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Article

The Impact of Sanitary Felling During Large-Scale Disturbances on Regulating Ecosystem Services in Norway Spruce-Dominated Pre-Alpine Beech Forests of Slovenia

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Abstract

Ecosystem services (ES) are closely linked to nature-based solutions, which can mitigate the negative impacts of climate change or provide society with direct tangible and intangible benefits. In the context of a changing climate, it is essential to preserve these services despite increasing disturbances. In this study, we analysed changes in the structure and composition of the Jelovica forest complex (NW Slovenia) over the past two decades and assessed the provision of key regulating forest ES—specifically, soil erosion control, regulation of surface and groundwater flows, and regional climate regulation. The area has historically seen the artificial promotion of Norway spruce and, in recent decades, has been increasingly affected by large-scale disturbances and bark beetle outbreaks. We examined how these climate-related disturbances have influenced the availability of regulating ES. Over the past twenty years, the share of spruce in the growing stock in the Jelovica area decreased from 67% to 62%. We compared structural and compositional changes between two periods, 2001–2009 and 2015–2023, based on available forest management data. In both periods, mature stands were the dominant developmental stage. In the northwestern part of the Jelovica plateau, where extensive sanitary felling was carried out, the proportion of sapling stands increased significantly—unlike in other parts of the plateau. Areas affected by extensive sanitary felling exhibited statistically significantly lower evapotranspiration and reduced soil erosion control capacity, as well as higher levels of groundwater recharge, compared to other areas.

Keywords: growing stock; natural disturbances; bark beetles; sanitary felling; regulating ecosystem services; groundwater recharge; evapotranspiration; erosion

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1. Introduction

A forest stand's native, species-rich, and structurally diverse horizontal and vertical composition enhances its resistance to disturbances and disease [1–3]. This is especially relevant in the context of climate change, to which European forests are increasingly exposed. Nevertheless, even today, most forests in Europe are even-aged, and 82% of European forests consist of only one to three tree species [4]. In Central Europe, the volume of sanitary felling is increasing, with the main causes being windthrow, snow and ice breakage, drought, bark beetle outbreaks, and forest fires [5,6]. Forests dominated by Norway spruce (*Picea abies*) outside its natural range are particularly challenging to manage, as they are more vulnerable to disturbances and bark beetle attacks [7–10].

As in Slovenia, beech (*Fagus sylvatica*) and spruce are also the most important tree species in the submontane and montane regions of Central Europe [11]. In Slovenia, over 70% of forests grow on beech, fir-beech, or beech-oak sites [12,13]. Beech is absent from only about one-fifth of Slovenia's forest area—namely, in lowland hydromorphic soils, the Alpine belt and frost hollows, extremely dry sites, and areas where it has been deliberately excluded due to plantations of spruce or other economically desirable species [14]. Only a small portion of spruce-dominated forests in Slovenia are naturally occurring spruce forests [12,14].

As in the rest of Central Europe, spruce was historically planted extensively in Slovenia outside of its natural distribution range. These forests are now heavily affected by disturbances and bark beetle outbreaks [7], which in recent years has led to a national decline in spruce growing stock. After 2020, beech once again became the leading tree species in Slovenia's growing stock, reaching 32%, while spruce fell to second place with 28% [15]. A further significant increase in beech growing stock is expected in spruce-dominated forests, particularly on submontane beech sites [14].

Disturbances such as windthrow, and bark beetle outbreaks have also increased in the spruce-dominated forests of Central Europe in recent decades. These disturbances not only accelerate the decline of spruce but also impair the ability of forests to provide various ecosystem services [16–18]. Recent large-scale assessments show that disturbances are increasingly threatening the ecosystem services provided by forests across Europe [19], reducing the multifunctionality of forests and limiting resilience to further climate change [20,21]. We conducted our analyses in the area of the Jelovica plateau in Slovenia, which is a relevant case study as it is one of the regions of the country most affected by spruce decline [7]. Furthermore, Jelovica is representative of many other Central European regions where spruce monocultures are increasingly vulnerable to climate change driven disturbances [22–24]. With the growing frequency and intensity of natural disturbances driven by climate change [7,25–30], there is a growing need to ensure the long-term availability of ecosystem services (ES) [31–35]. The importance of maintaining forest ecosystem services is highlighted in both the EU Biodiversity Strategy for 2030 [36] and the New EU Forest Strategy for 2030 [37]. Both documents are part of the EU Green Deal policy package, which strengthens the role of ecosystems in the transition toward a climate-neutral economy and the sustainable use of natural resources. In this context, ecosystems and the services they provide play a dual role. They serve as a foundation for nature-based solutions that can help mitigate the negative effects of climate change [38], and they also represent direct tangible or intangible benefits to society—benefits that must be preserved in the face of climate change, despite increasing disturbance [17,39].

This study focuses primarily on the second of these two roles. Its aim is to analyse changes in forest structure and composition over the past two decades and to assess the provision of selected regulating forest ecosystem services in an area where Norway spruce has been heavily promoted and where natural disturbances and bark beetle outbreaks have been particularly severe. In this context, the study links the effects of natural disturbances—driven in part by climate change—to the availability of regulating ecosystem services.

Regulating ecosystem services such as soil erosion control, regulation of surface and groundwater flows and regional climate regulation were selected in this study because they represent important regulating functions in pre-Alpine forests. Erosion control is important for stabilising soils in steep terrain and reducing the risk of landslides [40,41]. Groundwater recharge maintains hydrological balance and regional water supply, which is important in karst areas [42], in which Jelovica is also located. Climate regulation, including carbon storage and microclimate buffering, is important in the context of increasing droughts and heatwaves [43–45]. These regulating ecosystem services are also among the most sensitive to climate change related disturbances, making them suitable indicators of ecosystem integrity in the face of increasing sanitary felling.

2. Materials and Methods

2.1. Study Area Description

The study area is the Alpine karst plateau of Jelovica, located in the northwestern part of Slovenia (Figure 1). It is almost entirely forested. The terrain includes heterogeneous steep slopes on the plateau's edges (elevation ranging from 500 to 1000 m), a broad central section of relatively level terrain at elevations between 1000 and 1400 m, and a smaller southeastern section with varied slopes that increase in steepness toward the Ratitovec massif. Forests cover 15,868 ha, representing 88% of the entire area, while forest cover on the plateau itself reaches as high as 95%.

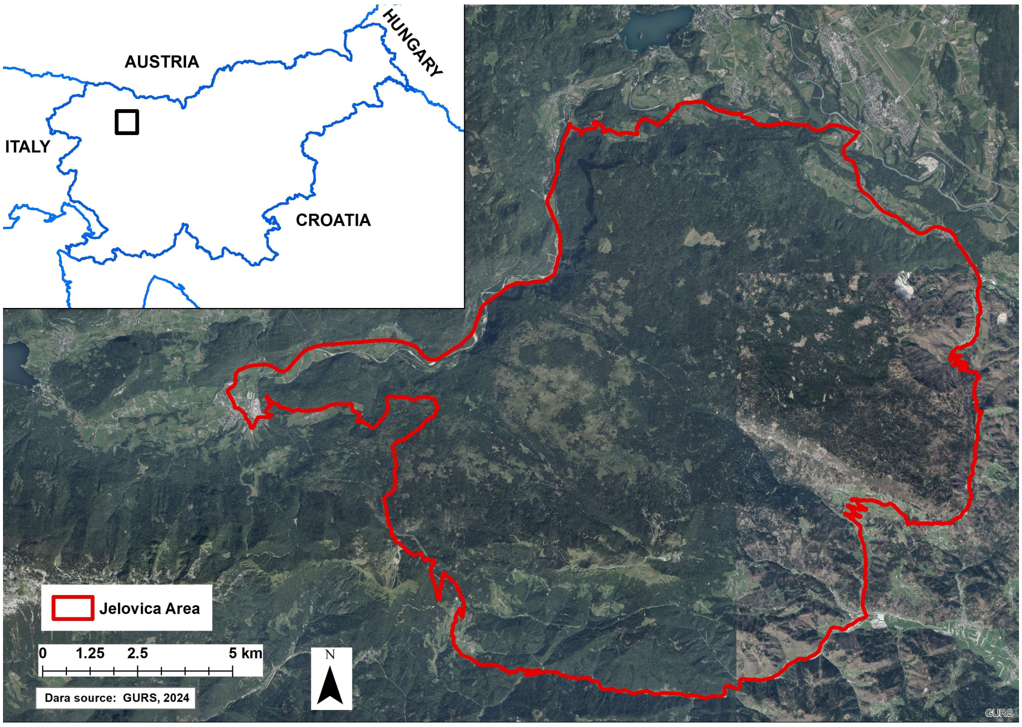


Figure 1. Boundaries of the Jelovica study area.

The plateau is predominantly influenced by an Alpine climate, while its lower margins are affected by a temperate continental climate [46,47]. The geological substrate consists mainly of thick-bedded and dolomitized limestones, with occasional dolomite [48]. Moraines and smaller silicate zones are also present, containing keratophyre, tuff, porphyry, quartz porphyry, and associated pyroclastic rocks with limestone inclusions. The southeastern slopes feature pseudozilite formations composed of dark grey siltstone, aleurolite, clay shale, tuff, and dark grey limestone [48]. The dominant soil type is rendzina, which develops on carbonate bedrock [49]. Rendzina is characterized by a shallow soil profile with limited rooting depth, high proportion of rocky material, and pH is between 5 and 8. Eutric and dystric brown soils occur in the silicate zone [50].

The dominant forest association on the Jelovica plateau is *Homogyno sylvestris–Fagetum*, which occupies 46% of the study area (Figure 2) [51]. This association represents zonal forests of the montane belt in the pre-Alpine phytogeographical region [52]. It occurs at elevations between 900 and 1400 m, and in shady (north-facing) locations can descend as low as 600 m. The dominant tree species in this association are European beech and silver fir, with their relative proportions shaped by forest management practices. Norway spruce is naturally present in small amounts. However, pure spruce stands have also been established on these sites, and they are now characteristic of the Jelovica plateau. Other types of beech forest associations cover an additional 46% of the study area. The only spruce-dominated forest association in the study area is *Sphagno-Piceetum*, which covers just 3% of the forested area. Historically, beech forests were predominant on Jelovica, but they were extensively cleared for charcoal production and ironworking [53] and gradually replaced by predominantly spruce forests. Today, forest stands across nearly the entire plateau are heavily dominated by Norway spruce [47,54].

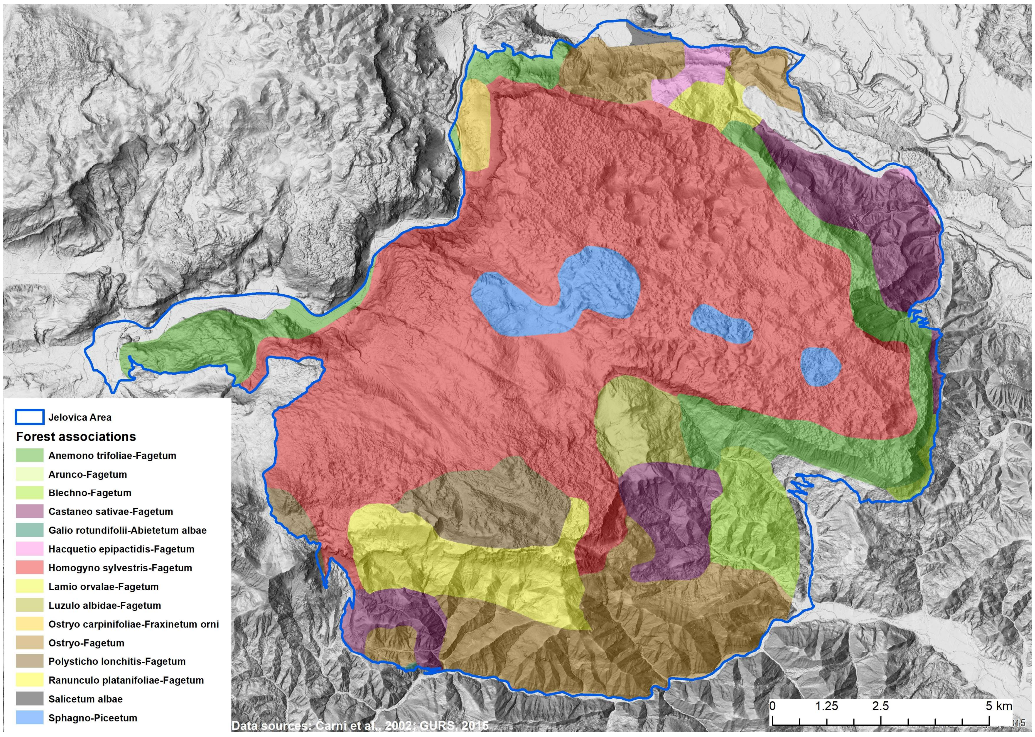


Figure 2. Shaded digital relief model and forest association in the Jelovica area.

2.2. *Growing Stock and Sanitary Felling*

Using the SFS logging database [55], we selected compartments within the study area where sanitary felling was conducted between 2018 and 2023. This database includes information such as felling time, tree species, felling volume, and felling reasons at the compartment scale. In the analyses we only included felling records caused by natural disturbances. For each compartment, we calculated the proportion of sanitary felling relative to the total growing stock [56].

We analysed stand maps from 2009 (first period) [57] and 2023 (second period) [58]. Since the Slovenia Forest Service (SFS) renews forest management plans for forest management units (FMUs) on a ten-year cycle, and the study area spans six FMUs, we included data from 2001, 2002, 2003, 2005, and 2009 in the first period, and data from 2015, 2019, 2021, 2022, and 2023 in the second period (Figure 3).

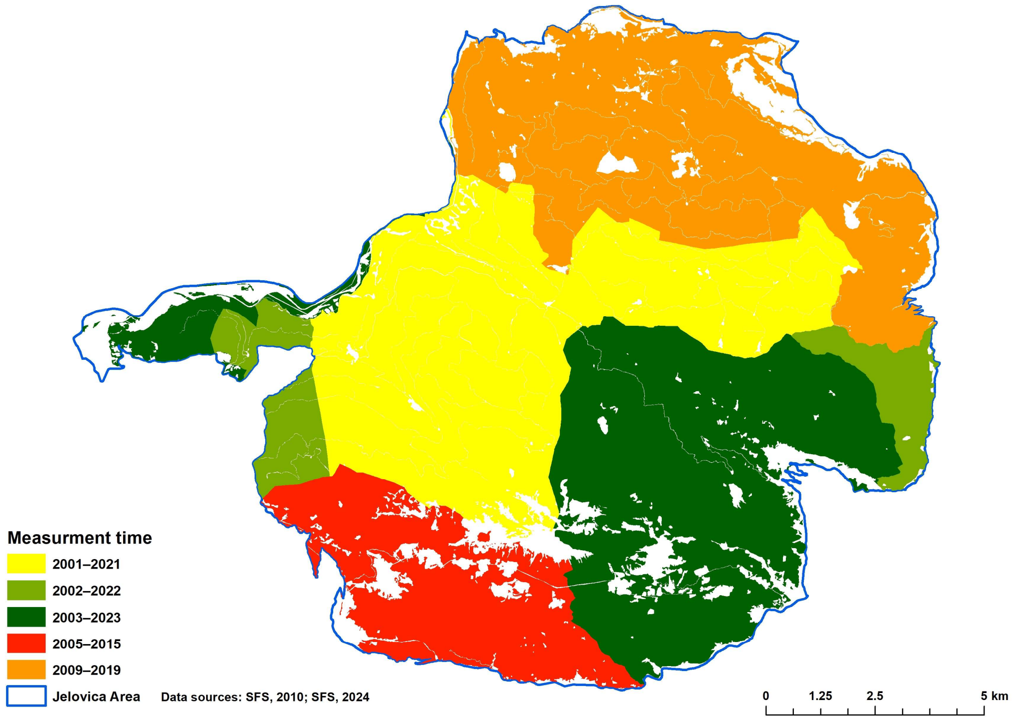


Figure 3. Timing of SFS stand map updates.

In both periods, we analysed the proportions of developmental phases and the composition of the growing stock by dominant tree species, with a particular emphasis on Norway spruce. Differences in the distribution of developmental phases between the two periods were tested using a chi-square test applied to surface areas as an approximation of frequencies.

2.3. Regulating Ecosystem Services

The availability of ecosystem services (ES) was assessed using quantitative indicators. For each of the three ES categories, we defined a single indicator that reflects current ES availability. Each indicator was assessed using the modelling approach deemed most suitable and reliable for that service and for which relevant data were available.

2.3.1. Soil Erosion Control

According to the Common International Classification of Ecosystem Services (CICES) [59], soil erosion control is defined as: *"The ability of vegetation cover to mitigate or prevent (water, wind, gravitational) soil erosion."* The impact of vegetation cover is assessed by comparing the extent of soil erosion under current land use to that under bare-soil conditions. The indicator used for this ES is retained (i.e., prevented) soil erosion, expressed in tons per hectare per year (t/ha/year).

In this study, we focused specifically on water erosion caused by rainfall and did not include other forms such as rill and gully erosion, bank erosion, or snowmelt-driven surface runoff. Rainfall causes erosion by detaching soil particles and transporting them downslope or into water catchment areas. Retained erosion thus represents the amount of soil erosion prevented due to the presence of vegetation, compared to bare soil. The indicator for soil erosion control was calculated for the broader Jelovica area [60] using the RUSLE model (Revised Universal Soil Loss Equation) [61,62]. This model estimates the amount of erosion that would occur under bare-soil conditions and compares it with erosion under current land use, accounting for vegetation cover.

2.3.2. Regulation of Surface and Groundwater Flows

According to the CICES classification [59], this ES is defined as: *"Natural surface and groundwater bodies that serve as sources of drinking water and regulate water flow in terms of the amount of available water that can be used."*

We assessed this ES using the regional water balance model mGROWA with monthly temporal resolution [63,64], developed for Slovenia by the Slovenian Environment Agency. The key input data for the water balance model included meteorological variables (precipitation, potential evapotranspiration, and temperature), land use, topography, geological substrate, soil properties, presence of impermeable surfaces, drainage, and water retention. Meteorological data from the period 1991 to 2020 were used.

The indicator used to assess this ES was the annual groundwater recharge from precipitation (rain, snow, etc.), expressed in millimetres per year (mm/year).

2.3.3. Regional Climate Regulation

According to the generic (and broader) definition from the CICES classification [59], this ES refers to: *"The mitigation of local atmospheric conditions (including micro- and meso-climates) due to the presence of vegetation, thereby improving human living conditions."* We assessed this ES using the indicator of actual average evapotranspiration during the period of full canopy leaf-out (mm). We used the monthly evapotranspiration values calculated with the mGROWA model [63,64] and calculated the average for the period of full canopy leaf-out. The indicator assumes that an increase in relative humidity due to evapotranspiration from vegetation (trees, shrubs, grasses, herbs, etc.) contributes to a decrease in local air temperatures. This is especially relevant during periods of full leaf cover and high summer temperatures. Stronger evapotranspiration is associated with greater cooling effects during heat events.

Previous research [65] has shown a close correlation between evapotranspiration and the leaf area index (LAI). The positive relationship between vegetation cover and the intensity of water loss through leaf stomata and cuticle is a key assumption underlying models of vegetation impact on microclimate. A higher LAI typically results in increased evapotranspiration, higher absolute and relative air humidity, and lower temperatures during the growing season—from late spring through summer and early autumn. This makes it possible to evaluate the contribution of ecosystems to local humidity and temperature regulation.

2.3.4. Comparison of the Availability of Selected Regulating Ecosystem Services in Areas with and Without Sanitary Felling

We examined how sanitary felling between 2018 and 2023 affected the availability of three ecosystem services: soil erosion control, surface and groundwater flow regulation, and regional climate regulation. Specifically, we analysed whether there were significant differences between areas where sanitary felling accounted for 20% or more of the growing stock and areas where no sanitary felling occurred or it represented less than 20% of the growing stock. We considered compartments in which more than 20% of the total stand growing stock had been felled to be severely disturbed. This threshold is not a universal indicator of forest dieback, but a conservative, context-specific criterion. The removal of 20% of the compartments growing stock by sanitary felling represents a structural change in the stand that is similar in scale to the disturbance thresholds proposed in previous studies. In hydrological studies, for example, forest disturbance of more than 20% of area or volume is often identified as the threshold at which ecosystem responses become significant [66–68]. This 20% threshold also closely matches the typical proportion of deadwood found in old-growth or primeval forests, where stand vitality and structural balance are considered stable. Research in the Western Carpathians and South-East Europe indicates that deadwood usually accounts for between 4% and 35% of the total stand volume [69,70]. Therefore, when the proportion of removed or dead volume in managed forests exceeds approximately 20%, it may be considered a disturbance intensity higher than natural mortality levels. Our 20% criterion is therefore a practical threshold to distinguish compartments with normal harvest dynamics from those that have been severely impacted by sanitary felling. That means there are also no naturally regenerated seedlings in these compartments, where seedlings would provide the dominant ground cover.

Since the Jelovica plateau is ecologically relatively homogeneous, we assume that sanitary felling is the primary factor influencing the availability of regulating ES in the study area. To assess differences in the values of the quantitative ES indicators between the two groups (≥20% logging vs. <20% or none), we used three weighted least squares (WLS) linear models, one for each ES. In each model, the dependent variable was the value of the ES indicator (soil erosion reduction, groundwater recharge, or evapotranspiration), and the independent (explanatory) variable was the presence of sanitary felling (coded as 1 for areas with ≥20% logging and 0 for areas with <20% or no logging). Weights were assigned based on the area of each spatial unit (in ha), allowing the models to account for the varying spatial importance of different units. All statistical tests were performed in R version 4.4.1 [71].

3. Results

3.1. Growing Stock and Sanitary Felling

Between 2018 and 2023, sanitary felling accounted for more than 20% of the growing stock on 14% of the forested area in the Jelovica area. More than 60% of all sanitary felling by timber volume was carried out on just 3% of the forested area. On 15% of the forest area, no sanitary felling occurred. The highest concentration of sanitary felling was in the western part of the area—on the plateau of Jelovica—where logging activity was also spatially aggregated (Figure 4). The main causes of sanitary felling were bark beetle infestations, windthrow, and snow damage.

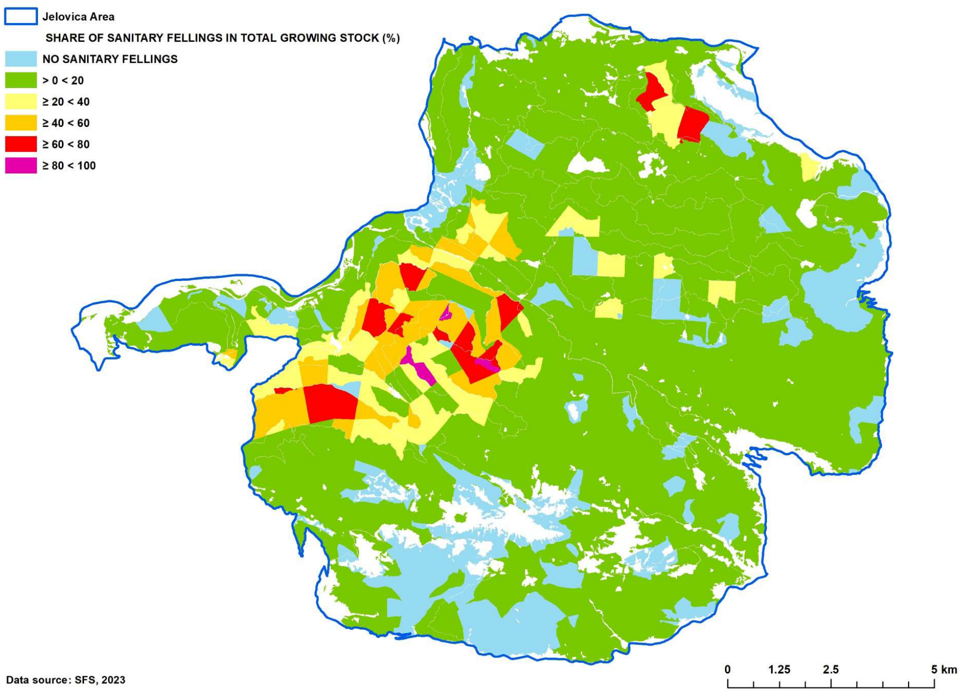


Figure 4. Proportion of sanitary felling in growing stock by forest compartment, 2018–2023.

The distribution of stand development phases differed significantly between the two analysed periods (2001–2009 vs. 2015–2023; $p < 0.001$), indicating a structural shift of development phases (Figures 5 and 6). In both the first and second analysis periods, mature stands were the predominant developmental phase across Jelovica. Nevertheless, their share of the total forest area declined slightly, from 40% to 37%. The shares of uneven-aged stands and pole-stage stands also decreased, while the shares of saplings stands increased from 8% to 14%, and regenerating stands from 15% to 17%. The share of saplings stands increased in a spatially aggregated pattern in the same area where extensive sanitary felling was carried out (the northwestern part of the Jelovica plateau). This led to the formation of larger, contiguous areas of saplings stands.

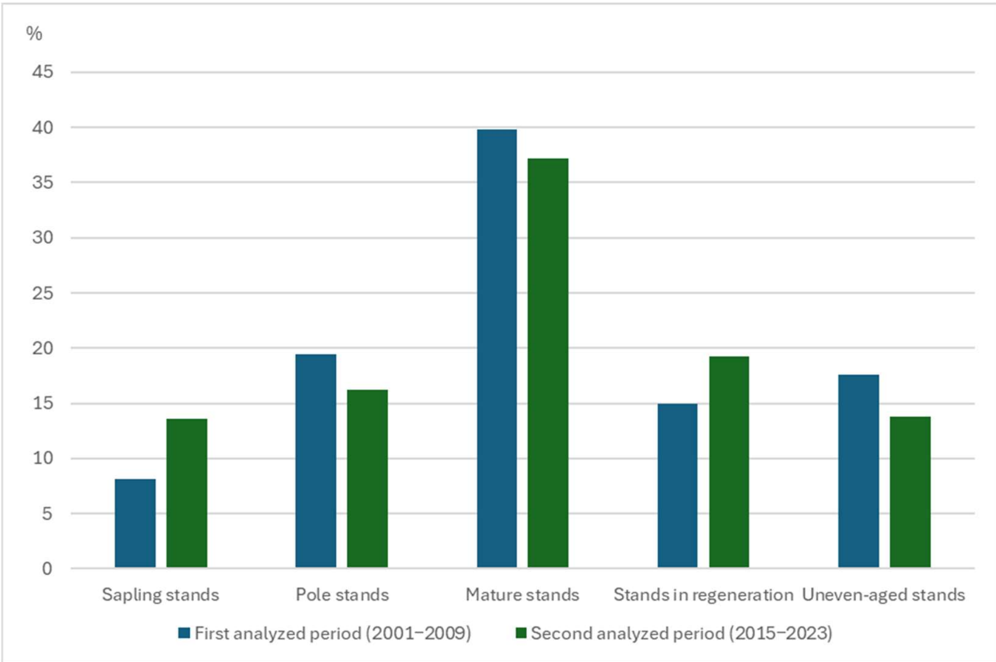
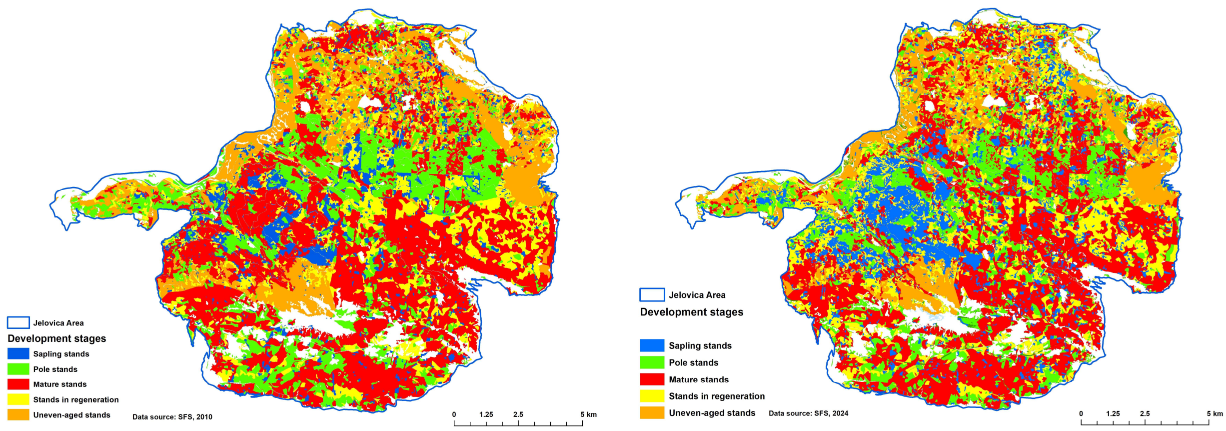


Figure 5. Comparison of developmental phase proportions based on datasets from 2001–2009 (first analysis period) and 2015–2023 (second analysis period).

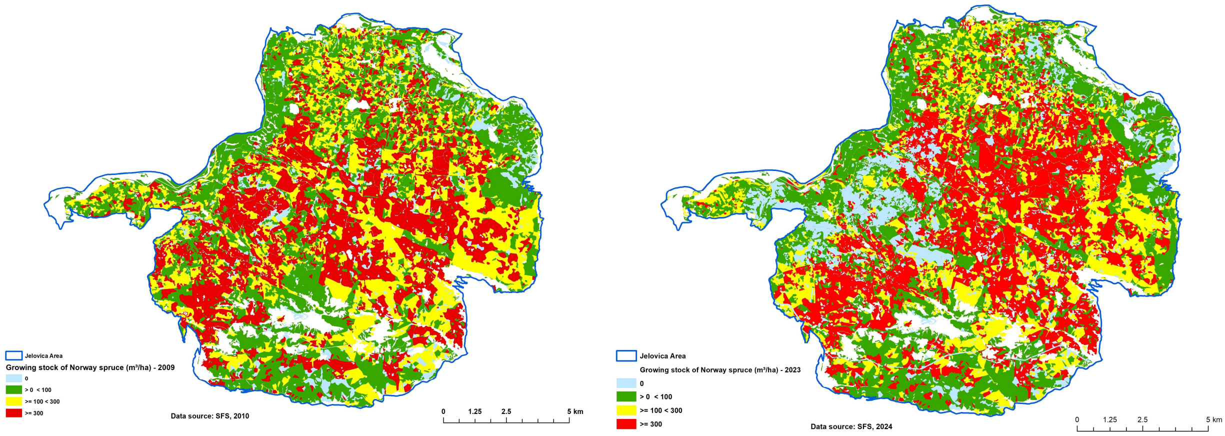


(**a**) (**b**)

Figure 6. Developmental phases in the Jelovica area based on datasets from 2001–2009 (**a**) and 2015–2023 (**b**).

In the first analysis period, Norway spruce strongly dominated the growing stock in Jelovica, accounting for 67%, followed by beech at 20%, silver fir at 8%, and other tree species at 5%. In the second period, spruce remained dominant, but its share declined to

62%, while the shares of beech and silver fir increased to 24% and 9%, respectively. In both analysis periods, the top three tree species made up 95% of the total growing stock. The share of forest area without spruce increased from 6.3% to 12.1% by the second analysis period (Figure 7).



(**a**) (**b**)

Figure 7. Norway spruce growing stock classes by stand, based on datasets from 2001–2009 (**a**) and 2015–2023 (**b**).

3.2. Regulating Ecosystem Services

3.2.1. Soil Erosion Control

The largest share of the area across the Jelovica area (42%) provides soil erosion reduction in the range of 0–2 t/ha per year. The proportion of land with increasing levels of erosion mitigation declines steadily (Figures 8 and 9). Forests with high erosion control capacity are located on the slopes of Jelovica where inclines exceed 40°—in the western, northern, and eastern parts of the area—as well as in the south, where the plateau transitions into the Ratitovec massif (highest peak: 1678 m). The average amount of erosion prevented by forests across the entire study area is 2.3 t/ha per year. In areas where sanitary felling exceeded 20% of the growing stock, the amount of retained (prevented) erosion is 1.3 t/ha per year, which is statistically significantly lower ($p < 0.001$) than in areas where no sanitary felling occurred or where it affected less than 20% of the growing stock (2.5 t/ha per year).

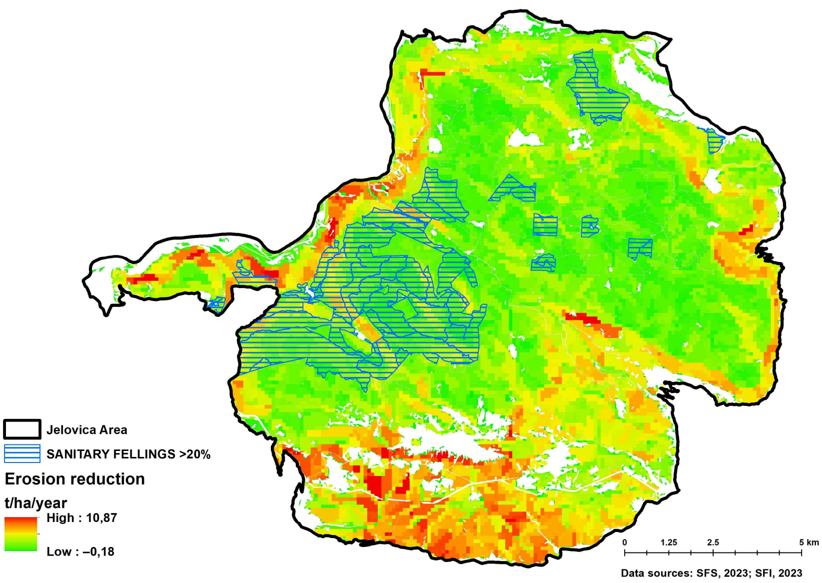


Figure 8. Spatial distribution of the availability of the "soil erosion control" ES in the Jelovica area.

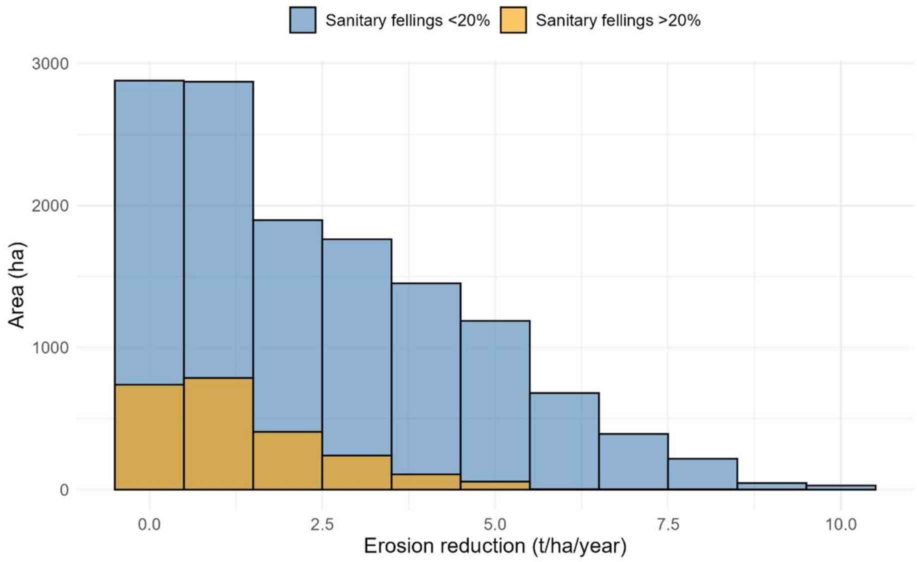


Figure 9. Distribution of soil erosion in areas where more than 20% of sanitary felling was carried out and in areas where no sanitary felling occurred or where it affected less than 20% of the growing stock.

3.2.2. Regulation of Surface and Groundwater Flows

The distribution of ES values for water flow regulation across the entire study area is positively skewed (Figures 10 and 11), meaning that a relatively large proportion of the area shows lower availability of this ES. This is primarily due to the high proportion of mature forests, which retain a substantial share of precipitation in their canopies, where it subsequently evaporates and does not infiltrate into the soil. Areas with high availability of this ES are primarily located in the far western and central-western parts of the Jelovica plateau. The average value of groundwater recharge for the entire study area is 550.5 mm per year. In areas where sanitary felling exceeded 20% of the growing stock, the groundwater recharge value is 681.8 mm per year, which is statistically significantly higher ($p < 0.001$) than in areas where sanitary felling was not conducted or where it accounted for less than 20% of the growing stock (527.6 mm per year).

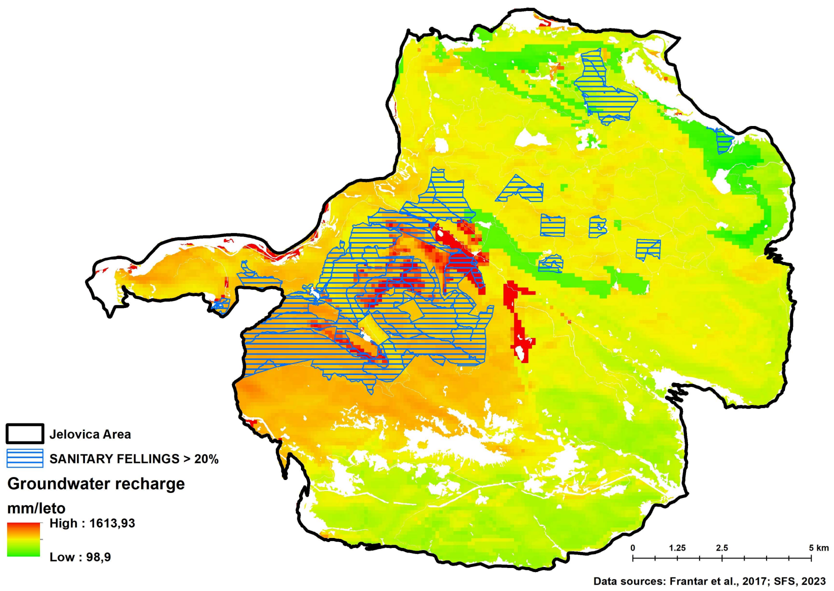


Figure 10. Spatial distribution of the availability of the "regulation of surface and groundwater flows" ES in the Jelovica area.

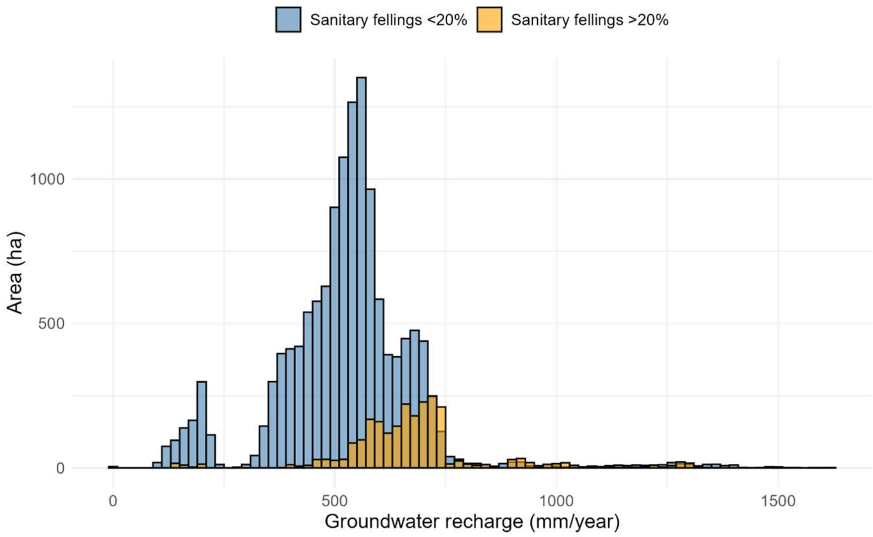


Figure 11. Distribution of groundwater recharge in areas where more than 20% of sanitary felling was carried out and in areas where no sanitary felling occurred or where it affected less than 20% of the growing stock.

3.2.3. Regional Climate Regulation

The availability of the ES related to regional climate regulation was assessed using the indicator of actual evapotranspiration. The distribution of evapotranspiration values across the entire study area reveals two distinct peaks: one around 70 mm (representing 14% of the total area) and another around 100 mm (representing 37% of the area) (Figures 12 and 13). The spatial distribution of areas with varying evapotranspiration values shows that zones with high evapotranspiration are concentrated in the southern part of the study area, and to a lesser extent in the northern, northeastern, and central parts. The average evapotranspiration value across the entire analysed area is 90.3 mm. In areas where more than 20% of the growing stock was affected by sanitary felling, the average evapotranspiration value is 79.6 mm, which is statistically significantly lower ($p < 0.001$) than in areas where no sanitary felling was conducted or where it accounted for less than 20% of the growing stock (92.2 mm).

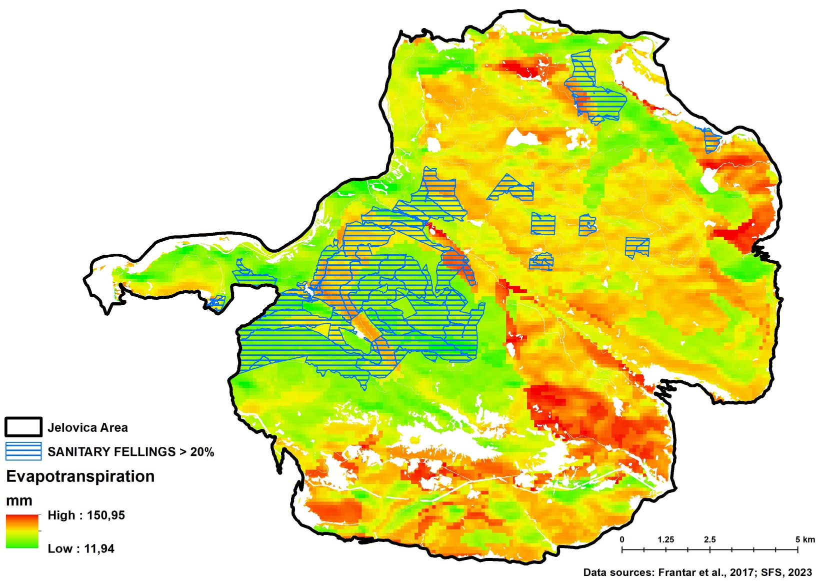


Figure 12. Spatial distribution of the availability of the "regional climate regulation" ES in the Jelovica area.

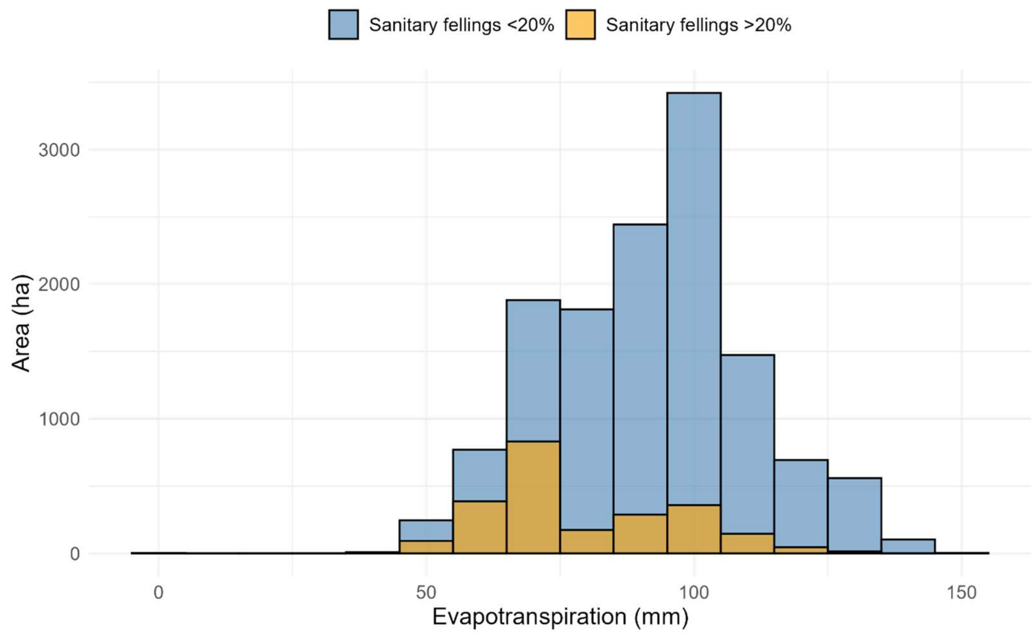


Figure 13. Distribution of evapotranspiration in areas where more than 20% of sanitary felling was carried out and in areas where no sanitary felling was carried out or was less than 20% of the growing stock.

4. Discussion

In this study, we analysed changes in forest structure and composition in the predominantly spruce-dominated forests of the Jelovica plateau, where large-scale windthrow events and bark beetle outbreaks have occurred over the past 20 years. We also assessed how these changes have affected the availability of selected regulating ES: soil erosion control, surface and groundwater flow regulation, and regional climate regulation. The Jelovica area is characterized by beech forest sites; however, beech was almost entirely removed in the past [53]. The occurrence of secondary spruce forests on *Homogyno sylvestris–Fagetum* sites, which dominate the Jelovica plateau, was also documented by [13].

In the area where sanitary felling was spatially concentrated between 2018 and 2023 (the western part of the Jelovica plateau), logging had also been carried out several times over the past two decades, including after the large windthrow event in 2006 [72], and again following smaller windthrows and especially bark beetle outbreaks [47], which have become increasingly frequent in recent years. Prior to this, sanitary felling on the plateau was minimal or virtually non-existent. This is also reflected in the high spruce growing stock and the dominance of large-diameter trees in this area in 2001 (Figures 6 and 7, left).

Over the last two decades, the share of spruce in the growing stock on Jelovica has declined. In the second analysis period, it was 62%, which is still somewhat higher than the average share of spruce in the Alpine ecological region (48.7%) [15], in which Jelovica is located, and in Austrian forests (46.2%) [73], which border the same ecological region.

The decline in spruce growing stock has been spatially dependent. In most areas affected by sanitary felling, spruce has either disappeared completely or remains only in small groups. In other parts of the plateau, however, the share of spruce is still increasing, which further contributes to the vulnerability of these stands. These areas are also dominated by even-aged spruce mature stands and pole stages, which are more susceptible to disturbances and bark beetle outbreaks. Although there was an increase in the area of sapling stands during the study period, this occurred primarily in areas with intensive sanitary felling (Figures 4 and 6). The reduction in the share of pole-stage stands and uneven-aged stands is concerning. In addition to the spatially aggregated increase in sapling stands, the decline in pole-stage stands—from 19% to 16%—is particularly troubling, especially given that the national sustainable forest management model proposes a share of 43% for these stands. A lack of younger developmental stages in Slovenian forests has also been reported by Skudnik et al. [74] and Kušar and Kovač [75]. On the other hand, Jelovica has a higher proportion of uneven-aged forests (14%) than the national target (2%), which is positive in terms of disturbance resistance and resilience. For Jelovica, it would be advisable to promote the development of uneven-aged stands dominated by beech and silver fir [76]. In the face of increasing variability and changing disturbance regimes, O'Hara and Ramage [77] recommend establishing multi-aged stands that include two or more age classes, as they tend to be more resilient to disturbances and recover more quickly. In Central Europe, natural regeneration in unmanaged forests usually takes place in small gaps [78].

Our analysis of differences in ES availability confirmed a link between the extent of sanitary felling—caused by natural disturbances and climate change—and the provision of three regulating ES. These differences are statistically significant and reflect the fact that sanitary felling exceeding 20% of a stand's growing stock affects the benefits people derive from forest ecosystems.

The ability of ecosystems such as forests to retain a portion of precipitation either on vegetation surfaces or in the soil is crucial for facilitating infiltration into deeper soil layers and, eventually, aquifers [79,80]. Ecosystems also act as natural filters, removing pollutants and impurities as water passes through vegetation and sediments. This filtration improves water quality and reduces the need for expensive treatment. Additionally, forests and wetlands store and slowly release water during periods of heavy rainfall or snowmelt, helping to prevent floods and maintain more stable water flows during dry periods. Forests also play an important role in regulating the local and regional microclimate [81]. Trees provide shade, reduce air temperature, and influence humidity in their immediate surroundings [43].

In the area with extensive sanitary felling, we observed statistically significantly lower evapotranspiration and higher groundwater recharge. This can be partly explained by the different geological substrate of this region, which consists of glacial moraine deposits, while other parts of the plateau are dominated by thick-bedded limestone, dolomitized limestone, and dolomite [48]. The reduced evapotranspiration in this area may also be attributed to the complete or partial removal of mature forests, as well as to the different geological characteristics. Lower evapotranspiration and higher groundwater recharge were also observed in mature spruce stands located south of the large sanitary felling area. In these stands, which grow on moraine deposits, hydromorphic soils (which are periodically saturated and poorly aerated) reduce root activity and stomatal conductance, thereby lowering transpiration [82] and overall stand evapotranspiration. In moraine zones, groundwater recharge is typically more diffuse and prolonged [83] compared to other parent materials found on the Jelovica plateau. In the future, special care will be needed in these areas, as spruce stands near existing clear-cut areas on moraine deposits will likely be more vulnerable to disturbances and bark beetle outbreaks. Spruce growing in such areas generally has shallower root systems [84] and is therefore more prone to windthrow than spruce on limestone or dolomite substrates. In areas where forests border harvested sites, the creation of stepped forest edges is recommended [85,86], as this can reduce the risk of future windthrow events, which are often followed by more widespread bark beetle outbreaks [87]. Based on the analysis of ES availability for regional climate regulation and water flow regulation, we can identify areas within Jelovica where the likelihood of future sanitary felling is higher.

Plants and fungi also help stabilize soil and reduce erosion, thereby mitigating or even preventing potential environmental damage [88,89]. Soil erosion is one of the major threats to soils in the European Union [62] and is among the key challenges in sustainable ecosystem management, particularly in agriculture and forestry. In Slovenia, the average soil erosion rate is 7.4 t/ha [62], while forests in Jelovica prevent an average of 2.3 t/ha/year. Our analysis of ES availability for soil erosion control shows that the current land cover structure contributes significantly to erosion mitigation compared to bare soil conditions. Forests on the Jelovica plateau effectively reduce soil erosion on the steep slopes of the plateau, where terrain inclination is most pronounced. In areas with extensive sanitary felling, statistically significantly lower values of soil erosion control were observed. This is primarily due to the fact that most sanitary felling occurred on the plateau, where slopes are gentler. However, even on the plateau, there are micro-locations with steeper terrain and increased erosion risk. The lower erosion control capacity in these areas may also be attributed to the near-total removal of mature trees or the retention of only small groups of trees. The most erosion-prone areas are spruce-dominated forests on steep slopes, which are poorly resistant to disturbances, especially windthrow, which often results in large, exposed surfaces. Natural regeneration after such events is uncertain in these locations, so artificial regeneration through planting should be considered. Selecting appropriate tree species can help prevent further damage and contribute to long-term soil erosion reduction.

Intensive sanitary felling thus negatively affects the availability of the ecosystem services soil erosion control and regional climate regulation. However, we observed a positive relationship between sanitary felling and water flow regulation, as precipitation infiltration into the subsoil is greater on logged sites. This kind of variability is not unusual. Reference [17] in their review of studies on boreal and temperate forests, also found that while disturbances generally have negative effects on most ecosystem services, they can simultaneously have a beneficial effect on habitat diversity and biodiversity. In this context, natural disturbance events can be used as a tool for forest ecosystem restoration [90]. It is clear that forest management—whether as a response to or preparation for disturbance—plays a critical role and can significantly influence the availability of ecosystem services [91], as demonstrated in this study.

Interactions of the effects between disturbances (e.g., bark beetle outbreaks, windthrow or drought) on forest structure, composition and ecosystem services over longer time period are increasingly recognised [17], and integrated analyses that consider their combined effects across extended timeframes are still rare. In practise, however, these multiple disturbance effects manifest together in sanitary felling, which is analysed in the present study.

Similar patterns of disturbance-driven decline in ecosystem services (erosion control and regional climate regulation) have been documented in recent studies showing that increasing disturbance pressure threatens the multifunctionality and resilience of forests [19–21]. By quantifying the impact of sanitary felling on erosion control, groundwater recharge and climate regulation, our case study fills an important gap: Although sanitary felling is becoming more widespread as a management response to cumulative disturbance, its consequences for the provision of ecosystem services have remained insufficiently examined. The Jelovica Plateau therefore provides insights that are not only relevant for Slovenia but can also be transferred to other spruce-dominated mountain regions in Central Europe and beyond.

Our results indicate a strong relationship between the intensity of sanitary felling and reductions in erosion control and climate regulation. This suggests that sanitary felling significantly alters selected regulating ecosystem services once it exceeds about 20% of the compartment's growing stock. In this study we analysed sanitary felling as the primary disturbance indicator because it integrates the combined effects of multiple disturbance agents. Frankly, we acknowledge that other factors—such as the geological substrate or changes in tree species composition—may also contribute to the observed patterns. Therefore, the relationships identified in this study should be considered as robust associations rather than definitive causal relationships. Future research should aim to disentangle the relative contributions of sanitary felling, geological conditions, and changes in tree species composition to the provision of ecosystem services. The inclusion of such covariates in long-term monitoring and modelling of ecosystem services would allow clearer attribution of associated factors and provide better guidance for adaptive forest management in changing disturbance regimes.

Shifts in tree species composition can influence ecosystem services independently of sanitary felling. This is especially true in areas where mature stands are present and will be affected by potential future disturbances. European beech, silver fir, and Norway spruce differ in their water use strategies and soil water dynamics [92–94], furthermore root reinforcement and slope stability are generally stronger under beech communities [95]. These results suggest that some of the observed differences in erosion control, groundwater recharge and climate regulation, especially in mature stands, may be due to species-specific characteristics. In order to improve the provision of selected ecosystem services in future forests established in areas undergoing sanitary felling, it is important to establish forests with a mixed tree composition and a sufficient proportion of deciduous trees (especially beech). A tree composition should be established that is suitable for the site and was already present in the area in the past before spruce monocultures were planted.

5. Conclusions

This study shows that sanitary felling in spruce-dominated forests of the Jelovica Plateau influences the provision of selected regulating ecosystem services. In areas with pronounced sanitary felling we observed a statistically significant reduction in soil erosion control and regional climate regulation with an increase in the regulation of surface and groundwater flows. These results illustrate that sanitary felling can significantly alter forest regulation ecosystem services as a cumulative response to multiple disturbance factors. In order to maintain ecosystem services in Norway spruce-dominated pre-alpine beech forests under increasing disturbance pressure, it is important to reduce the vulnerability of these stands by promoting structurally diverse mixed forests with a sufficient proportion of deciduous trees, especially European beech. The results of this study apply primarily to the Norway spruce-dominated pre-alpine beech forests of the Jelovica plateau and the surrounding forests. However, they are also relevant for other Central European mountain regions and beyond where spruce monocultures have been established. In such areas, similar disturbance patterns and management responses can be expected, and changes in ecosystem services will occur. Future research should aim to disentangle the relative contributions of sanitary felling, geological conditions, and changes in tree species composition to the provision of ecosystem services. More comprehensive comparative studies across larger areas and regions should also improve knowledge about the influence of disturbances on ecosystem services.

This study has two main limitations. First, we analysed sanitary felling as a primary disturbance indicator, assuming ecological homogeneity of the Jelovica plateau. However, some differences in soil, geology and tree species composition may influence the provision of ecosystem services. We have also addressed this in detail in the discussion. Second, the threshold for the removal of 20% of the growing stock in the compartments by sanitary felling as an indicator of severe disturbance is context-specific and is not universally applicable. It would need to be adapted to local conditions in further studies.

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