resilient and resistant in regard to disturbances and hence best protecting people and assets on the long run. Here, we estimated the naturalness of the tree species composition by comparing Swiss National Forest Inventory (NFI) data with current and future potential Natural forest Site Types (NST). Based on this analysis, we identified species that are under or over-represented in protective mountain forests and derived the subsequent potential for management interventions. The urgency of management interventions is expected be small if all predominant tree species of the idealized potential natural forests are present and only their relative portions in the stand need adjustment. In contrast, interventions are advisable, if predominant tree species of the current and future potential natural forests are absent. Based on NFI data, the tree species composition of 47% of the protective mountain forests were classified as "natural" or "close-to-natural," while the remaining 53% were classified as "not natural" or "partly natural." Norway spruce [*Picea abies* (L.) H. Karst.] and European larch (*Larix decidua* Mill.) were the two most over-represented species under current and even more so under predicted future climatic conditions. To date, silver fir (*Abies alba* Mill.) and European beech (*Fagus sylvatica* L.) were the two species most frequently absent in protective mountain forests, in which they should prevail. Apart from European beech, the most prominent increase in prevalence is predicted for oak (sessile oak and pubescent oak; *Quercus petrea* Liebl., *Q. pubescens* Willd.) and small-leaved lime (*Tilia cordata* Mill.). These species were currently missing from more than 75% of the stands, in which they are expected to be dominant under future conditions.

Our analysis indicates the need to transform tree species compositions of protective mountain forests to optimize fitness under future climates. Some of these transformations will take place naturally, incited by disturbances, others—the majority of them—will need active management interventions.

KEYWORDS

bark beetle, hemeroby, Norway spruce, Switzerland, climate change, ecosystem services, Forest Inventory data

Introduction

Forests in mountain areas provide several ecosystem services (Ninan, 2014; Acharya et al., 2019) including protection for critical infrastructure such as roads, railroads, and buildings resulting in considerable economic and cultural value (Teich and Bebi, 2009; Miura et al., 2015). In Switzerland about 50% of mountain forests protect 130,000 buildings and several thousand kilometers of traffic routes generating an estimated ecosystem service value of 4 bn $ per year (Losey and Wehrli, 2013). Continued protective function is therefore essential to further mitigate socio-economic risks.

It is generally assumed that forests/ecosystems in equilibrium with the environmental conditions (i.e., natural forests) are most stable and consequently best suited to provide continued ecosystem services (Stritih et al., 2021; Scherrer et al., 2023a). As ongoing climate change affects tree habitat ranges and community compositions (e.g., Dyderski et al., 2018; Lenoir et al., 2020) these protective forests should necessarily adapt to stay in equilibrium with their dominant environmental conditions (Brang et al., 2014; Albrich et al., 2018). This poses several challenges. Firstly, forest ecosystems transform very slowly with environmental change, especially in the absence of stand-level disturbances (Thom et al., 2017; Scherrer et al., 2020, 2022). Secondly, after a large-scale disturbance, forests go through a decade-long series of successional stages before reaching a new climax state (Breshears et al., 2011; Seidl et al., 2017). And finally, most forests in Switzerland are highly managed systems with a long land-use history leading to differing degrees of naturalness (Scherrer et al., 2023a). A steady adaptation of mountain forests by management is therefore necessary to maintain the suitability of forests to environmental conditions and ensure a continued protective function (Pluess et al., 2016; Daniel et al., 2017; Runting et al., 2017). The type and intensity of management intervention needed to promote a high naturalness in future mountain forests strongly depends on its the current degree of naturalness.

In Switzerland, forest management practices aim at creating more resilient, "climate-smart" forests (e.g., Bowditch et al., 2020; Mathys et al., 2021; Santopuoli et al., 2021) ensuring continued ecosystem services (e.g., Nabuurs et al., 2017; Temperli et al., 2020; Verkerk et al., 2020). Many Swiss forests are currently managed by a "close-to-nature" silviculture system (Bürgi, 2015; Spathelf et al., 2015) favoring natural regeneration (Brändli et al., 2020b) in small gaps by direct regrowth. An important aspect of "close-to-nature" silviculture is to create forests adapting to changing environmental conditions due to increased naturalness (Brang et al., 2014; Spathelf et al., 2015). In line with this idea, the Swiss Forest Act (WaG, SR 921.0) states that tree recruitment or planting should be based on site-adapted species (i.e., species of the potential natural forest community). Consequently, information about the potential natural forest community has been provided for different cantons and regions, and an integral classification system provides now comparability nationwide: the NaiS [Nachhaltigkeit und Erfolgskontrolle im Schutzwald (Sustainability in the Protection Forest); Frehner et al., 2009; Frey et al., 2021] natural forest site system. The Natural forest Site Types (NST; i.e., idealised potential natural vegetation with characteristic tree species composition; e.g., Prentice et al., 1992; Koca et al., 2006) of a given location is determined by expert knowledge based on abiotic conditions (e.g., elevation, geographic region, soil water availability and pH), site/topographic factors (e.g., big boulders, streams, avalanche tracks) as well as by the composition and growth of the understory vegetation. A NST provides several parameters used to judge the protective function of a forest stand, including the potential natural tree species composition. The naturalness of a forest stand can, therefore, be determined by comparing the observed tree species composition with the "potential," i.e., assumed natural, tree composition of an NST. As the composition of the canopy trees is defined by both, site conditions and former/current management, naturalness might give a good indication of the current and future need for management interventions to ensure optimal forest stability (i.e., high naturalness).

In this study, we used data from the 4th Swiss National Forest Inventory (NFI4; 2009–2017) in combination with information on the current and projected future NST (1) to evaluate the current and projected future naturalness of protective mountain forests, (2) to identify tree species that are accordingly over-, underrepresented or even missing from forest stands where they are expected to prevail and (3) to determine the indicated need for forest management interventions to ensure continued protective function under climate change.

Materials and methods

Idealized natural forest compositions according to NST

In Switzerland the quality of protective forests is evaluated based on the NaiS-System (Frehner et al., 2005). The NaiS-System evolved from the old Swiss forest classification system of Ellenberg and Klötzli (1972) and provides information about the NST, as well as associated minimal or ideal stand requirements for the protective

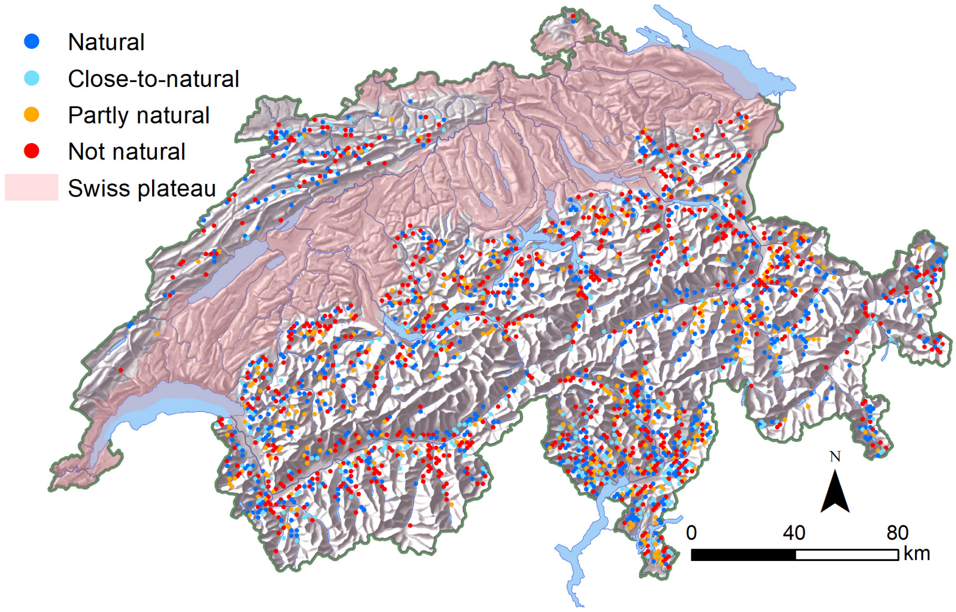

FIGURE 1
Location and calculated current naturalness (i.e., based on $NST_{current}$) of the Swiss National Forest Inventory (NFI) plots located in protective mountain forests.

function (e.g., number of stems, gap sizes, crown length; Frehner et al., 2005). We focused on the NST's assumed natural tree species composition that is indicated by the floristic composition of the herbaceous layer, site quality and structural characteristics. NSTs depict the tree species composition (including recruitment) in an idealized natural forest at the optimum developmental stage that is considered being in balance with the dominant environmental conditions (e.g., climate, topography, soil, canopy closure; Ott et al., 1997; Frey et al., 2021). Currently, there are more than 433 NSTs defined for Switzerland, each with its own potential natural tree species composition. Based on NFI data, 266 of those NSTs are currently recorded in Switzerland and the remaining 167 represent potential new NSTs expected to appear until the end of the century (i.e., according to diverse climate change scenarios; **Supplementary Table 1**; Frehner et al., 2019). These future potential NST were based on the existing NST and extended with potential new better adapted tree species based on species distribution models (Zimmermann et al., 2014), studies about analog climatic regions (Huber et al., 2017), and species range maps (Schütt et al., 2006; for more details see Frehner et al., 2019). All tree species occurring in Switzerland (N = 75, both native and non-native), are assigned to each of these NSTs, following a classification into four categories (a) "dominant tree species of the idealized natural forest," (b) "important supplementary tree species of the idealized natural forest," (c) "additional tree species of the idealized natural forest" and (d) "tree species not part of the idealized natural forest" (**Supplementary Table 1**). Of the 266 NSTs currently observed in Switzerland, 62% are monodominant (e.g., European beech forests), 32% are co-dominated by two species (e.g., silver fir-Norway spruce forests) and only 6% are co-dominated by more than two species (e.g., oak-lime forests). The proportion of future NSTs with more than two co-dominant species is higher (25%), reflecting the uncertainty in potential species composition under future climatic conditions.

National Forest Inventory data (NFI)

The 4th Swiss National Forest Inventory (NFI4; 2009–2017) was recorded on a 1.4 × 1.4 km systematic permanent sampling grid covering the whole forested area of Switzerland (Brändli et al., 2020a). We restricted the data of NFI plots to the perimeter of protective mountain forests delimitation of the cantons according to the federal office of environment (Losey and Wehrli, 2013; **Figure 1**). A terrestrial NFI plot assessment consists of numerous elements (Lanz et al., 2019), of which we used the proportion of all canopy-forming tree species (i.e., species-specific area cover in the canopy layer) of the reference stand (i.e., the stand with the plot centre within the 50 × 50 m interpretation area; Fischer and Traub, 2019), the presence of all woody species in a 200 m^2 circle around the plot centre, and the assigned current and future Natural forest Site Types ($NST_{current}$, $NST_{RCP4.5}$ and $NST_{RCP8.5}$; ARGE Frehner et al., 2020, Frey et al., 2021) covering the plot centre. The $NST_{current}$ was defined by experts for 40% of the NFI sample plots in the field and for 60% of the plots by analogy conclusions using topography and factor maps (ARGE Frehner et al., 2020). The future NSTs were determined based on potential shifts in the vegetation belts, resulting from climate warming (Zischg et al., 2021) in combination with local site factors based on existing ecograms (for more details see Frehner et al., 2019) using the website Tree-App.ch.[1] Future NSTs were projected for 2085 (average of 2070-2099) under global warming scenarios using

1 https://www.tree-app.ch/

two different Representative Concentration Pathways (RCP 4.5 and RCP 8.5) based on the climate projection of MeteoSwiss (CH2018, 2018). Data on the proportion of all canopy-forming tree species was used to infer dominance of species as well as an indication on the availability of seed trees. Data on the presence of woody species was mainly used to determine if a species is present at all, even just as a single seedling. In total, the NFI covered 2,072 plots located in protective forests in mountain regions for which data on the tree species composition and NSTs were available (**Figure 1**).

Naturalness and species composition

The naturalness of a NFI plot was determined by comparing the reported tree species composition of the canopy layer based on NFI data with the natural tree species composition based on the NST of the plot. We distinguished four categories of naturalness: (1) "natural forest," (2) "close-to-natural forest," (3) "partly natural forest," and (4) "not natural forest" based on the criteria of **Table 1**. All these calculations were done separately for $NST_{current}$, $NST_{RCP4.5}$, and $NST_{RCP8.5}$ but always in comparison with the tree species composition observed during the NFI4 (2009–2017). The classification of NFI plots into the four different categories of naturalness is illustrated by several examples in **Supplementary Appendix 1**.

For each NFI plot we determined the tree species that are currently dominant in terms of canopy cover as well as the tree species that should be dominant in an idealized natural forest under current and future conditions ($NST_{current}$, $NST_{RCP4.5}$, $NST_{RCP8.5}$). In addition, we evaluated which tree species are dominant or important supplementary species of the idealized natural forest under current and future conditions but currently missing from the plots. This was calculated (1) based on the canopy cover data (i.e., counting a tree species as absent if not reaching the canopy layer) and (2) based on the presence data of all tree species (i.e., counting a species as present even if present only as a seedling). This allowed us to identify tree species that are under or over-represented in protective forests and to derive the subsequent need for management interventions. The urgency of management intervention might be relatively low, if all predominant tree species of the potential natural forests are present and only their relative portions in the stand need adjustment. Or it might be high, if predominant tree species of the current and future expected natural forest are absent.

Results

Naturalness of Swiss protective mountain forests

Under current conditions, 47% of the NFI plots in protective mountain forests were covered by "natural" or "close-to-natural" tree species compositions while 14 and 39% were classified as "partly natural" and "not natural," respectively (**Figure 1**). Without any adaptations (by natural succession or by management), the proportion of NFI plots with "natural" or "close-to-natural" tree species composition would drop to 28 and 19% until 2085 under global warming scenarios RCP 4.5 and RCP 8.5, respectively (**Figure 2**).

Most NFI plots in protective mountain forests were dominated by Norway spruce [48.7%; *Picea abies* (L.) H. Karst.]. Under current conditions, 48.1% of these Norway spruce dominated NFI plots were considered "natural" or "close-to-natural" (i.e., NST dominated by Norway spruce) and 29.7% "not natural" (**Figure 3**). Other tree species frequently dominating the NFI plots in protective mountain forests were European beech (22.4%; *Fagus sylvatica* L.), silver fir (16.3%; *Abies alba* Mill.), and European larch (15.3%; *Larix decidua* Mill.) which, under current conditions, were considered "natural" or "close-to-natural" in 67.9, 57.8, 19.8, and "not natural" in 17.9, 31.2, 61.5%, respectively (**Figure 3**). Assuming no changes in tree species composition, their naturalness was strongly decreasing under future conditions (**Figure 3** and **Supplementary Figure 1**). In fact, only NFI plots currently dominated by sessile oak (1.25%; *Quercus petraea* Liebl.) and small-leaved lime (0.8%; *Tilia cordata* Mill.) were projected to increase in naturalness under future conditions (i.e., they had a tree species composition better fitting expected future than current site conditions; **Figure 3** and **Supplementary Figure 1**).

Dominant and lacking species in Swiss protective mountain forests

The decrease in naturalness under future climatic conditions corresponded with the expected changes in NSTs of protective mountain forests (**Figure 4**). Currently, protective forests should be dominated by Norway spruce, European beech, and silver fir (**Figure 4**). In the future, the dominance of the most frequent conifers was predicted to strongly decrease while the proportion of European beech dominated NFI plots remained rather constant. Many other broadleaf species were predicted to increase within protective forests, especially oak (sessile oak and pubescent oak; *Quercus petrea* Liebl., *Q. pubescens* Willd.) and lime (*Tilia* spp.; **Figure 4** and **Supplementary Figure 2**).

Norway spruce and European larch were the two most over-represented species (i.e., species dominating NFI plots where other species should be dominant according to the NST) under current and even more so under predicted future conditions (**Figure 5**). In general, the over-representation of conifers was predicted to increase while the over-representation of broadleaf species was rather constant with the notable exceptions of European beech and sweet chestnut (*Castanea sativa* Mill.; **Figure 5**). This indicates that while the proportion of NFI plots dominated by European beech and sweet chestnut are rather constant across time (**Figure 4**), the location of plots dominated by those species will shift in elevation.

Regarding the latest NFI inventory, silver fir and European beech were the two species most frequently absent from NFI plots, even though they would dominate under natural conditions. This held for both, the canopy layer (i.e., seed trees) and in general (i.e., not even a seedling present; **Figure 6** and **Supplementary Figure 5**). In the case of silver fir, the expected presence as dominant species should decrease due to adverse climatic conditions in the future. The importance of European beech will further increase by proportions, as a result of extended suitability toward higher elevations where the species would prevail in

TABLE 1 Overview of the criteria used to evaluate the naturalness of the tree species composition of a forest stand.

	Natural forest	Close-to-natural forest	Partly natural forest	Not natural forest
All dominant species of the NST present in the canopy	X	X	–	–
At least one of the dominant species of the NST makes maximum canopy cover	X	X	X	–
At least one of the important supplementary species of the NST present in the canopy	X	–	–	–
Canopy cover of the important supplementary species of the NST > cover of additional species of the NST	X	–	–	–
Canopy cover of species not part of the NST = 0%	X	–	–	–
Canopy cover of species not part of the NST < 5%	X	X	X	–

NST, Natural forest Site Types.

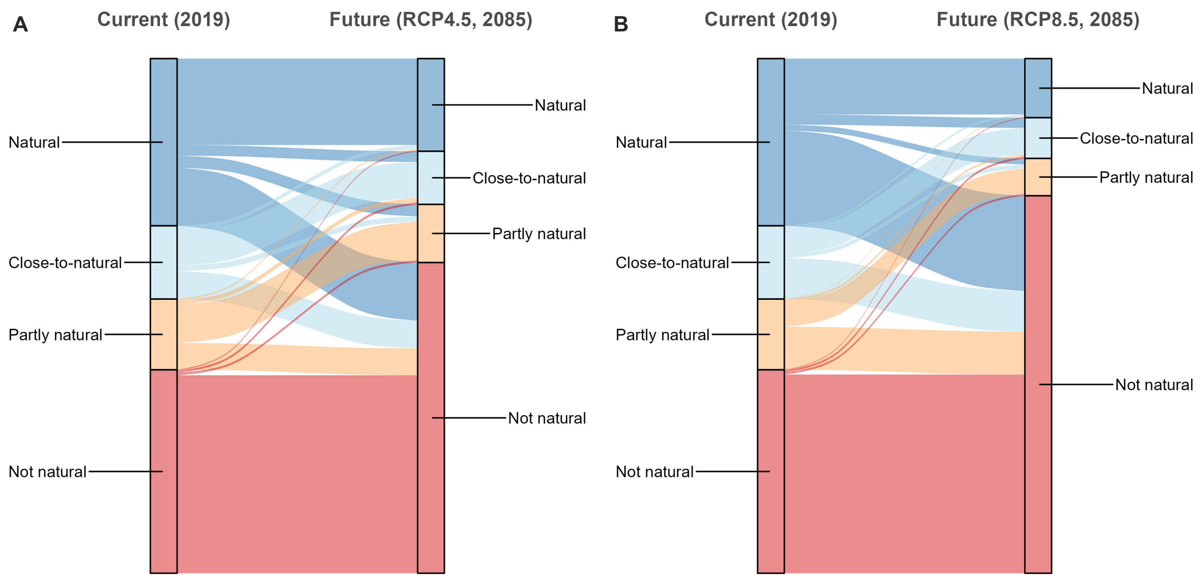

FIGURE 2
Proportions and development of naturalness indices of Swiss National Forest Inventory (NFI) plots in protective mountain forests under current and future conditions using scenarios RCP 4.5 **(A)** and RCP 8.5 **(B)**.

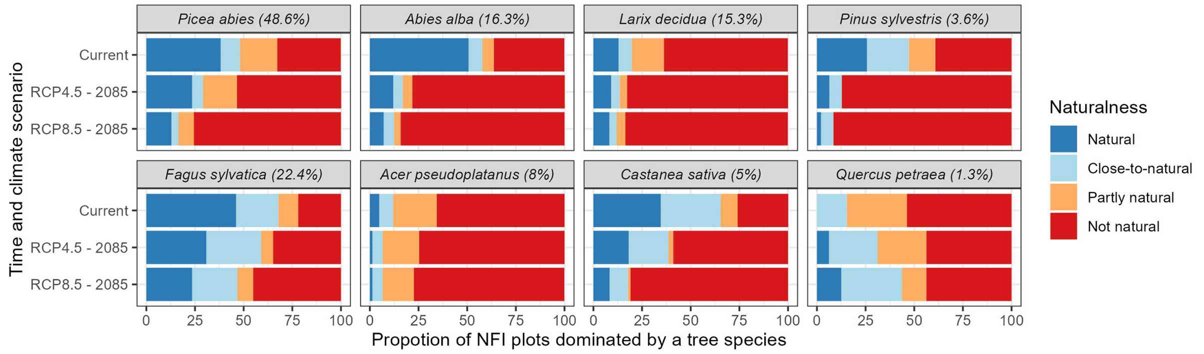

FIGURE 3
Naturalness of National Forest Inventory (NFI) plots dominated or co-dominated by the principal four conifer **(top)** and four broadleaf species **(bottom)** in protective mountain forests under current and future climatic conditions assuming no changes in species composition. The numbers in the brackets indicate the proportion of protection forests currently (co-)dominated by the species.

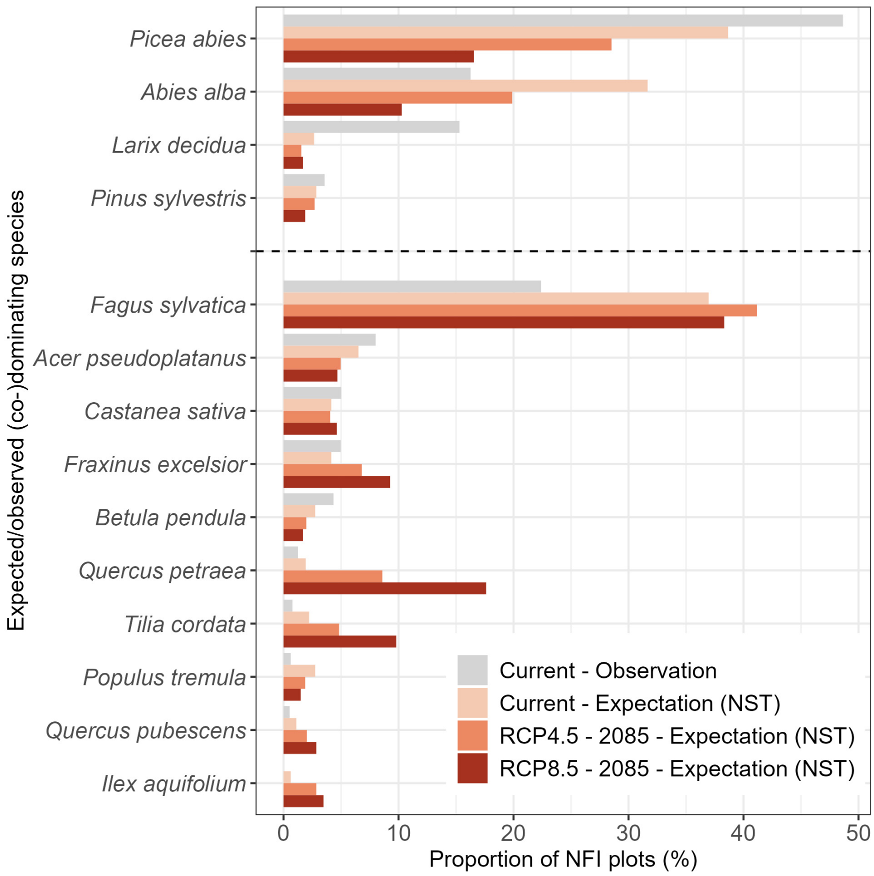

FIGURE 4
Tree species that were currently (co-)dominating the NFI plots in protective mountain forests (gray) or were expected to (co-)dominate based on the Natural forest Site Types (NST) under current and future climatic conditions in 2085 (shades of red). Species are separated into conifers **(top)** and broadleaves **(bottom)**. Only species that (co-)dominated at least 2.5% of the NFI plots in protective mountain forests are shown (for all species see Supplementary Figure 2).

the future but was currently missing in the last NFI inventory (Figure 6). Many broadleaf species such as oak, small-leaved lime, ash (*Fraxinus excelsior* L), holly (*Ilex aquifolium* L.) and sweet chestnut were rarely (co-)dominating, but their importance was predicted to drastically increase under future climatic conditions (Figure 6). These broadleaf species were currently missing from the majority (≥50%) of NFI plots, where they are expected to be present and eventually prevailing under future conditions, according to the $NST_{RCP4.5}$ and $NST_{RCP8.5}$ (Supplementary Table 2).

In the inventory, *Sorbus* spp. (rowan and whitebeam; *Sorbus aucuparia* L. and *Sorbus aria* (L.) Crantz), ash, sycamore (*Acer pseudoplatanus* L.) and elm (*Ulmus glabra* Huds.) were the important supplementary species of the idealized natural forest that were most frequently missing from NFI plots according to the $NST_{current}$ (Figure 7). Under future conditions ($NST_{RCP4.5}$ and $NST_{RCP8.5}$), the species most frequently missing as important supplementary species of the idealized natural forests were projected to be *Quercus* spp. (*Q. petraea*, *Q. robur*, *Q. pubescens*, *Q. cerris*), *Acer* spp. (*A. pseudoplatanus*, *A. platanoides*, *A. campestre*, *A. opalus*), *Tilia* spp. (*T. cordata*, *T. platyphyllos*), wild cherry (*Prunus avium* L.) and ash (Figure 7). Like the dominant species, these future broadleaf species were currently completely missing in the inventories (i.e., not even present as seedlings) where they are expected to be important elements of the future protective mountain forests (Supplementary Table 3).

Discussion

Based on the NFI data, tree species composition of almost 40% of protective mountain forests did not match tree species composition of the potential natural forest ($NST_{current}$). As this mismatch is predicted to further increase with ongoing environmental change ($NST_{RCP4.5,\ RCP8.5}$), many protective mountain forests might pose a risk in regard to reduced stability and higher disturbance susceptibility both potentially undermining their protective function (Elkin et al., 2013; Albrich et al., 2018).

Current and future drivers of naturalness

The two main tree species negatively impacting naturalness due to their over-representation are Norway spruce and European larch, which relates to past management practices favoring these two species for diverging reasons. Norway spruce has been and still is the main timber species used in Switzerland (Bundesamt

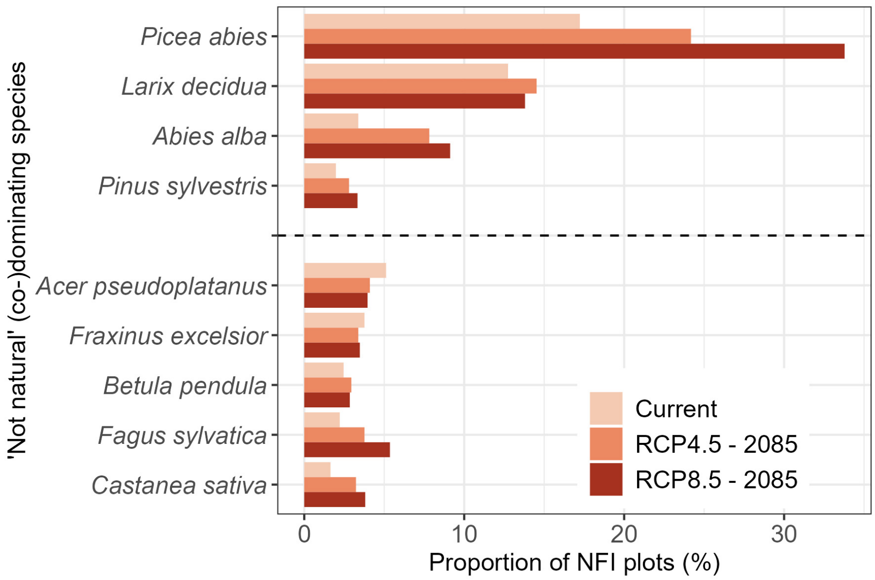

FIGURE 5
Proportion National Forest Inventory (NFI) plots currently (co-)dominated by a tree species not matching the current or future Natural forest Site Types (NST). Species are separated into conifers **(top)** and broadleaves **(bottom)**. Only species mismatches that occurred on more than 2.5% of the NFI plots in protective mountain forests are shown (for all species see **Supplementary Figure 3**).

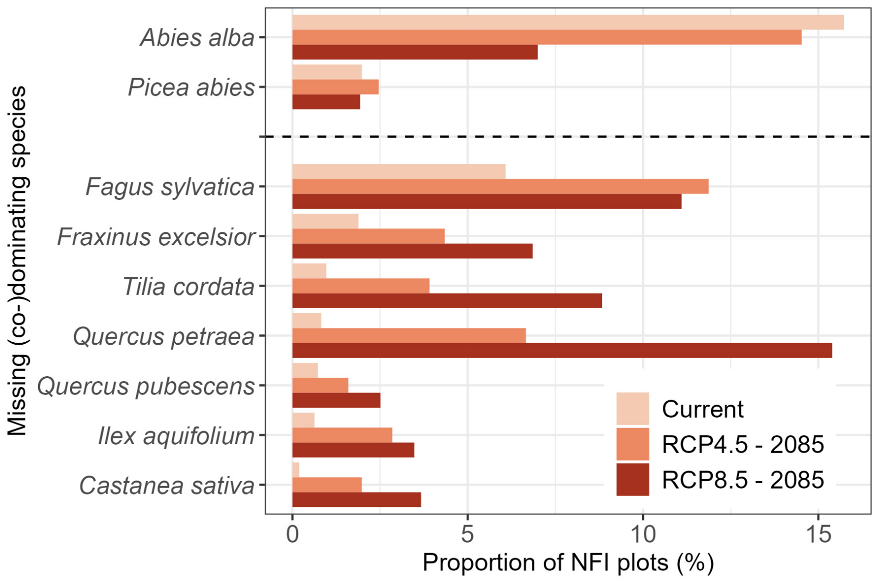

FIGURE 6
Proportion of National Forest Inventory (NFI) plots with canopy layers lacking a tree species that should be (co-)dominating the current or future protective mountain forest stands based on the Natural forest Site Types (NST). Species are separated into conifers **(top)** and broadleaves **(bottom)**. Only species missing from more than 2.5% of the NFI plots in protective mountain forests are shown (for all species see **Supplementary Figures 4, 5**).

für Statistik, 2018; Cioldi et al., 2020). European larch, on the other hand, was for long favored by farmers to create more sunlight forests, i.e., pastured woodland, enabling more productive grazing (Meyer, 1951). As European larch is profiting from high disturbance frequencies (especially avalanches) and lower susceptibility to snow related damages and diseases (Meyer, 1955), it is abundant in abandoned pastured woodlands and in avalanche paths. All conifers, especially Norway spruce and European larch, are projected to have a diminished importance in future protective mountain forests, at the cost of increasingly climate-suitable European beech and other broadleaf species such as oaks and limes. The NSTs projected for the future also suggest an increasing importance of ash and elm. However, ash is heavily affected by ash dieback (Queloz et al., 2017; Enderle et al., 2019) and elm by Dutch elm disease (Karnosky, 1979; Nierhaus-Wunderwald and Engesser, 2003). These two invasive pathogens make it unlikely that ash and elm will increase in proportion unless resistant variants are found, planted, and promoted

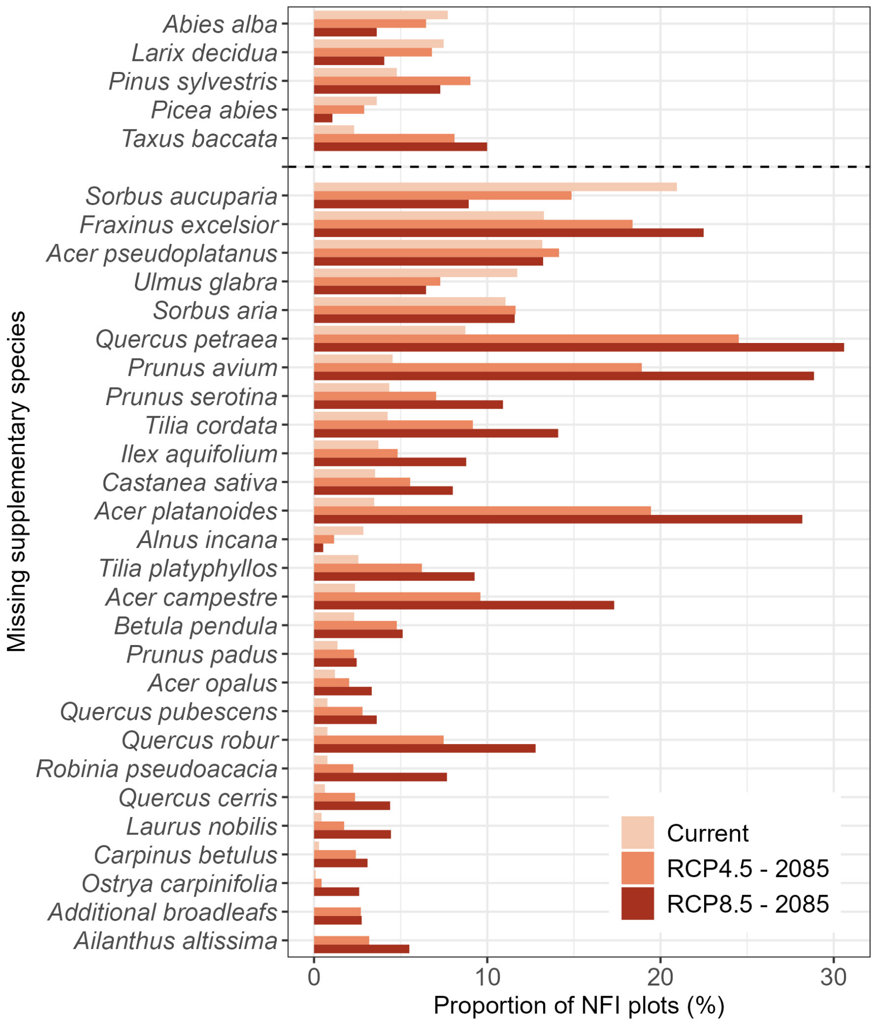

FIGURE 7
Proportion of National Forest Inventory (NFI) plots lacking a tree species that should be an important supplementary element of the current or future protective mountain forest stand based on the Natural forest Site Types (NST). Species are separated into conifers **(top)** and broadleaves **(bottom)**. Only species missing from more than 2.5% of the NFI plots in protective forests are shown (for all species see **Supplementary Figure 6**).

(Smalley and Guries, 1993; Klesse et al., 2021; Martín et al., 2021). Another important broadleaf species hindered by diseases is sweet chestnut (Meyer et al., 2015; Rigling and Prospero, 2018). While sweet chestnut is not expected to increase in overall dominance, the species remains locally important.

With ongoing climate warming, many mountain forest stands ought to transform from conifer to broadleaf dominated to reach equilibrium with environmental conditions (Albrich et al., 2020). The potential future tree species pool ($NST_{RCP4.5}$, $NST_{RCP8.5}$) also includes several neophytes [e.g., *Pseudotsuga menziesii* (Mirb.) Franco, *Ailanthus altissima* (Mill.) Swingle, *Robinia pseudoacacia* L.]. These species are climatically well-suited for the expected future conditions and potentially can contribute to the protective function of forests (Eilmann and Rigling, 2012; Lévesque et al., 2014; Knüsel et al., 2015, 2019). However, these neophytes might be very problematic regarding other ecosystem services such as biodiversity and might therefore not be planted or even actively removed, especially if they are on the blacklist for invasive species (BAFU, 2022). In addition, forests invaded by these exotic species might have a lower protective effect against the prevalent natural hazard (Knüsel et al., 2015; Moos et al., 2019).

Impacts of low naturalness on protective forests

Low naturalness of tree composition directly impacts the main ecosystem service of protective forests, as many criteria used to determine the protective capabilities of a forest against a certain natural hazard (e.g., avalanches, rockfall and landslides), are linked to species mixtures (Frehner et al., 2005). Our study was based on NFI plot data (i.e., maximum 0.25 ha), an area considerably smaller than recommended for the field evaluation (1–1.5 ha) of the protective effects of mountain forests according to NaiS. While this scale mismatch might explain some of the divergences in species composition, it is apparent that many mountain forests show reduced naturalness, especially if assumed dominant tree species of the potential natural forest are not even present in the NFI plots.

Low naturalness might not necessarily indicate insufficient protective function, e.g., if the number of stems and gap sizes are within the desired parameters to protect efficiently against rockfall. However, low naturalness has been shown to increase the susceptibility of forest stands to detrimental disturbances (Scherrer et al., 2023a) disrupting essential ecosystem services especially in conifer dominated stands (Thom and Seidl, 2016; Stritih et al., 2021; Scherrer et al., 2022). In the long-term it is desirable to transform the tree species composition of mountain forest stands to reach a (pseudo-)equilibrium with the environmental conditions. However, this might be challenging for several reasons, especially, if important tree species that should currently or in the future dominate or co-dominate are missing today. With accelerating climate warming the principle of natural regeneration alone is unlikely to be expedient to adapt/transform mountain forests if key species are missing from the seed pool even if favorable micro-sites are generated for the target species (Schönenberger, 2001). Even if those species reach climatically favorable micro-sites they might still fail to establish under current conditions due to biological factors such as competition of existing dominant tree species and browsing (Kupferschmid et al., 2019; Abegg et al., 2020; Scherrer et al., 2020). In fact, it is assumed that the regeneration of current and future key species such as silver fir or oak is mostly hampered due to a high browsing pressure, mainly by deer (Kupferschmid et al., 2015; Abegg et al., 2020). Given the slow growth rates of high elevation forests it is unlikely that species currently only present as single seedlings will rapidly, i.e., within the next decades, develop into stand dominating tree species. As a result of this seed source limitation the missing tree species are often planted to improve recruitment success (Wohlgemuth et al., 2017; Frehner and Plozza, 2018). However, planting of tree seedling considerably increases management requirements and associated costs as these seedlings often need artificial protection from browsing damage by deer.

Continued protective function in a changing environment

Ongoing climate change forces protective mountain forests to adapt (i.e., change their tree species composition) to stay in equilibrium with environmental conditions minimizing the risk of ecosystem failures (Albrich et al., 2018). However, several studies showed that (undisturbed) forests are highly inert to gradual change (Küchler et al., 2015; Scherrer et al., 2020). It means that despite recent climate warming, many undisturbed forests persist in terms of species composition (Küchler et al., 2015; Scherrer et al., 2017), due to asymmetric competition, seed load of the existing dominant climax species (Lenoir et al., 2010; Scherrer et al., 2021) and browsing pressure (Côté et al., 2004; Didion et al., 2009; Cailleret et al., 2014). The aforementioned likely increases the risk of stand level disturbances leading to sudden dieback of large proportions of the stand forming trees (Albrich et al., 2018; Scherrer et al., 2023a). After such a stand-replacing disturbance the tabula- rasa-situation allows for the establishment of adapted pioneer tree species and ultimately will develop toward a new climax forests (Scherrer et al., 2022). However, this succession processes take decades to centuries to reach a new climax state, especially in mountain forests (Schumacher and Bugmann, 2006). While large-scale disturbances and associated temporary loss of certain ecosystem functions might be unproblematic or even beneficial in nature reserves (e.g., Müller et al., 2008), the continued ecosystem service provisioning is the key target for protective mountain forests to reduce socio-economic risks (e.g., Losey and Wehrli, 2013; Teich et al., 2019).

Especially, the combination of the projected over-representation of Norway spruce with accelerated climate warming might prove a major risk factor (Scherrer et al., 2023a). Next to increasing weather extremes, increased temperatures will allow for multiple generations of bark beetles per year, even at high elevation sites, multiplying the pressure on susceptible Norway spruce stands (Stadelmann et al., 2014; Caduff et al., 2022). Once a stand is "destroyed" by a bark beetle attack or wind throw it takes decades before the protective function is restored by natural regeneration and succession dynamics (Schwarz, 2019; Caduff et al., 2022; Moos et al., 2022).The target is therefore a gradual adaptation of the tree species composition in accordance with the environmental change. This might be challenging if forest stands need to be transformed from conifer to broadleaf dominated and if important future tree species are currently absent. In cases where seed trees of important current/future species are missing despite already favorable climatic conditions supplementary planting is advisable to accelerate forests transformation and adaptation. In addition, the browsing pressure needs to be regulated to allow for establishment and natural regeneration of desired tree species to ensure a stable forest in the longer term.

In our view, the concept of naturalness is a useful tool for guiding forest management of protective mountain forests, ensuring continued forest stability (i.e., resilience and resistance). However, the concept has its limitation and numerous other factors must be considered when managing protective mountain forests e.g., the uncertainty of climate projections, potential spread and emergency of pathogens, society driven changes in priorities of ecosystem services.

Furthermore, it remains the question which natural hazards the forests will need to protect against in the future and if the protective effect of the forests will be still the same. While avalanches might decrease with climate warming, landslides and rockfall might increase (Bebi et al., 2016). Climate warming is shifting the suitability of conifer dominated forest to higher elevations, while the objects the forest should protect (i.e., roads or houses), stay in place. The different stand architecture of conifer and broadleaf dominated forests might therefore cause problems to sustainably provide the hitherto large breath of protective functions of conifer forests against natural hazards (e.g., Stokes et al., 2005; Wehrli et al., 2006). Transitioning from evergreen conifers to deciduous broadleaves might be problematic regarding avalanches but broadleaves protect equally or better against rockfall (Berger and Dorren, 2007) and landslides than conifers (Schwarz, 2019). Ongoing research can provide useful information to forest managers about the growth, regeneration, and protective potential of different tree species mixtures and provenances under the expected future conditions. This information should not only be based on model predictions but supported by experimental data from provenance research (e.g., Martínez-Sancho et al., 2021; Wang et al., 2022), climate manipulation experiments (e.g., Schönbeck et al., 2022) and long-terms observations (e.g., Frei et al., 2018; Bogdziewicz et al., 2020).

Data availability statement

The data and R-scripts used in this manuscript are stored in the EnviDat repository (https://www.doi.org/10.16904/envidat.400; Scherrer et al., 2023b). The raw data from the Swiss NFI can be provided free of charge within the scope of a contractual agreement (http://www.lfi.ch/dienstleist/daten-en.php).

Author contributions

DS: methodology, formal analysis, writing—original draft, and visualization. BA and MF: resources, writing—review, and editing. CF: data curation, writing—review, and editing. TW: conceptualization, writing—original draft, funding acquisition, and supervision. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2023.1191639/full#supplementary-material

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