

Modelling the Long-Term Effects of Climate Change and Silvicultural Systems on Rockfall Protection: A Case Study from the Slovenian Alps

Tine Ferk

University of Ljubljana, Biotechnical Faculty

Gal Fidej

University of Ljubljana, Biotechnical Faculty

Simon Mutterer

Forest Resources and Management, Swiss Federal Institute for Forest, Snow and Landscape Research WSL

Clemens Blattert

Forest Resources and Management, Swiss Federal Institute for Forest, Snow and Landscape Research WSL

Maxime Cailleret

INRAE, UMR RECOVER, Aix-Marseille Université

Janine Schweier

Forest Resources and Management, Swiss Federal Institute for Forest, Snow and Landscape Research WSL

Ulrike Hiltner

Department of Environmental Systems Science, Institute of Terrestrial Ecosystems, ETH Zürich

Andrej Rozman

University of Ljubljana, Biotechnical Faculty

Jurij Diaci

jurij.diaci@bf.uni-lj.si

University of Ljubljana, Biotechnical Faculty

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Abstract

Alpine forests mitigate gravitational hazards such as rockfall, but climate change, natural disturbances, and declining management may threaten their protective function. We simulated forest development under no management, selection management, and shelterwood management, combined with current and projected climate conditions. The forest gap model ForClim simulated stand dynamics over 200 years, with assessments at the 35- and 200-year horizons, and the resulting forest structures were transferred to the rockfall model Rockyfor3D. The study focused on the Ljubelj protection forest in northern Slovenia.

Beech basal area declined under all scenarios. Norway spruce increased under no management under both climate conditions and in managed stands under current climate but declined under management and climate change. Management favoured light-demanding conifers under current climate and light-demanding broadleaves under climate change. During the first 40–60 years, management effects on stand composition exceeded the gradual effects of climate change.

Rockfall kinetic energy was highest without forest and during the initial shelterwood regeneration period. After 200 years, shelterwood provided the strongest mean protection among future management scenarios but also produced the highest local peak energies, indicating spatially and temporally uneven protection. Selection and no management provided similar mean protection after 200 years, although initial protection declined without management and improved under selection management. Climate change did not alter the relative ranking of management strategies. Selection management provided the most temporally stable long-term protection. Because ForClim did not explicitly simulate disturbance events, the projected decline in protection under no management was probably underestimated.

1. Introduction

Mountain forests in the European Alps provide essential protection against gravitational hazards, including rockfall (Dorren et al. 2004a). Climate change may enhance forest protective functions at higher elevations but reduce them at lower elevations through drought stress, forest decline, and intensified disturbances (Mina et al. 2017a; Bebi et al. 2017; Moos et al. 2023). At the same time, climate warming may increase gravitational activity, further challenging the long-term provision of protection (Stoffel et al. 2024). Among gravitational hazards in the Alps, rockfall poses a recurrent threat to settlements and transport infrastructure (Dorren et al. 2007).

Maintaining or enhancing protective capacity is a central management objective, yet mountain forest management is often constrained by steep slopes, limited accessibility, and trade-offs among ecosystem services (Thrippleton et al. 2023; Blattert et al. 2024). In many mountain regions, declining management intensity associated with land abandonment and limited economic viability has contributed to stand ageing and growing-stock accumulation, with potential consequences for stand stability and disturbance regimes (Kräuchi et al. 2000; Bebi et al. 2017; Mantero et al. 2020). Non-management may benefit carbon storage, deadwood-related biodiversity, and some regulating services in the absence of major disturbances (Seidl et al. 2019), while also avoiding the immediate reductions in protective capacity associated with intensive harvesting (Moos et al. 2023). However, passive stand development may respond too slowly to rapidly changing environmental conditions, and disturbance susceptibility may increase where ageing results in structurally vulnerable stands (Jandl et al. 2019; Mohr et al. 2024). In the absence of management, stand development may proceed through successive phases of canopy-tree mortality, gap formation, and regeneration, resulting in temporal variation in stand density and diameter structure (Mayer and Ott 1991; Nygaard et al. 2018). In contrast, systems maintaining continuous canopy cover, such as selection management, have been proposed as effective for sustaining rockfall protection (Kräuchi et al. 2000; Frehner et al. 2005; Rammer et al. 2015). These contrasting views on the effects of management highlight the need to evaluate how different management approaches influence long-term forest structure and protective capacity under current and future climate conditions.

Much of the established knowledge on Alpine protection-forest dynamics and management originates from conifer-dominated mountain forests (Ott et al. 1997; Kräuchi et al. 2000; Hillebrand et al. 2023). This knowledge has informed practical guidelines for assessing and managing protection forests (Frehner et al. 2005). However, the relative merits of

active management and non-management remain debated because management decisions involve trade-offs among long-term protection, biodiversity, carbon storage, and other ecosystem services (Seidl et al. 2019; Moos et al. 2023; Blattert et al. 2024).

Forest protection under climate change depends not only on stand structure but also on species composition. Norway spruce (*Picea abies* (L.) H. Karst.), one of the dominant tree species in Alpine protection forests, is expected to experience increasing drought stress and disturbance-related mortality, particularly at lower and warmer sites (Seidl et al. 2017; Hillebrand et al. 2023; Fischer et al. 2025). In many cool and humid mountain forests, European beech (*Fagus sylvatica* L.) may gain a competitive advantage relative to Norway spruce, although its response will depend on local site conditions, drought intensity, and management. Under stronger warming, however, the competitive position of beech may also weaken, potentially favouring more thermophilous broadleaved species (Bugmann 1997; Thurm et al. 2018). Silvicultural systems can influence these compositional shifts by altering stand density, light availability, regeneration conditions, and the removal of particular diameter classes or species groups (Rasche et al. 2011). Understanding the combined effects of climate change and silviculture on future species composition is therefore essential for assessing the long-term stability of protection forests.

Addressing these challenges requires a multidisciplinary perspective integrating forest ecology, climate science, natural-hazard research, and forest management. Long-term assessments must link models of stand regeneration, growth, and mortality with models of hazard processes and protective effects (Wehrli et al. 2006; Hiltner et al. 2025). The climate-sensitive forest gap model ForClim simulates long-term stand dynamics under alternative silvicultural treatments (Rasche et al. 2011; Huber et al. 2020), while Rockyfor3D simulates three-dimensional rockfall trajectories and tree–rock interactions based on terrain, block, surface, and forest properties (Dorren, 2024; Noël et al. 2023).

In practice, forest management planning commonly operates over relatively short planning periods, typically about ten years in Slovenia, and relies partly on expert judgement (FMP 2025; Kajdiž et al. 2015). However, the effects of climate change and silvicultural interventions on forest structure and protective functions unfold over several decades or even centuries. Coupling forest-dynamics and hazard models can complement conventional planning by enabling the systematic evaluation of long-term effects under alternative management and climate scenarios (Wehrli et al. 2006; Woltjer et al. 2008). Such integrated modelling is therefore important for assessing how silvicultural strategies influence the persistence and temporal stability of protective functions beyond conventional planning horizons.

Although several studies have coupled forest-dynamics and rockfall models (Wehrli et al. 2006; Rammer et al. 2010), few long-term assessments have compared contrasting silvicultural systems under climate change, particularly in beech-dominated forests of the south-eastern Alps. Beech-dominated stands can provide effective rockfall protection because stem diameter, wood properties, and stand density determine the frequency and energy-dissipation capacity of tree–rock interactions (Dorren and Berger, 2006; Stokes et al. 2005). These functional differences among tree species are represented in Rockyfor3D through contrasting energy-dissipation parameters. However, managing beech-dominated stands on steep terrain is operationally demanding, and harvesting productivity is generally lower than in coniferous stands; cable yarding may therefore be particularly important at such sites (Latterini et al. 2023). This combination of potentially strong protective capacity and difficult management creates a need to assess how alternative silvicultural systems affect the long-term protective function of these forests.

This study addressed these knowledge gaps through a case study in a Slovenian Alpine protection forest. Specifically, we aimed to (1) assess long-term changes in forest composition and structure under selection, shelterwood, and no-management scenarios and under current and projected climate conditions using ForClim; (2) evaluate how the simulated changes in forest structure and composition influence rockfall dynamics by coupling ForClim outputs with Rockyfor3D; and (3) compare the effectiveness and temporal stability of the three silvicultural strategies in maintaining long-term rockfall protection. We hypothesized that (i) climate change would accelerate the decline of Norway spruce; (ii) unmanaged stands would exhibit greater long-term fluctuations in density and diameter structure because stand renewal would depend on

mortality, gap formation, and natural regeneration; and (iii) selection management would provide more temporally stable long-term rockfall protection than shelterwood management or non-management by maintaining continuous canopy cover and a more continuous distribution of protective stems over time.

2. Materials and methods

2.1. Study site

The study site is located above the Ljubelj Pass, an important mountain crossing between Slovenia and Austria, within the Tržič Forest Management Unit of the Kranj Forest Management Area (Fig. 1). The protection forest covers approximately 75 ha and lies between 980 and 1,500 m a.s.l. The prevailing forest associations are *Anemono-Fagetum* and *Adenostylo-Fagetum* according to the Zürich–Montpellier phytosociological classification (Zorn, 1975).

The morphologically diverse terrain includes ridges, steep colluvial slopes, and torrent channels that influence rockfall trajectories. The area lies on carbonate bedrock, and rockfall release areas occur mainly at lower and middle elevations, with fewer sources along the upper ridge (Fig. 1). Climate data from nearby weather stations indicated a mean annual temperature of 6.9°C and mean annual precipitation of 1,518 mm for 1980–2012. Mean monthly temperatures ranged from –2.2°C in January to 15.9°C in July, and June was the wettest month, with 169 mm of precipitation (FMP, 2025).

The stands were predominantly mature, with an average growing stock of 535 m³ ha⁻¹ and a mean canopy height of approximately 26 m. European beech accounted for 65% of the growing stock and Norway spruce for 24%. Other species exceeding 1% included silver fir (*Abies alba* Mill.), sycamore maple (*Acer pseudoplatanus* L.), European larch (*Larix decidua* Mill.), European ash (*Fraxinus excelsior* L.), and common whitebeam (*Sorbus aria* L.).

For analysis and presentation, European beech, Norway spruce, and silver fir were treated individually. European larch and Scots pine (*Pinus sylvestris* L.) were grouped as light-demanding conifers, whereas all deciduous species other than European beech were grouped as light-demanding broadleaves. The latter group consisted primarily of sycamore maple, European ash, grey alder (*Alnus incana* (L.) Moench), common hazel (*Corylus avellana* L.), and rowan (*Sorbus aucuparia* L.).

The site was historically managed at low intensity, with selective cutting near forest roads and two strip regeneration cuttings using cable yarding in the western part. The occurrence of older Norway spruce trees with deep crowns suggests that parts of the site were formerly more open and influenced by forest management and grazing before the Second World War. The current occurrence of Norway spruce may therefore partly reflect historical land use and earlier successional conditions.

2.2. Field measurements

Forest structure and species composition were assessed in 2022 on 52 circular sample plots of 400 m², systematically distributed over the accessible forest area using a 75 × 75 m sampling grid (Fig. 1). Potential locations on roads, precipitous terrain, or other non-forested and inaccessible sites were not inventoried. All trees with DBH > 1.27 cm, corresponding to the minimum size represented in ForClim, were identified by species and measured for DBH. Tree heights were measured for a subset of trees.

The 2022 inventory was used to initialize the long-term ForClim simulations. For consistency with the 1991–2020 climate reference period, management schedule, and calendar years used in the simulation outputs, 2020 was designated as the model reference year. The stand structure recorded in 2022 was used as an approximation of the initial condition in 2020. The two-year difference was considered minor relative to the 35- and 200-year assessment horizons. Accordingly, simulation years 35 and 200 corresponded to the model years 2055 and 2220.

Natural regeneration was assessed in two 1.5 × 1.5 m subplots positioned at the northern and southern intersections of the plot circumference with the north–south transect through the plot centre. Juvenile trees were identified, counted, and

classified into four height classes: ≤ 20 cm, 21–50 cm, 51–130 cm, and > 130 cm up to a DBH of 1.27 cm.

For Rockyfor3D parameterization, active rockfall release areas were identified and mapped. Geological substrate and representative block dimensions were recorded for each release area (Fig. 1).

2.3. Model descriptions

2.3.1. ForClim

Future forest development was simulated using ForClim v4.0.1, an individual- and cohort-based forest gap model (Huber et al. 2020). ForClim simulates tree establishment, growth, and mortality on independent forest patches at an annual time step. Trees with similar characteristics are represented as cohorts, enabling the model to simulate long-term changes in stand structure and species composition with relatively low computational requirements.

Tree establishment and development are influenced by light availability, temperature, soil-water availability, nitrogen availability, and stochastic demographic processes. Tree growth and survival are also determined by species-specific characteristics, including maximum tree dimensions, crown properties, and tolerance to shade and drought (Botkin et al. 1972; Bugmann 2001; Huber et al. 2020). The model can represent alternative silvicultural interventions through a management submodel and is therefore suitable for comparing the long-term effects of climate and management on forest development (Rasche et al., 2011).

ForClim has been evaluated across a wide range of environmental conditions, including managed European mountain forests, and has been applied to assess long-term forest responses to climate change and silvicultural management (Didion et al., 2011; Mina et al., 2017b; Huber et al., 2020). Because model performance depends on local site conditions, stand structure, and the selected model configuration, an additional local evaluation was conducted for the Ljubelj study site, as described in Section 2.4.2.

As with other forest gap models, ForClim provides a simplified representation of forest dynamics. It does not explicitly resolve fine-scale spatial interactions among individual tree crowns or detailed physiological processes such as tree hydraulics. The model configuration used in this study represented background mortality but did not explicitly simulate disturbance events such as windthrow and bark-beetle outbreaks. Consequently, long-term projections, particularly those for unmanaged stands, were interpreted as comparative scenario trajectories rather than deterministic predictions of future stand conditions.

2.3.2. Rockyfor3D

Rockfall propagation was simulated using Rockyfor3D v5.3 (Dorren 2024), a process-based model that calculates three-dimensional rockfall trajectories over spatially explicit terrain. The model simulates free fall, rebound, rolling, and sliding according to local topography, surface characteristics, and vegetation conditions (Bozzolo and Pamini 1986; Dorren et al. 2004b; Dorren and Berger 2006).

The principal model inputs include a digital elevation model, the location of rockfall release areas, block dimensions and shape, substrate type, surface roughness, and forest structure. Forest effects are represented through tree density, DBH distribution, tree locations, and the relative representation of coniferous and broadleaved trees. These variables influence the probability and consequences of interactions between falling rocks and tree stems.

Rockyfor3D has been widely applied in Alpine environments because it combines a spatially explicit representation of rockfall propagation with computational efficiency. Nevertheless, the model necessarily simplifies complex interactions among rocks, soil, surface roughness, topography, and vegetation. In the present study, Rockyfor3D was used to compare rockfall kinetic energy and block passage frequency among forest-management and climate scenarios rather than to

conduct a comprehensive assessment of risk, which would additionally require explicit information on exposure, vulnerability, and potential consequences.

2.4. Simulation setup

2.4.1. ForClim parameterization and model-variant selection

The long-term simulations comprised 300 independent forest patches of 800 m². Initial stand conditions were derived from the 2022 forest inventory described in Section 2.2. Because the inventory plots covered 400 m², tree numbers from each selected plot were scaled by a factor of two to represent an 800-m² ForClim patch. The 52 inventory plots were sampled with replacement to generate 300 initial patches. This procedure preserved the observed variability in stand composition and structure while providing sufficient replication for the stochastic simulations.

The simulations were restricted to tree species recorded in the 2022 inventory. Consequently, the model represented the development of the locally established species pool but did not account for the future immigration of tree species not currently present at the site. Species-specific growth, establishment, and mortality parameters followed the parameterization implemented in ForClim v4.0.1 (Huber et al. 2020). These parameters were not modified to force agreement with the observed abundance of individual species.

Climate data for model parameterization were obtained from the Slovenian Environment Agency for the 1991–2020 reference period, using gridded climatic indicators at a spatial resolution of 1 × 1 km for the Ljubelj site (longitude 14.2629628° E, latitude 46.4346126° N; ARSO, 2022). Soil water-holding capacity was estimated from vegetation maps and refined using field observations. It was represented in ForClim by a bucket size of 12 cm.

Alternative regeneration configurations available in ForClim v4.0.1 were compared using the available field information on regeneration and stand structure as a reference. Model variant 21 was selected because it provided the most plausible representation of regeneration and subsequent stand development under local site conditions (Huber et al. 2020). The selected configuration was applied consistently in all climate and management scenarios.

The 2022 regeneration inventory was treated as a temporally specific reference rather than as an exact calibration target. An earlier inventory at the same site recorded a greater representation of Norway spruce regeneration (Kajdiž et al. 2015), indicating temporal variability in regeneration composition. Accordingly, field regeneration data supported the selection and interpretation of the regeneration configuration, but species-specific parameters were not adjusted to reproduce a single inventory year. The short-term performance of the selected ForClim configuration was additionally assessed through a ten-year local evaluation, as described in the following section.

2.4.2. Local evaluation of ForClim

ForClim v4.0.1 was locally evaluated over the ten-year interval between the 2012 and 2022 forest inventories. The model was initialized with the stand recorded in 2012 and run for ten years using the selected local configuration. The simulated condition was then compared with the 2022 inventory.

Because harvesting occurred between the inventories but was not included in the simulation, recorded removals were added to the 2022 inventory values. Harvest records covered three forest compartments totalling 59.19 ha and provided the number of harvested trees by species and 5-cm DBH class for trees with DBH ≥ 10 cm. Harvest-adjusted empirical values were calculated for tree density, total basal area, basal area of trees with DBH ≥ 7 cm, mean DBH, and species-specific basal area. Dominant DBH and height could not be adjusted because harvested trees could not be assigned to individual plots.

Relative differences were calculated as $100 \times (X_{\text{simulated}} - X_{\text{empirical}}) / X_{\text{empirical}}$, using harvest-adjusted values where available. The adjustment did not account for removals below 10 cm DBH, foregone growth or mortality of harvested trees, or harvest-related effects on residual-tree growth. The evaluation assessed the plausibility of short-term stand development under the selected ForClim configuration rather than validating the long-term projections. Detailed comparisons between

simulated, observed, and harvest-adjusted stand attributes are provided in Appendix A. The regeneration data used as supplementary information in selecting and interpreting the model configuration are summarized in Appendix B.

2.4.3. Climate and management scenarios

Future climate projections for 2061–2080 were obtained from WorldClim 2 and based on the CMIP6 CNRM-CM6-1-HR model under SSP5-8.5 (Fick and Hijmans, 2017). Monthly differences between projected and baseline WorldClim values were applied to the 1991–2020 ARSO climate data to reduce model bias. SSP5-8.5 was selected to examine an upper-range climate response under the relatively cool and humid conditions of the study site.

Three management strategies were simulated. No_M represented stand development without intervention. Sel_M gradually transformed the predominantly mature, even-aged stand towards a negative exponential diameter distribution by reducing basal area by approximately $5 \text{ m}^2 \text{ ha}^{-1}$ per intervention until reaching a target of approximately $30 \text{ m}^2 \text{ ha}^{-1}$. Subsequent decadal harvests returned basal area towards the target level. Shel_M included preparatory cuttings of 10% every ten years, a 20% seed cut, and a final removal cut in 2050, during which trees with DBH > 15 cm were removed. The 120-year cycle was repeated, with a seed cut in 2160 and final removal cut in 2170 (Rasche et al. 2011; FMP 2025).

Scenarios were assessed at two complementary horizons. The 35-year horizon captured the first major structural divergence among management strategies and the initial shelterwood regeneration phase. The 200-year horizon captured repeated interventions, long-term compositional changes, and a second shelterwood regeneration phase; a 100-year simulation would not have encompassed the complete 120-year shelterwood cycle. The long-term simulations were interpreted as comparative trajectories rather than predictions for specific future years.

All management strategies were simulated under constant and changing climate. Because differences between climate conditions were minor at the 35-year horizon, only the climate-change scenarios were transferred to Rockyfor3D at this horizon. Both climate conditions were included at the 200-year horizon, resulting in nine future forest scenarios.

2.4.4. Rockyfor3D

To evaluate the effects of the simulated forest structures on rockfall protection, stand attributes from the nine future forest scenarios were transferred from ForClim to Rockyfor3D. Mean values from the final 30 simulated years preceding each assessment horizon were used as inputs, thereby representing prevailing stand conditions rather than forest structure in a single simulation year. The transferred attributes included tree density, mean DBH and its standard deviation, and the conifer share of stand basal area (Table 1).

Because ForClim does not provide geographic coordinates for individual trees, an artificial tree grid was generated from the stand-level attributes following the procedure implemented in Rockyfor3D (Dorren, 2024). The generated forests reproduced the average density, diameter distribution, and conifer proportion of each scenario, but not the actual fine-scale spatial arrangement of trees. This simplification is particularly relevant to Sel_M, in which small-scale structural heterogeneity is an important stand characteristic.

The nine future forest scenarios were supplemented by two reference conditions: the initial forest condition and a no-forest scenario, resulting in eleven Rockyfor3D scenarios (Fig. 5). The influence of trees on rockfall trajectories primarily depends on tree density, DBH, tree position, and the capacity of tree stems to dissipate kinetic energy, which differs between coniferous and broadleaved trees (Dorren and Berger 2006; Stokes et al. 2005).

Following Dorren (2024), the study area was divided into polygons characterized by slope angle, terrain position, substrate properties, surface roughness, and the properties of the dominant rock fragments. Terrain positions were classified as rockfall release, transition, or deposition zones. Rock fragments were represented as rectangular blocks with dimensions ranging from 0.1 to 0.5 m and a random volume variation of $\pm 10\%$.

Substrate types were classified as deep fine material (> 100 cm), shallow fine material (10–100 cm), forest roads, coarse scree or talus, asphalt roads, or bedrock. Surface roughness was characterized by three obstacle-height classes measured perpendicular to the slope, corresponding to encounter frequencies of 70%, 20%, and 10%. Bedrock density was set at 2,700 kg m⁻³ for limestone and 2,800 kg m⁻³ for dolomite.

A digital elevation model with a spatial resolution of 2 × 2 m, derived from post-2014 LiDAR surveys, was used to represent the terrain (Cekada and Bric, 2015). All spatial input data were formatted as raster files with a cell area of 4 m². Each scenario was simulated with 500 runs and an initial fall height of 5 m. Terrain, substrate, surface roughness, rock-release, and block parameters were kept constant across scenarios, while forest attributes varied according to the corresponding ForClim outputs.

2.5. Data analysis

Rockfall protection was evaluated using the mean maximum kinetic energy per raster cell along the analysed Ljubelj Pass road section (Fig. 1). Cells with zero energy under all scenarios were excluded. The mean number of blocks passing through each cell was used as a supplementary indicator.

Differences among scenarios were tested using the Friedman test because the same road cells were evaluated under each scenario and kinetic-energy values were positively skewed. Road cells were treated as blocks and scenarios as repeated treatments. Significant tests were followed by all-pairs Nemenyi comparisons. Lower mean ranks indicated lower kinetic energy and stronger protection.

An overall test compared all eleven scenarios. Management strategies were additionally tested separately for (i) the 35-year horizon under climate change, (ii) the 200-year horizon under climate change, and (iii) the 200-year horizon under constant climate. Separate analyses avoided treating observations from the two developmental horizons as independent temporal replicates. Pairwise comparisons from the overall analysis were also used to compare corresponding management strategies under constant and changing climate at the 200-year horizon. Statistical significance was evaluated at $p < 0.05$. All statistical analyses were conducted in R version 4.5.1 (R Core Team, 2025).

3. Results

3.1. Simulated long-term changes in stand structure

The ten-year local evaluation showed reasonably close agreement between simulated and empirical stand conditions, with differences generally ranging from 6 to 13% across the principal structural and species-level attributes (Appendix A). Dominant DBH showed particularly close agreement.

In the subsequent long-term simulations, basal area trajectories differed primarily among management strategies, while the effects of climate became more pronounced towards the end of the simulation period (Fig. 2). Under No_M, basal area gradually increased, although the rate of increase declined towards the end of the simulation. No_M generally maintained the highest basal area, with the difference among management strategies being most pronounced under climate change. By the end of the simulation, basal area was higher under climate change than under constant climate for all three management strategies, with increases ranging from 3% under Sel_M to 25% under Shel_M. Basal areas under Sel_M and Shel_M remained below that of the existing forest in 2020 (Fig. 2).

Under Sel_M, basal area initially decreased as the mature, predominantly even-aged stand was gradually transformed towards the target selection structure. Once the target basal area had been reached, decadal harvesting returned basal area towards approximately 30 m² ha⁻¹ after each intervention, resulting in relatively stable long-term basal area (Fig. 2).

Diameter distributions followed contrasting trajectories among management strategies. No_M produced marked temporal shifts associated with recruitment, growth, and mortality; Sel_M gradually approached the target negative exponential

diameter distribution; and Shel_M generated abrupt structural changes following regeneration cuttings and subsequent stand development (Fig. 3 and Appendix C). The general structural trajectories were similar under constant and changing climate conditions.

The aggregated initial DBH distribution reflected structural heterogeneity among the inventory plots, combining a pronounced modal component associated with the mature, predominantly even-aged cohort and a declining component arising from younger cohorts and more uneven-aged stand conditions. Under No_M, the diameter distribution gradually shifted towards larger diameter classes, reflecting an increasing proportion of medium- and large-diameter trees. Recruitment became more pronounced after approximately 100 years, coinciding with a decline in the frequency of trees in the larger diameter classes (Fig. 3a).

Under Sel_M, recruitment occurred earlier than under No_M (Fig. 3b). Thereafter, the diameter distribution maintained a relatively stable, declining shape consistent with the target selection structure. Under Shel_M, recruitment occurred earliest, approximately 30 years after the start of the simulation, and regeneration cuttings caused more abrupt changes in diameter structure than under No_M or Sel_M (Fig. 3c). Following the final shelterwood removal cut in 2170, which removed all trees with DBH > 15 cm, only trees with DBH < 10 cm remained because the simulated stand contained no trees in the 10–15 cm class. The corresponding DBH distribution is therefore not shown.

The management and climate scenarios also produced contrasting changes in tree species composition (Fig. 4). Beech basal area decreased under all scenarios, with the greatest declines occurring in the managed stands under constant climate. Norway spruce basal area increased under both No_M scenarios and under Sel_M and Shel_M under constant climate but decreased markedly in the managed scenarios under climate change.

Silver fir remained a minor component of the simulated stands. Its basal area increased slightly under No_M and Sel_M under constant climate but decreased under all three management strategies when climate change was included. Light-demanding conifers increased under all scenarios, with the largest increases under Sel_M and Shel_M under constant climate. Light-demanding broadleaves decreased under No_M and Shel_M under constant climate but increased under the remaining scenarios. Overall, management favoured light-demanding species relative to No_M. Under constant climate, this shift mainly favoured light-demanding conifers, whereas under climate change it favoured light-demanding broadleaves (Fig. 4).

3.2. Simulated protective effects of future forests against rockfall

The stand structures transferred to Rockyfor3D differed substantially in tree density, mean DBH, DBH variability, and conifer proportion (Table 1). At the 200-year horizon under climate change, tree density was highest under Shel_M, intermediate under Sel_M, and lowest under No_M. Despite having the lowest tree density, No_M had the largest mean DBH and the greatest DBH variability. Under Sel_M and Shel_M, climate change resulted in higher tree density and lower mean DBH than under constant climate. Under No_M, climate change resulted in slightly lower density and a higher mean DBH. Climate change also reduced the proportion of conifers under all three management strategies, with the largest reductions occurring under Sel_M and Shel_M.

Table 1

Forest stand attributes of the initial reference condition and the nine future forest scenarios used as inputs to Rockyfor3D at the 35- and 200-year assessment horizons. Simulated forest attributes represent mean values over the final 30 simulated years preceding each assessment horizon.

Management strategy	Year	Climate scenario	Tree density (stems ha ⁻¹)	Mean DBH (cm)	Standard deviation of DBH (cm)	Conifer share of basal area (%)
Initial forest condition (Ref.) in 2020 ¹	2020	constant climate	1132	26	13	22
No management	2055	climate change	671	40	18	33
Selection system	2055	climate change	514	30	15	21
Shelterwood system	2055	climate change	18	11	1	81
No management	2220	climate change	547	38	37	42
Selection system	2220	climate change	926	22	14	5
Shelterwood system	2220	climate change	1277	20	8	5
No management	2220	constant climate	565	35	35	50
Selection system	2220	constant climate	801	24	14	70
Shelterwood system	2220	constant climate	1365	18	6	94

¹ The model reference condition for 2020 was represented by the forest inventory conducted in 2022.

The no-forest reference scenario had the highest simulated rockfall kinetic energy, whereas the existing forest in 2020 provided the strongest protection among all scenarios (Fig. 5). The Friedman test indicated significant differences in mean maximum kinetic energy among the eleven scenarios ($\chi^2 = 1214.4$, $df = 10$, $p < 0.001$). The post hoc Nemenyi test showed that the no-forest scenario had a significantly higher mean rank, and thus higher kinetic energy, than every forested scenario. Shel_M under climate change after 35 years had the second-highest mean rank. In contrast, the existing forest had the lowest mean rank and provided significantly stronger protection than all simulated future management scenarios under both constant and changing climate conditions (Appendix D).

Because the two assessment horizons represented different stages of stand development, management scenarios were also analysed separately after 35 and 200 years. The 35-year horizon represented the early regeneration phase under Shel_M, while the 200-year horizon represented the long-term outcomes of the simulated management trajectories. Separate Friedman tests were conducted for the 35- and 200-year scenarios under climate change and for the 200-year scenarios under constant climate (Table 2). All tests indicated significant differences among scenarios ($p < 0.001$), and the separate analyses supported the same general conclusions regarding differences among management strategies.

After 35 years under climate change, all three pairwise comparisons among management scenarios were statistically significant. No_M had the lowest kinetic energy, followed by Sel_M, whereas Shel_M had the highest kinetic energy because of the marked reduction in tree density during its regeneration phase (Figs. 5 and 7). Kinetic energy under Shel_M approached the values obtained in the no-forest reference scenario.

After 200 years under climate change, Shel_M had the lowest mean kinetic energy, followed by Sel_M and No_M. The difference between Sel_M and No_M was not statistically significant (Table 2). The same ranking occurred under constant climate, with no significant difference between Sel_M and No_M. However, despite its lower mean kinetic energy after 200 years, Shel_M produced the highest local peak values of maximum kinetic energy under climate change at both assessment horizons (Fig. 7). Pairwise differences between corresponding management strategies under constant and changing climate conditions were not statistically significant (Appendix D).

The number of simulated rocks passing through each cell produced results broadly consistent with those based on mean maximum kinetic energy. Under constant climate, No_M ranked ahead of Sel_M for this supplementary indicator, but the difference between the two scenarios was small.

Table 2

P-values from the post hoc Nemenyi pairwise comparisons following three separate Friedman tests of the management scenarios at the 35-year horizon under climate change, the 200-year horizon under climate change, and the 200-year horizon under constant climate. Scenario abbreviations follow Fig. 5.

Sel_M_35_CC	No_M_35_CC	Sel_M_35_CC	No_M_CC	Sel_M_CC	No_M	Sel_M		
	< 0.001	/	Sel_M_CC	0.0780	/	Sel_M	0.4200	/
Shel_M_35_CC	< 0.001	< 0.001	Shel_M_CC	< 0.001	< 0.001	Shel_M	< 0.001	< 0.001

The Rockyfor3D output for No_M under climate change after 200 years illustrates the spatial distribution of rockfall trajectories and mean maximum kinetic energy across the study area (Fig. 6). This scenario is presented as a representative example of the spatial outputs used to compare management scenarios. The map covers the same terrain as Fig. 1 and identifies locations along the analysed section of the Ljubelj Pass road that were exposed to the highest simulated rockfall energies.

The longitudinal distribution of mean maximum kinetic energy along the analysed road section revealed marked spatial variation (Fig. 7). The largest differences among scenarios occurred between approximately 250 and 500 m and between 1350 and 1600 m along the transect, where the highest kinetic energies were also recorded. These sections indicate locations where forest protection was weakest and where the potential need for supplementary technical protection should be evaluated.

4. Discussion

4.1. Climate change and long-term stand dynamics

The three management strategies generated distinct long-term trajectories of stand structure and species composition. Under Sel_M, the initial predominantly even-aged stands were gradually transformed towards the target selection structure, which was reached after approximately 70 years. This timescale is consistent with practical experience and previous studies of the conversion of even-aged stands to selection forests (Schütz 2001b; 2002; Hilmers et al. 2020). Once the target structure was established, decadal interventions maintained basal area and diameter structure relatively close to their target levels.

The management algorithms did not directly favour particular tree species, but species-specific responses emerged through differences in shade tolerance, establishment, growth, and competition. By reducing stand basal area and increasing light availability, active management favoured light-demanding species relative to No_M, consistent with the importance of light competition in forest gap models (Bugmann 2001). Under constant climate, this response mainly favoured light-demanding conifers, whereas under climate change light-demanding broadleaves increased more strongly, consistent with projected climate-related shifts in tree-species suitability towards more thermophilous species (Thurm et al. 2018; Fu et al. 2024).

Management and climate change thus interacted in shaping long-term species composition. By promoting regeneration and modifying competitive conditions, active management may accelerate climate-driven shifts towards more drought-adapted broadleaved species (Moos et al. 2021).

The first hypothesis, that climate change would accelerate the decline of Norway spruce, was supported under the two active-management scenarios but not under No_M, where spruce basal area increased under both climate conditions (Fig. 4). This increase should not be interpreted solely as evidence of abundant future spruce regeneration because basal-area development also reflects the growth, survival, and gradual transition of trees already present at initialization.

Norway spruce regeneration was limited in the 2022 inventory (Appendix B), but an earlier inventory at the same site recorded a greater representation of spruce regeneration (Kajdiž et al. 2015). This difference indicates that a single regeneration inventory provides a temporally specific snapshot and may not adequately represent recruitment over the much longer periods considered in the simulations. Temporal variation in seed production, canopy conditions, microsite availability, browsing, and establishment success may all contribute to differences among inventory years. The historical occurrence of grazing and more open forest conditions may also help explain the current presence of older spruce and its role during earlier stages of forest succession.

Nevertheless, the projected persistence and increase of spruce under No_M remain uncertain. Local conditions, including steep colluvial slopes and the land-use and successional history of the site, may constrain spruce establishment in ways that are only indirectly represented in ForClim. Previous Alpine modelling studies have generally predicted succession towards beech-dominated forests under comparable conditions (Bugmann 1997; Wohlgemuth et al. 2006), while maritime influences may additionally restrict the distribution of Norway spruce in parts of Dinaric and south-eastern Alpine Slovenia (Horvat et al. 1974; Klopčič et al. 2017; Mina et al. 2017b).

Forest models, including ForClim, may also underestimate tree mortality during and after extreme drought events. In a recent multi-model comparison, most models failed to reproduce the high drought-related mortality observed in Norway spruce, despite capturing drought-related reductions in forest productivity (Fischer et al. 2025). The simulated increase in spruce under No_M should therefore be interpreted as a scenario-dependent trajectory of gradual stand development rather than as a precise prediction of future regeneration or episodic dieback.

Differences among management strategies emerged earlier than differences between the climate scenarios, indicating that management may exert a stronger influence on stand structure and species composition during the next 40 to 60 years. This temporal pattern reflects the immediate effects of harvesting on stand density, light availability, and regeneration conditions, whereas climate-related compositional changes generally develop more gradually. The long-term influence of climate nevertheless became increasingly apparent, particularly through contrasting responses of light-demanding conifers and broadleaved species.

The larger basal area simulated under climate change may reflect the positive effects of warmer conditions and a longer growing season at this relatively cool and humid mountain site. Forest responses to warming vary regionally: lower-montane and drought-prone Alpine forests may undergo substantial structural and compositional changes, whereas some subalpine forests may benefit from rising temperatures and a longer growing season (Bugmann, 1997; Hillebrand et al. 2023). However, this result reflects the gradual climate effects represented in ForClim and does not account for abrupt losses caused by extreme drought, windthrow, or bark-beetle outbreaks (Bebi et al. 2017; Seidl et al. 2017; Fischer et al. 2025). The simulated increase in basal area should therefore not be interpreted as evidence that future climatic limitations or disturbance effects will be negligible.

The simulated DBH trajectories were consistent with general patterns reported in previous evaluations of ForClim in Swiss mountain forests (Risch et al. 2005; Wehrli et al. 2005). These trajectories illustrate the slow pace of structural development in mountain forests and the long periods required to transform regular stands into irregular target structures (Ott et al. 1997; Schütz 2001a; 2001b). Once established, Sel_M maintained a relatively stable, declining diameter distribution. In contrast,

Shel_M produced abrupt structural changes associated with regeneration cuttings, whereas No_M showed successive phases of stand ageing, decline in larger diameter classes, and increasing representation of smaller trees.

The development under No_M supports the second hypothesis that unmanaged stands would exhibit structural dynamics distinct from those regulated by silvicultural interventions. Although basal area changed relatively little during parts of the simulation, the underlying diameter structure varied substantially as recruitment, growth, and mortality altered the relative representation of diameter classes. These changes illustrate why basal area alone is insufficient for evaluating long-term stand development and suggest that unmanaged forests may undergo periods of reduced structural continuity even when total growing stock remains comparatively high.

4.2. Long-term changes in the protective effects of forests managed with different silvicultural systems

The implications of simulated stand development for rockfall protection were assessed by coupling ForClim outputs with Rockyfor3D. Tree density and stem diameter are important determinants of rockfall protection, although their relative importance varies with block size and stand conditions. Larger stems can dissipate more kinetic energy during impact, whereas high stand density increases the probability that a falling rock encounters a tree (Dorren and Berger 2006; Dorren et al. 2007; Wehrli et al. 2006). The blocks simulated in this study were relatively small, with maximum dimensions of approximately $0.5 \times 0.3 \times 0.3$ m. Together with the short forest transition zones between release areas and protected infrastructure, this may explain why tree density was particularly important and why differences among scenarios were comparatively modest (Kajdiž et al. 2015).

Rockyfor3D incorporated tree density, mean DBH, DBH variability, and conifer proportion when simulating tree–rock interactions (Dorren 2024). These attributes differed considerably among the management and climate scenarios. The initial, predominantly mature forest provided the strongest mean protection among all forested scenarios. This result is consistent with earlier findings that dense stands can initially provide strong protection, although their protective performance may decline as the stands age and tree density decreases (Wehrli et al. 2006). As expected, the no-forest scenario provided the least protection. Previous studies have similarly shown that forest cover can substantially reduce rockfall propagation and intensity compared with non-forested conditions (Moos et al. 2018; Scheidl et al. 2020).

At the 35-year assessment horizon, No_M provided the strongest protection among the management scenarios, followed by Sel_M, whereas Shel_M produced kinetic-energy values approaching those of the no-forest reference. This result reflected the low average tree density representing the first shelterwood regeneration period. Since the Rockyfor3D inputs represented mean stand conditions over the final 30 years preceding the assessment horizon, the result characterizes the broader regeneration period rather than the single moment of minimum forest cover immediately following the final removal cut.

After 200 years, Shel_M provided the strongest mean protection among the future management scenarios and ranked second overall after the initial forest reference. This reflected the high simulated tree density during the later stage of the shelterwood cycle. However, the shelterwood system generated alternating phases of high stand density and strongly reduced overstorey cover across repeated management cycles. Its performance therefore depended strongly on the developmental stage at which protection was assessed.

Despite achieving the lowest mean kinetic energy after 200 years, Shel_M also produced the highest local peak values of maximum kinetic energy at both assessment horizons. These results show that a low mean value does not necessarily indicate consistently strong protection along the entire road section. Local peaks may remain high where forest structure, terrain configuration, and rockfall trajectories combine unfavourably. The evaluation of management strategies should therefore consider not only mean protection at a selected horizon but also temporal variability, local extremes, and periods of reduced overstorey density. Previous modelling studies have likewise shown that forest development and regeneration cuttings can cause substantial temporal variation in rockfall protection (Wehrli et al. 2006; Woltjer et al. 2008; Rammer et al. 2015).

Protection under No_M was lower at the 200-year horizon than under the initial forest condition, reflecting declining tree density and long-term changes in diameter structure. Because ForClim does not explicitly simulate episodic disturbances such as windthrow or bark-beetle outbreaks, the long-term decline in protection under No_M may have been underestimated, particularly because management history and the resulting stand structure can influence susceptibility to bark-beetle outbreaks (de Groot et al. 2019). Sanitary fellings accounted for approximately 25% of the harvested volume in the Tržič Forest Management Unit in recent decades (FMP, 2025), indicating the regional importance of disturbance-related tree mortality. In unmanaged stands, such disturbances could therefore cause greater and more abrupt losses of protection than those represented in the simulations.

Sel_M initially provided weaker protection than No_M because stand density and basal area were reduced during the structural transformation phase. Protection subsequently improved as the stand approached the target selection structure. Its relatively continuous diameter distribution and the absence of regeneration-related reductions in overstorey density resulted in more stable long-term protection than under Shel_M. This result is consistent with previous modelling studies indicating that continuous forest cover and small-scale regeneration interventions reduce temporal fluctuations in rockfall protection (Wehrli et al. 2006; Woltjer et al. 2008; Rammer et al. 2015) and supports the third hypothesis.

Within the simulated scenarios, climate change did not alter the relative ranking of the management strategies. The gradual climate effects represented in ForClim improved structural indicators of protection under No_M and Sel_M but reduced protection under Shel_M. These results reflect changes in stand density, diameter structure, and species composition within the model and do not include potential losses caused by climate-related disturbances.

In reality, climate change may simultaneously weaken protective stands and increase gravitational hazards. Drought, windthrow, bark-beetle outbreaks, precipitation extremes, and warming-related slope instability may reduce forest stability and increase gravitational activity (Gobiet et al. 2014; Bebi et al. 2017; Seidl et al. 2017; Stoffel et al. 2024). These disturbance-mediated effects should be distinguished from the gradual climate effects represented in the model. Climate-adapted, close-to-nature management may reduce disturbance predisposition and help maintain continuous forest cover, although its effects depend on site conditions and may involve trade-offs among ecosystem services (Blattert et al. 2024; Mutterer et al. 2025).

Maintaining rockfall protection depends not only on average stand density and diameter structure but also on the fine-scale spatial arrangement of gaps and tree clusters and on tree-species composition (Motta and Haudemand 2000; Rammer et al. 2015). ForClim simulates independent, spatially non-explicit patches, and the transfer of stand-level averages to an artificial tree grid in Rockyfor3D could not reproduce this spatial heterogeneity. This simplification is particularly relevant to Sel_M and No_M, in which the location of gaps and tree clusters may strongly influence rockfall trajectories. Spatial homogenization may overestimate protection by filling corridors that would otherwise allow relatively unobstructed rock movement. Consequently, relative comparisons among scenarios are likely more robust than the absolute kinetic-energy estimates.

ForClim is suitable for analysing broad, stand- or compartment-level management trajectories but is less suited to representing the fine-scale spatial effects of small gaps, irregular shelterwood systems, and individually positioned residual trees. Future studies could explore coupling Rockyfor3D with a spatially explicit, individual-tree forest model such as HETEROFOR when the location and development of individual trees and canopy gaps are central to management evaluation (Jonard et al. 2020).

The coupled modelling framework did not represent feedbacks from repeated rockfall impacts on subsequent forest development. Rockfall impacts can increase local tree mortality and gradually alter stand structure and protective capacity. Explicitly representing these feedbacks could improve simulations of the long-term interactions between forest dynamics and rockfall protection, particularly at the fine spatial scales relevant to protection-forest management (Moos and Lischke, 2022).

Although the local evaluation showed reasonably close agreement for the principal stand attributes and dominant tree species, uncertainty remains in long-term species-specific responses, regeneration, and disturbance-related mortality. Further evaluation using repeated inventories would improve confidence in projections for broadleaved-dominated protection forests of the south-eastern Alps. Nevertheless, the present modelling framework provides a useful basis for comparing the relative long-term consequences of alternative management strategies under a consistent set of assumptions.

5. Conclusions

Forests in the south-eastern Alps differ from many previously studied Alpine protection forests because they are frequently dominated by European beech and are characterized by relatively short transition zones between rockfall sources and protected infrastructure. Steep slopes and large, asymmetric broadleaved crowns complicate harvesting, while differences between coniferous and broadleaved stands influence interactions between forest structure and rockfall. These conditions increase the importance of site-specific and long-term evaluation of silvicultural alternatives.

This study compared selection management, regular shelterwood management, and no management under current and projected climate conditions by coupling ForClim with Rockyfor3D. Simulating forest development and protective function over two centuries made it possible to assess management effects beyond conventional ten-year planning horizons. During the first 40 to 60 years, management was projected to exert a stronger influence on stand structure and species composition than the gradual effects of climate change, with corresponding consequences for rockfall protection.

The simulations indicated that the relative performance of the management strategies depended on both the evaluation criterion and the developmental stage. Shel_M achieved the strongest mean protection among the future scenarios at the 200-year horizon but showed the greatest temporal variability and the highest local peak kinetic-energy values. It may therefore be less suitable where uninterrupted protection is required. No_M initially maintained strong protection but showed a long-term decline associated with falling tree density and may be particularly vulnerable to stand-replacing disturbances that were not explicitly represented in the simulations.

Sel_M did not achieve the strongest mean protection at either assessment horizon, but its stand structure and protective function became comparatively stable over time. By maintaining continuous overstorey cover and avoiding pronounced regeneration-related reductions in tree density, selection management provided the most balanced and temporally robust long-term strategy. The result supports the use of close-to-nature silvicultural approaches where continuous rockfall protection is a primary management objective.

The climate-change scenario did not alter the relative ranking of management strategies, although it affected tree density, diameter structure, and species composition. These results describe gradual climate responses represented in ForClim and do not include potentially abrupt losses caused by drought, windthrow, bark-beetle outbreaks, or other disturbances. Long-term management planning should therefore consider both modelled stand-development trajectories and the possibility of disturbance-related reductions in protection.

Coupling forest-dynamics and rockfall models provides a valuable interdisciplinary decision-support framework. The approach can identify trade-offs between strong average protection, local peak energies, and temporal stability, while supporting the comparison of alternative management trajectories. The results emphasize the importance of climate-adapted, close-to-nature, and site-specific management for sustaining the protective function of mountain forests in the south-eastern Alps.

Declarations

CRedit authorship contribution statement

Clemens Blattert: Writing – review & editing, Methodology. Maxime Cailleret: Methodology, Writing – review & editing. Jurij Diaci: Supervision, Funding, Methodology, Conceptualization, Writing – review & editing, Writing – original draft. Tine Ferk: Methodology, Investigation, Formal analysis, Conceptualization, Writing – original draft. Gal Fidej: Writing – review & editing, Methodology, Conceptualization. Ulrike Hiltner: Writing – review & editing, Methodology, Conceptualization. Simon Mutterer: Writing – review & editing, Methodology. Andrej Rozman: Writing – review & editing, Methodology. Janine Schweier: Writing – review & editing, Methodology, Supervision, Funding.

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Restrictions may apply to third-party forest inventory, harvesting, climate, and spatial data.

Code availability

The R scripts used for data processing and statistical analysis are available from the corresponding author upon reasonable request. ForClim and Rockyfor3D are available from their respective developers subject to their applicable terms of use.

Authors' contributions

Clemens Blattert: Methodology, Writing – review and editing.

Maxime Cailleret: Methodology, Writing – review and editing.

Jurij Diaci: Conceptualization, Methodology, Supervision, Funding acquisition, Writing – original draft, Writing – review and editing.

Tine Ferk: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft.

Gal Fidej: Conceptualization, Methodology, Writing – review and editing.

Ulrike Hiltner: Conceptualization, Methodology, Writing – review and editing.

Simon Mutterer: Methodology, Writing – review and editing.

Andrej Rozman: Methodology, Writing – review and editing.

Janine Schweier: Methodology, Supervision, Funding acquisition, Writing – review and editing.

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Figures

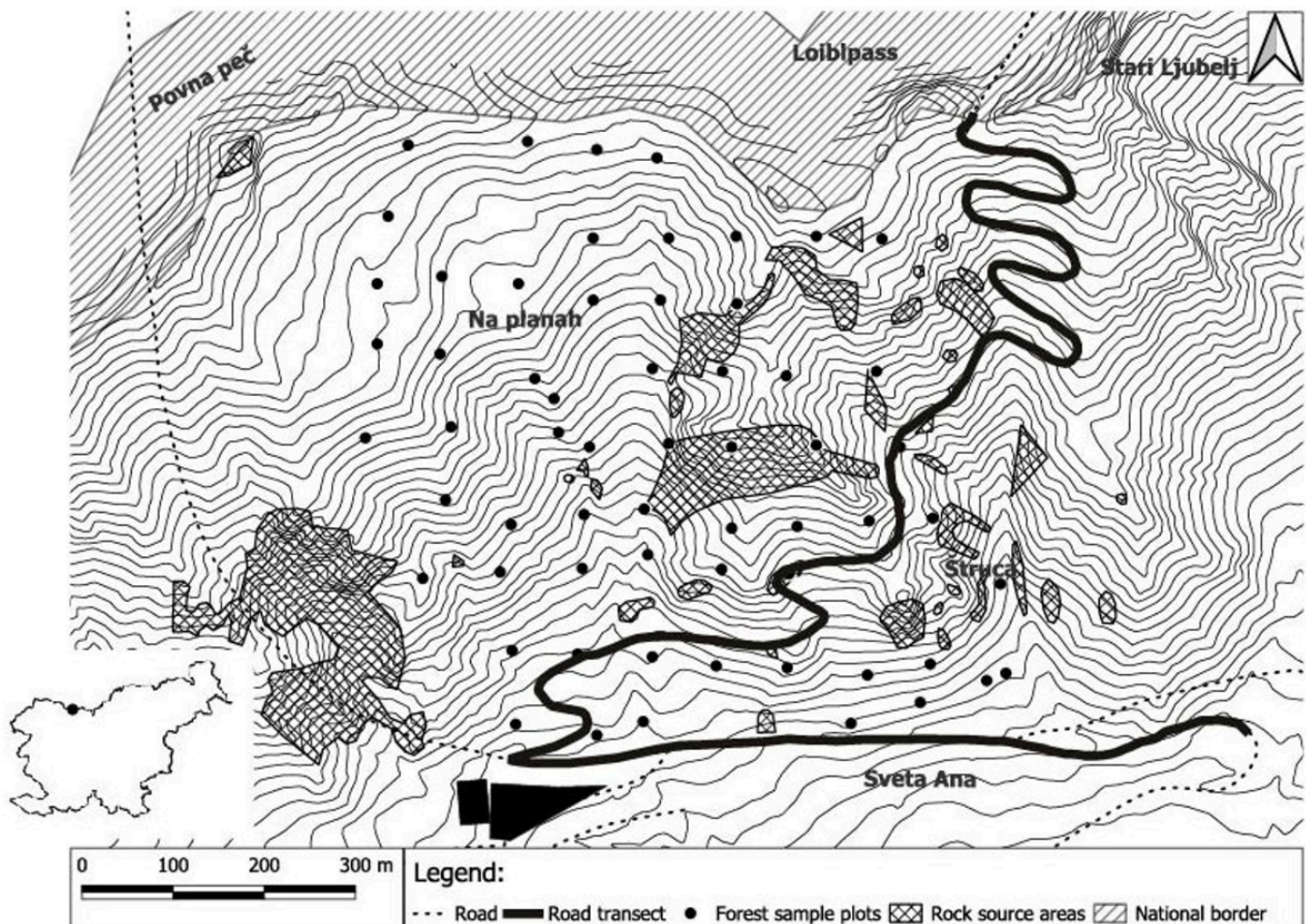


Figure 1

Location of the study site in the Karawanks Mountains, Slovenian Alps. Hatched areas indicate active rockfall release zones. Roads potentially exposed to rockfall are shown as dotted lines, and the bold line marks the road section along which maximum rockfall kinetic energy was evaluated. Black dots indicate permanent forest inventory plots included in the simulation study.

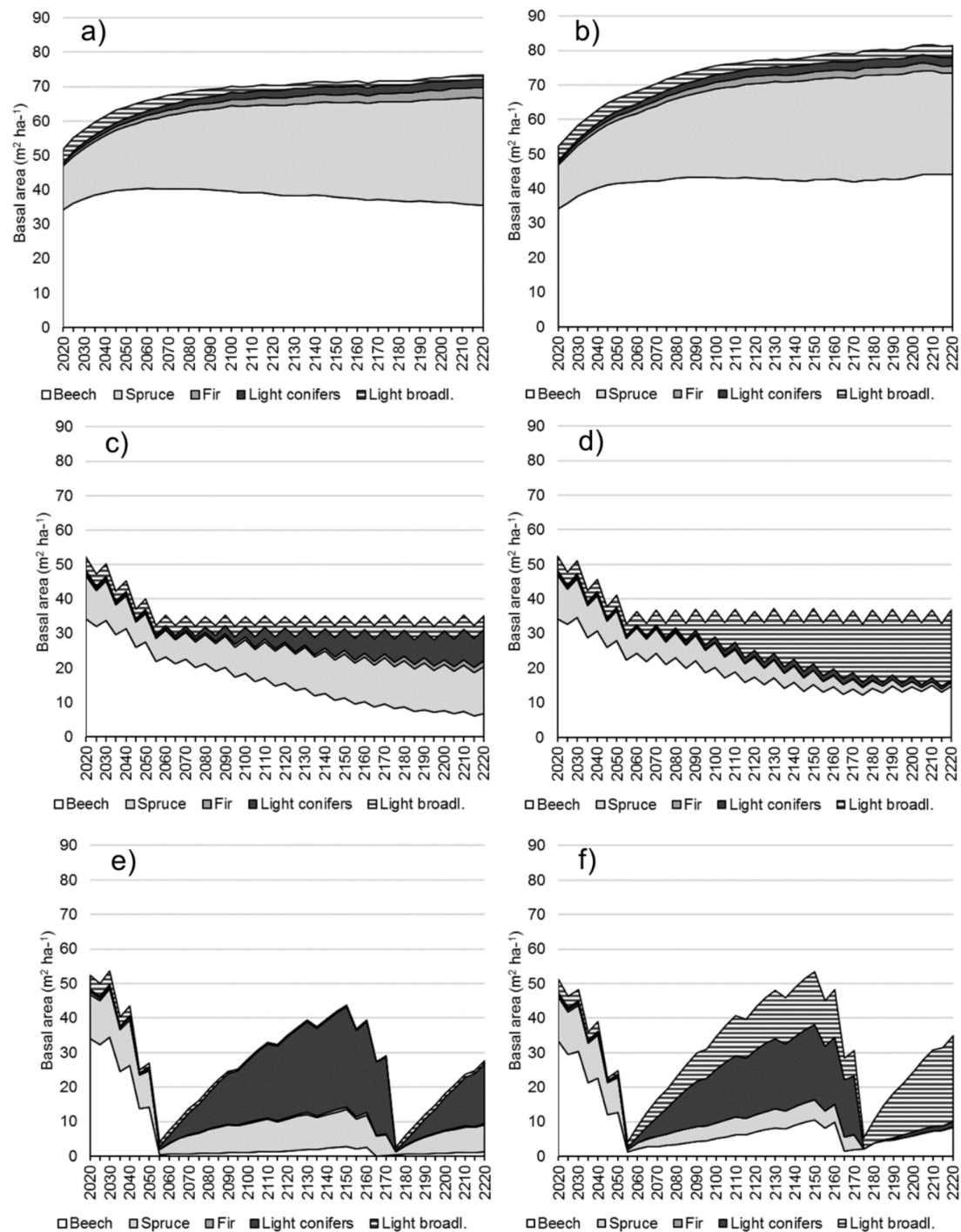


Figure 2

Time series of basal area under six combinations of management and climate conditions: (a) no management under constant climate (No_M), (b) no management under climate change (No_M_CC), (c) selection management under constant climate (Sel_M), (d) selection management under climate change (Sel_M_CC), (e) shelterwood management under constant climate (Shel_M), and (f) shelterwood management under climate change (Shel_M_CC). Light-demanding conifers comprise European larch and Scots pine. Light-demanding broadleaves comprise all deciduous species other than European beech, primarily sycamore maple, European ash, grey alder, common hazel, and rowan.

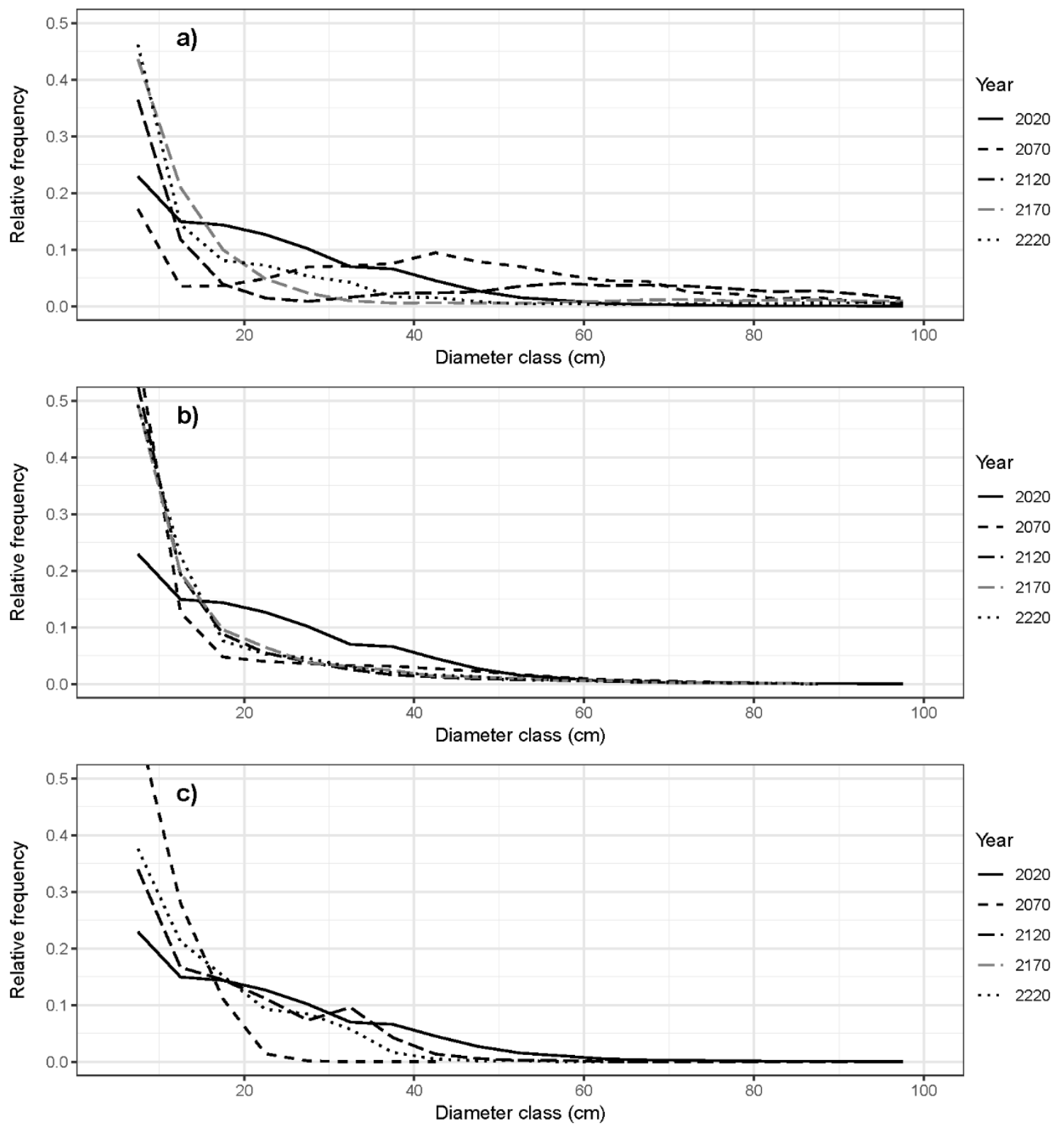


Figure 3

Simulated relative diameter distributions in 5-cm DBH classes at selected years under the climate-change scenario for (a) no management, (b) selection management, and (c) regular shelterwood management. Only trees with DBH > 5 cm were included. The distributions illustrate the contrasting structural development resulting from natural stand dynamics and the applied management algorithms. For comparability among management strategies, the x- and y-axes were limited to 100 cm and 0.5, respectively.

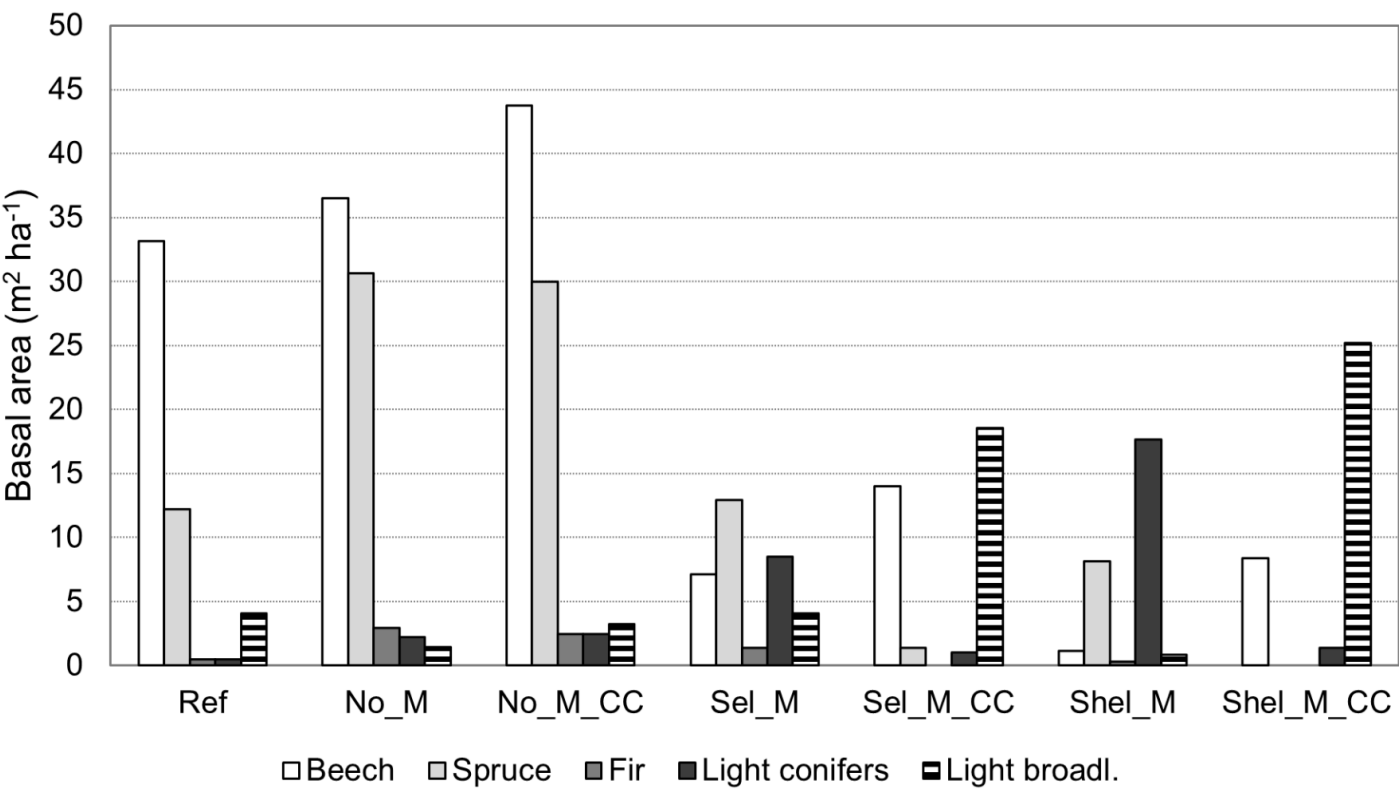


Figure 4

Basal area by tree species or species group in initial forest condition (Ref; model reference year 2020), based on 2022 inventory and under the no-management (No_M), selection-management (Sel_M), and shelterwood-management (Shel_M) scenarios under constant climate and climate change (CC). Simulated values represent averages over the final 30 years of the simulation period (2190–2220). Light-demanding conifers comprise European larch and Scots pine; light-demanding broadleaves comprise all deciduous species other than European beech.

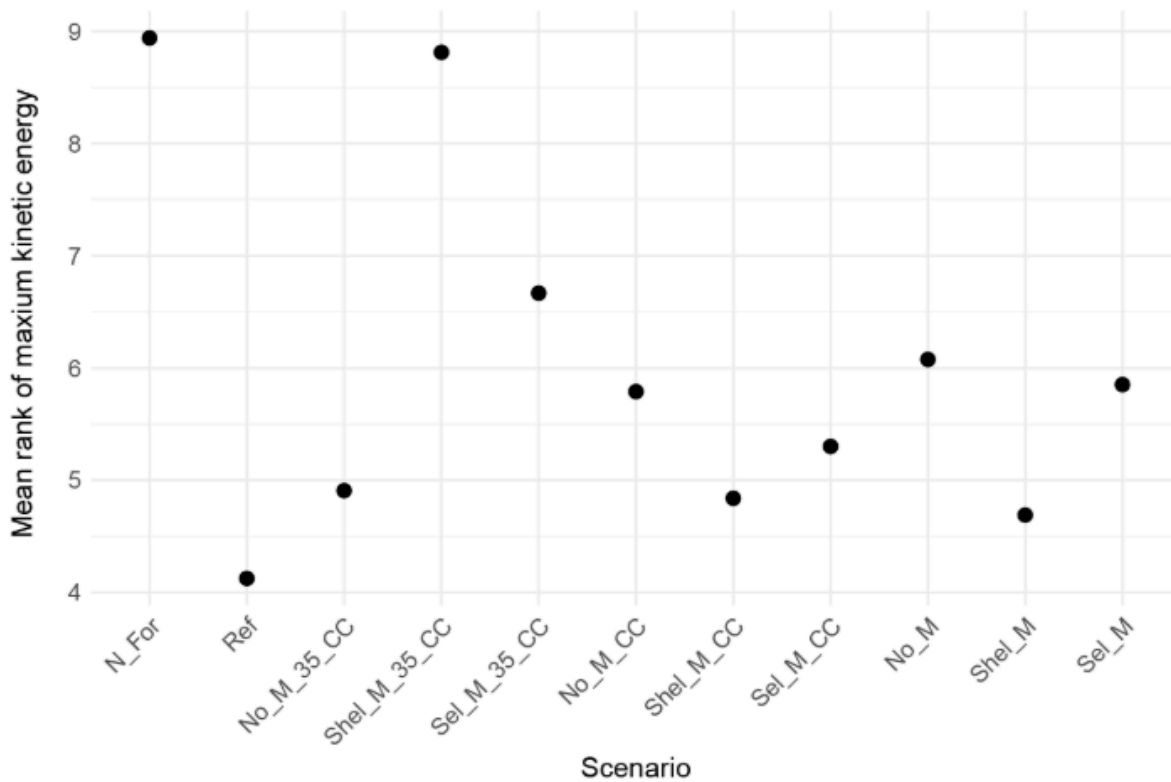


Figure 5

Mean ranks from Friedman’s test of mean maximum kinetic energy among the reference and management scenarios after 35 and 200 years of stand development. Lower mean ranks indicate lower kinetic energy and a stronger protective effect. N_For: no forest; Ref: existing forest in 2020; No_M_35_CC: no management after 35 years under climate change; No_M_CC: no management after 200 years under climate change; No_M: no management after 200 years under constant climate. The abbreviations for Sel_M and Shel_M follow the same structure.

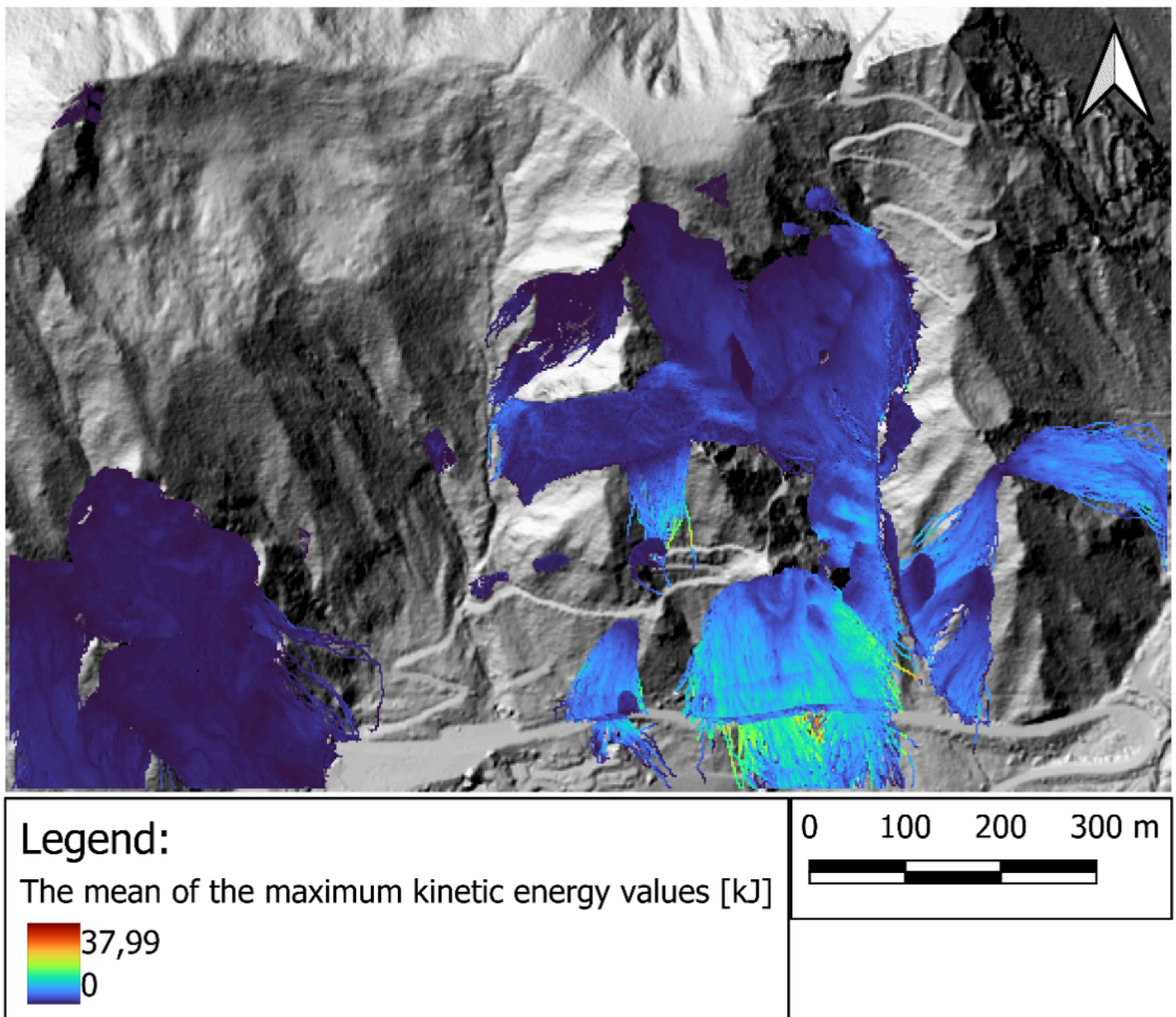


Figure 6

Spatial distribution of the mean maximum kinetic energy of falling rocks (kJ) under the no-management scenario (No_M) and climate change after 200 years. The map covers the terrain shown in Fig. 1, where the analysed section of the Ljubelj Pass road is explicitly marked. Mean maximum kinetic energy along this section was used in the statistical comparisons among scenarios.

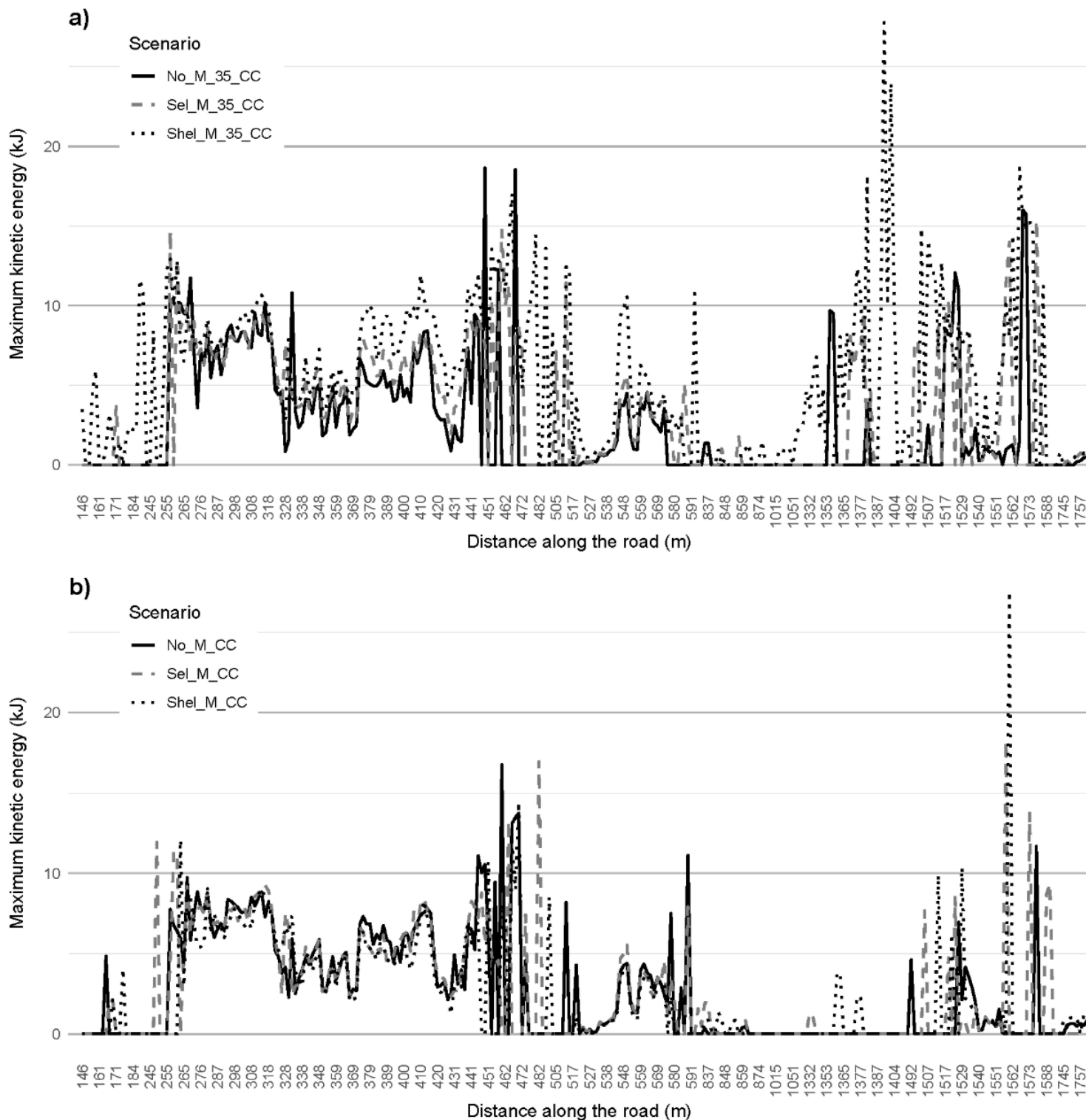


Figure 7

Simulated maximum kinetic energy of falling rocks along the analysed road section under the three management strategies and climate change: (a) after 35 years of stand development, during the early regeneration phase under Shel_M, and (b) after 200 years of stand development. Scenario abbreviations follow Fig. 5. The analysed road section is identified in Fig. 1.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [FerketalModellingtheLongTermAppendixv4.docx](#)