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Abstract:	Beech (Fagus sylvatica L.) forests covering relief rich terrain often provide direct protection for humans and their assets against rockfall. However, the efficacy in protecting against such hazards may abruptly and substantially change after disturbances such as fires, wind-throws, avalanches and insect outbreaks. To date, little knowledge exists on the mid-term protective capacity against rockfall of fire-injured beech stands. We selected 39 beech stands in the Southern European Alps that burnt with different severities over the last 40 years. We inventoried all living and dead trees in each stand and subsequently applied the rockfall model Rockfor.net to assess the protective capacity of fire-injured forests against falling rocks with volumes of 0.05, 0.2 and 1 m3. We tested forested slopes with mean gradients of 27°, 30°, and 35° and lengths of 75 and 150 m. Burnt beech forests hit by low severity fires provide nearly similar protective capacity as unburnt forests, because only thin fire-injured trees die while intermediate-sized and tall trees mostly survive. The protective capacity of moderate to high severity sites is significantly reduced, especially between 10 and 30 years after the fire. In those cases, silvicultural or technical measures may be necessary. Beside the installation of rockfall nets or dams, small-scale felling of dying trees and the placement of stems in oblique direction to the slope can mitigate the reduction of protection provided by the forest.

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1 **Temporal trends in the protective capacity of burnt beech forests (*Fagus***

2 ***sylvatica* L.) against rockfall**

3

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Abstract

Beech (*Fagus sylvatica* L.) forests covering relief rich terrain often provide direct protection for humans and their assets against rockfall. However, the efficacy in protecting against such hazards may abruptly and substantially change after disturbances such as fires, wind-throws, avalanches and insect outbreaks. To date, little knowledge exists on the mid-term protective capacity against rockfall of fire-injured beech stands. We selected 39 beech stands in the Southern European Alps that burnt with different severities over the last 40 years. We inventoried all living and dead trees in each stand and subsequently applied the rockfall model Rockfor.net to assess the protective capacity of fire-injured forests against falling rocks with volumes of 0.05, 0.2 and 1 m^3. We tested forested slopes with mean gradients of 27°, 30°, and 35° and lengths of 75 and 150 m.

Burnt beech forests hit by low severity fires provide nearly similar protective capacity as unburnt forests, because only thin fire-injured trees die while intermediate-sized and tall trees mostly survive. The protective capacity of moderate to high severity sites is significantly reduced, especially between 10 and 30 years after the fire. In those cases, silvicultural or technical measures may be necessary. Beside the installation of rockfall nets or dams, small-scale felling of dying trees and the placement of stems in oblique direction to the slope can mitigate the reduction of protection provided by the forest.

Keywords: forest fires, stand structure, burn severity, Rockfor.net

1 Introduction

In mountain regions forests often provide a direct protection for humans and for their assets against natural hazards (Dorren et al. 2005a; Brang et al. 2006). In comparison to man-built structures the protective effect of forests is naturally re-growing and relatively cost-efficient (Olschewski et al. 2012). In case of rockfall events, standing and lying trees act as barriers against falling rocks (Motta and Haudemand 2000) and the understory vegetation increases the surface unevenness that also may contribute to the energy dissipative capacity of a forest stand (Dorren et al. 2004b; Brauner et al. 2005). Whether the protection provided by a particular forest stand is effective or not is mainly determined by: (1) terrain characteristics and the total length of the forested part of a slope between the rockfall release area and the area to be protected, (2) the size and kinetic energy of the falling rock, and (3) the basal area of the forest and dendrometrical characteristics that reduce or adsorb the impact energy of falling rocks (Dorren et al. 2015).

Since forests are dynamic ecosystems, their protective capacity changes constantly. In particular, natural disturbances such as forest fires, wind-throws, insect and pest outbreaks and snow avalanches have the potential to abruptly and substantially reduce the protective capacity of the concerned stands. Their influence on the protective capacity highly depends on (1) the intensity and scale of the disturbance, (2) the resistance and resilience of the disturbed stand, and (3) on the post-disturbance management (Bebi et al. 2015). For instance, insect outbreaks or low intensity wind-throw causes dispersed tree damages that increases light- and nutrient availability to favour the pre-regeneration (Kupferschmid Albisetti 2003; Collet et al. 2008; Kramer et al. 2014). In case of an immediately and comprehensive loss of living trees after the disturbance event, remnant dead wood may significantly decrease terrain patency and

73   may thus at least partly compensate for this loss. However, slow succession rates after

74   a disturbance event and relatively fast decay of dead wood may result in a time

75   window of temporarily reduced protection against natural hazards (Bebi et al. 2015).

76   Fire affects both the pre-fire regeneration and the dead wood structure (Wohlgemuth

77   et al. 2010), which may additionally reduce the protective capacity of burnt forests

78   with respect to wind-throw areas. Unfortunately, to date little is known about fire

79   resistance and post-fire resilience of different forest types with potentially important

80   protection functions. This is particularly true for European beech (*Fagus sylvatica* L.)

81   forests, an often used tree species in the protection against rockfall (Perzl 2009;

82   Schmidt 2005). In the Swiss Alps, beech forests hold a share of 16% on the overall

83   protection forests against rockfall (Brändli and Huber 2015).

84   However, recent studies demonstrated that fire-injured beeches generally collapse

85   within first 20 years post-fire due to a lack in protection from heating by its thin bark

86   and subsequent infections by wood decaying fungi (Maringer et al. subm. a). Within

87   the same period, seed germination and seedlings emergence is enhanced by

88   progressive canopy opening and by the removal of thick litter layers (Ascoli et al.

89   2015; Maringer et al. subm.). Both processes highly depend on the fire severity (i.e.

90   immediate effect of fire; cf. Morgan et al., 2014). In case of very severe fires, most

91   beeches die within the first few post-fire seasons. Due to the immediate collapse of

92   seed providing trees, seed production and seedlings emergence may be hindered.

93   Additionally, fast growing early post-fire colonizers like shrubs and ferns tend to

94   build dense layers inhibiting additionally seedlings emergence (Maringer et al.

95   subm.). Contrasting, after low severe fires only a few individuals (and usually small

96   trees) are critically injured with marginal consequences to the stand dynamic. Fires of

97   intermediate severity cause a progressive dieback of the stand according to the

98   proportion of the bole injured and the proliferation of decaying fungi (Conedera et al.

99   2007; Conedera et al. 2010; Maringer et al. subm. a). Here the probabilities of

100 successful seed germination and seedlings emergence are highest, especially when a

101 mast year immediately follows the fire event (Ascoli et al. 2015). Those post-fire

102 processes in beech forests show that there might be a lack in the forest protective

103 capacity; particularly in moderate and high fire severity stands. It is thus crucial for

104 foresters to know about the post disturbance processes and their influence in order to

105 prevent the related risks.

106 Based on the assumption that the energy release by moving rocks is compensated by

107 either rock-soil contact (Zinggeler et al. 1991), rock-tree contact (Berger and Dorren

108 2007), or both, process orientated models are able to assess the protective capacity of

109 a concerned stand. In the present study we employed the rockfall model Rockfor.net

110 (Berger and Dorren 2007) for quantifying the protective capacity of burnt beech

111 forests. The model was originally developed to quickly quantify the protective

112 capacity of different structured forest stands and has been often applied in the

113 European Alps (Berger and Dorren 2007; Wehrli et al. 2006; Kajdiž et al. 2015). We

114 used a dataset of 39 burnt beech stands differing in terms of years post-fire (2 to 40

115 years) and burn severity (burn severity refers to the long-term fire effects; cf. Morgan

116 et al. 2014). In particular, we evaluated the conditions (rock size, forested slope

117 length, slope inclination, burn severity) and post-fire phases under which deficits may

118 be expected in the protective capacity against rockfall.

119 **2 Materials and methods**

120 **2.1   Study area**

121 The study was conducted in the Southern European Alps across the neighboring

5

122 regions of Canton Ticino (Switzerland) and Piedmont (Italy). The area is

123 characterized by a marked elevation gradient ranging from the Lake Maggiore (197 m

124 a.s.l.) to the Adula Peak (3402 m a.s.l.) in Ticino and to Punta Nordend (4609 m a.s.l.)

125 in Piedmont, respectively. The geology is characterized by the tectonics of the Alps

126 with granit and gneiss dominating the bedrock (Pfiffner 2015). Due to the relief rich

127 terrain, rockfalls are one of the major natural hazards threatening mountain

128 settlements and roads in both regions (Regione Autonoma Valle d'Aosta - Regione

129 Piemonte 2011; Ambrosi and Thüring 2005).

130 The regional climate can be described as warm and humid showing a high annual

131 precipitation gradient ranging from 778 mm in Piedmont (climate station Susa:

132 07°3`0``E, 45°08`0``N) to 1897 mm in Ticino (climate station Locarno Monti:

133 08°47`43``E, 46°10`12``N) (ARPA 2015; MeteoSwiss 2015). More than half of the

134 annual precipitation falls during the transition seasons (April-May and September-

135 November), and in winter (December-March) precipitation is particularly low (162

136 mm for Piedmont, 316 mm for Ticino). Winters are generally mild with mean January

137 temperatures around 3.5°C, and summers are warm with mean July temperatures

138 around 21.7°C. In summer, periods without rain may last up to thirty consecutive days

139 (Isotta et al. 2014), whereas in winter a katabatic warm and dry wind from the

140 northern Alps (*north foehn*) drops the relatively humidity below 20% in average on 40

141 days yr^{-1} (Spinedi and Isotta 2005). These north-foehn winds dry the fine fuel of the

142 forest understory and increase the fire danger. Forest fires are mostly of human origin

143 and consist of surface fires in the understory of the deciduous forests. Those fires

144 usually start from the urban-forest interface (Conedera et al. 2015) and spread into the

145 higher elevated beech belt (900-1500m a.s.l.) mostly during prolonged dry conditions

146 (Pezzatti et al. 2009). Fire in the region of Piedmont yearly affects 1.7% of the beech

6

147 protection forests (Regione Autonoma Valle d`Aosta – Regione Piemonte 2011).

148 **2.2   Selection of fire sites and data collection**

149 Fire perimeters with less than 40 years were selected from the forest fire databases of

150 Switzerland (Pezzatti et al. 2010) and of the State Forestry Corps of Italy (Inventorio

151 nazionale delle foreste e dei serbatoi di Carbonio (INFC 2005), Corpo Forestale dello

152 stato – ispettorato generale). They were overlaid with local vegetation (Ceschi 2006;

153 Camerano et al. 2004) and geological maps in a geographical information system

154 (ArcGIS version 10.0; © ESRI) to identify fires in beech stands on crystalline

155 bedrock. First field observation took place in 2011 to indicate potential study sites: (i)

156 larger than 0.25 ha, (ii) with no signs of pre-fire pasture or post-fire artificial

157 plantation, (iii) and dominated by beech (> 95%) before the fire event. From the

158 initial 94 potential sites, 36 satisfied all of the selection criteria and were retained for

159 the field survey in the years 2012 and 2013 (Appendix 1).

160 Depending on the area burnt, we placed one to three transects, spaced 50 m apart in

161 elevation, from the unburnt to the burnt beech forests (Figure 1). Circular plots of 200

162 m^2 were placed regularly with 30 m distances in between starting in 10 m distance to

163 the burn edge and following the contour lines. Whenever possible, a minimum of one

164 control plot was placed in the unburnt beech forests at 20 m distance to the burn edge.

165

166 [**Fig. 1** Sampling design in a burnt and unburnt beech forests with regularly placed

167 circular 200 m^2 plots placed 30 m apart along horizontal transects (figure left). Each

168 plot is further characterized in terms of burn severity as a function of the portion of

169 dead and living beeches (photographs)]

170

171 Data collection followed guidelines of the Swiss National Forest Inventory (NFI;

172 Keller 2005) with specific focus on stand stability parameters (Herold and Ulmer

173 2001). Therefore, general plot characteristics were surveyed like slope [°], aspect,

174 elevation [m a.s.l.], mircorelief (plane, convex, depression), as well as the cover of

175 inhibitors for emerging regeneration such as common bracken (*Pteridium aquilinum*

176 [L.] KUHN), common broom (*Cytisus scoparius* [L.] LINK), purple moor grass

177 (*Molinia arundinacea* SCHANK), as well as the surface roughness in the form of

178 deposited rocks (see Brauner et al. 2005). The coverages of common bracken,

179 common broom and purple moor grass were summed up per plot (hereafter referred to

180 as cover of early post-fire colonizers).

181 We inventoried all trees with diameter to breast height (DBH) ≥ 8 cm and omitted

182 smaller trees because of their negligible role in the protective effectiveness (Wehrli et

183 al. 2006). Each standing tree was identified down to the species level (Wagner et al.

184 2010) and the following characteristics were recorded: vitality, i.e., tree being alive or

185 dead (snags and dead standing tree with crown portions but without visible green

186 foliage, hereafter referred to as snags), DBH (at 1.30 m to the nearest cm), tree height

187 (to the nearest meter), and the percentage of crown volume killed. The latter was

188 visually estimated by the volumetric proportion of crown killed compared to the space

189 occupied by the pre-fire crown volume (Hood et al., 2007). Data collection further

190 included lying dead trees (hereafter referred to as logs) of which the average diameter

191 and the length were recorded. For both snags and logs, the wood decay stage was

192 recorded in four classes: (1) cambium still fresh, (2) knife penetrates low, cambium

193 disappeared, (3) knife penetrates into the fiber direction, but not transversely or (4)

194 knife penetrates in both directions. Lying branches and brushwood originated from

195 falling crowns of dead trees with a decay stage below 4 were assessed after the

8

196 method of Brown (1974). Pieces in the 200 m^2-plots were recorded in different

197 diameter classes (1: 2.5-5 cm, 2: >5-7.5 cm, 3: >7.5-15 cm, 4: >15-30 cm) along the

198 four cardinal directions. The obtained volume was then scaled up to standard hectare

199 values (m^3 ha^{-1}).

200 In regions with such a relief rich terrain fires burn very heterogeneously. Therefore

201 each plot was categorized in low, moderate and high burn severity. In accordance

202 with a parallel study by Maringer et al. (subm.), we assessed burn severity by

203 calculating the ratio of post-fire and pre-fire basal area of living trees. For fire sites

204 older than 10 years, pre-fire conditions were assessed exclusively from the control

205 plots, because of fast decaying dead wood. Whereas in burnt sites younger than 10

206 years, the number of visible dead trees in burnt plots determined the pre-fire stand

207 characteristics. Based on this assumption, we defined low burn severity in plots with

208 less than 5% crown volume loss and less than 20% basal area loss. High burn severity

209 was indicated by extensive crown loss (> 50%) and basal area killed (> 60%), and all

210 plots with intermediate losses— in terms of crown and basal area— were assigned to

211 the moderate severity class.

212 **2.3   Analysis methods**

213   **2.3.1**   The Rockfor.net model

214 We employed the Rockfor.net model developed by Berger and Dorren (2007) for

215 simulating the temporal trends in the protective capacity against rockfall in fire-

216 injured beech stands.

217 The underlying idea of the model is to compare the theoretical basal area required for

218 absorbing the kinetic energy of downhill moving rocks ($G_{required}$) and the available

219 basal area of a particular forest stand ($G_{available}$). Therefore, the model regards all

220 standing trees distributed in a forest as virtual tree lines parallel to the contour lines.

221 All trees have the same species composition and diameters (weighting of the tree

222 species see Dorren and Berger 2005), representing the mean values in the original

223 forest stand. The model starts by calculating the total kinetic energy developed by a

224 rock falling down the slope. Then it calculates the energy dissipative capacity of each

225 tree line. The number of trees required to dissipate all kinetic energy are subsequently

226 converted in a required basal area ($G_{required}$) using the mean DBH. In the last step the

227 Rockfor.net model quantifies the protective effect of a forest stand by comparing the

228 required theoretical $G_{required}$ with the available $G_{available}$ (see Berger and Dorren 2007

229 for more details).

230 In the Rockfor.net model we considered also the contribution of logs, assuming that

231 their capacity of absorbing kinetic energy is proportional to the ratio between log-

232 diameter and rock size. Olmedo-Manich (2015) demonstrated that deposited tree logs

233 with rock/log diameter ratios between 0.8 and 1.55 favour optimal energy loss. In this

234 study we assumed that energy dissipation efficiency is linearly related to the rock/log

235 diameter ratio. The amount of lying logs was estimated in terms of volume (in m^3 ha$^-$

236 ^{1}) in the field. In our tool, this volume was converted into a total log length per

237 hectare and finally into the number of potential logs impacts per hectare. Here we

238 assumed that an efficient rock-log contact, meaning with a rock/log diameter ratio of

239 1 or smaller, is required every 10 m on a slope length of 100 m to stop 100% of the

240 rocks by logs (see also Dorren et al 2015). The following equation was used to

241 calculate the percentage of rocks stopped by logs (%$R_{stopped}$):

242 $\%R_{stopped} = Eff_{contact} \times Vol_{Log} \div (\pi \times \left(\frac{D_t^2}{2}\right)) \div 100m \div 10 \times 100\%$ eq.

243 (1)

244

245 Where,

246    $Eff_{contact}$ = rock-log contact efficiency = $min[1, D_t / D_b]$

247   D_t = tree diameter (in m)

248   D_b = rock diameter (in m)

249   Vol_{Log} = volume of lying logs (in m^3 ha^{-1})

250

251   The contribution of lying branches and brushwood to rockfall energy dissipation is

252   hard to quantify in a model such as the Rockfor.net and was therefore neglected.

253   Therefore, temporal changes of their volumes were only graphically visualized (see

254   Figures 3-4).

255   In sum, the Rockfor.net model requires as input parameters both site and forest stand

256   characteristics. Required site characteristics are cliff height (m), length of both the

257   forested and unforested slope on the trajectory of a fallen rock, and mean slope

258   inclination (°). Species composition, DBHs and densities of standing trees (including

259   snags) as well as diameter and length of the logs (wood decomposition rate below 4)

260   are required as stand characteristics.

261   ### 2.3.2   Input data preparation and scenario specification

262   Data preparation followed the new rockfall protection guidelines of the

263   "Sustainability and success monitoring in the protection forests of Switzerland

264   (NaiS)" (see Frehner et al. 2005 and Dorren et al. 2015). Tree diameters were grouped

265   in four DBH-classes (8-12 cm, 12-24 cm, 24-36 cm, and ≥ 36 cm) separately for

266   living and dead standing trees and standardized to number of stems per hectare. Trees

267   with large DBH values diameter most effectively dissipate the kinetic energy of

268   falling rocks, especially those of large rocks, whereas small trees significantly

269   increase the probability of rock—tree contacts due to the (generally) large stem

270   densities. Therefore, the required basal area ($G_{required}$) to stop a falling rock within a

271   specific forested slope is weighted for the DBH-classes according to the rock size

272 (Dorren et al. 2015). Moreover, to account for the differences in capacity of different

273 tree types to dissipate the kinetic energy of falling rocks, Rockfor.net converted the

274 proportions of the presence of 5 different tree 'types' in each stand into a mean energy

275 dissipative capacity per study site. The following 5 tree 'types' were taken into

276 account: beech, Norway spruce (*Picea abies* [L.] Karst.), silver fir (*Abies alba* Mill.),

277 other broadleaves, and other conifers (cf. Dorren and Berger 2005).

278 Further we used standardized rock sizes, mean slope gradients, cliff heights and

279 lengths of forested slopes. We defined standard rock volumes (0.05 m^3, 0.2 m^3, and 1

280 m^3, which corresponds to the rock diameters 0.37 m, 0.58 m and 1 m; Table 1) as

281 traditionally used in NaiS (Frehner et al. 2005, Dorren et al. 2015). In order to

282 simulate realistic field conditions, two options of horizontal distances (75 m, 150 m)

283 have been defined in which a rock had to be stopped from the bottom of a cliff to the

284 downslope forest edge. Finally, three different slope gradients were considered

285 representing the 1st (27°) and 3rd quantile (35°), as well as at the mean (30°) of the

286 slope distribution from the surveyed plots (Table 1). Slope inclination was

287 standardized after testing the statistical non-significance between tree stem densities

288 and slopes using a mixed effect model (Appendix 2).

289 The estimation of the protective effect as calculated by the Rockfor.net model

290 represents the probability of a rock to be stopped in the stand, which is expressed in

291 the following categories: ≥ 90% very good protection, 75 - 90% good protection, 50 -

292 75% adequate protection, 25 - 50% moderate protection, and < 25% inadequate

293 protection. Whether or not the level of protection provided by a forest stand is

294 sufficient, can only be determined by means of a risk analysis in which the effective

295 risk reduction of the forest is quantified and is therefore out of the scope of the

296 present paper.

297

Table 1: Scenario specification for the Rockfor.net model

Input parameters	Scenario specification					
Cliff height (m)	20					
NFS[1] (m)	0					
Rock density (kg m^{-3})	2800					
Forested slope length (m)		75			150	
Mean slope inclination (°)	27	30	35	27	30	35
Mean rock volume (m^3)	0.05	0.05	0.05	0.05	0.05	0.05
	0.2	0.2	0.2	0.2	0.2	0.2
	1	1	1	1	1	1

299   [1] NFS: Non forested slope length between the foot of the cliff and the upper forest limit

2.3.3 Analysis of the modeled results

301   The protective capacity for each scenario was given as the sum of rocks stopped by

302   standing trees (living and dead) and for logs at the plot-level. The result was set to

303   100% in case the sum exceeded the 100% mark. In order to assess the temporal post-

304   fire evolution of the protective capacity, the results were plotted against the time since

305   burning and visualized using standard loess-smoothing curves (Chambers and Hastie

306   1992) separately for low, moderate and high severity sites. The corresponding unburnt

307   forests served as reference. Significant temporal trends in those smoothing curves

308   were detected by employing linear regression models with protective capacity as

309   response variable and the number of post-fire years as explanatory variable. Since the

310   protective capacity is expressed as percentage (probability), the data was log-

311   transformed $(y` = \log(\frac{y}{1-y}))$ and the numbers of post-fire years were included as

312   linear and quadratic term. Additionally, Mann-Whitney-Wilcox tests were applied in

13

313   each of the calculated scenario for detecting significant differences in distributions of

314   the forest protective capacity in different burn severity sites and the corresponding

315   unburnt forests.

316   All analyses of the modeled results and the regression models were performed using

317   R, the free software environment for statistical computing (R Development Core

318   Team 2014). Negative binomial logistic regression models were fitted and validated

319   using the glmmADMB package (Bolker et al.). Graphical outputs are mainly based on

320   packages lattice (Deepayan 2008) and ggplot2 (Wickham and Chang 2015).

321   **3   Results**

322   **3.1   Forest characteristics and development after fire**

323   We assessed a total number of 189 plots in burnt and 27 plots in unburnt (control

324   plots) beech dominated forests. Most of the burnt plots were classified as moderate

325   (44.2%) and high (40.3%) (burn) severity sites, whereas only the remaining 15.5%

326   were considered as low burn severity sites. Elevation of the fire sites and the

327   corresponding unburnt forests ranged from 700 to 1486 m a.s.l. with mean slope

328   inclinations of $30 \pm 0.34°$.

329   Beech grew frequently in the burnt forests, with percentages ranging from 20.75% to

330   100% (Appendix 1). The overall average tree height was 10.3 ± 0.11 m, and

331   approximately 2 m higher when referring to living trees only. Average tree density

332   was 227.6 ± 14.4 stems ha^{-1} with a decreasing tendency from low (360.5 stems ha^{-1})

333   to high (235.7 stems ha^{-1}) burn severity sites. Temporal patterns in tree densities

334   (DBH $\geq$ 8 cm) followed a parabolic course, showing denser stands in early and late

335   post-fire stages and a minimum between 10 and 20 years post-fire (Figure 2).

336   In low severity sites younger than 15 years post-fire, tree densities were only slightly

14

337 lower than in the unburnt forests (Figure 2). Whereas the average basal area at the

338 minimum (around 16-20 years post-fire) was only 1.5-times less than the ones

339 recorded at the early ($\leq$ 9 years) and late ($>$ 32 years) post-fire stages. Only few thin

340 (DBH $<$ 12 cm) trees died, and densities of intermediate-sized (DBH 12-36 cm) and

341 large (DBH $>$ 36 cm) trees remained constant throughout the post-fire period of 40

342 years.

343 In moderate severity sites, tree densities decreased by half of the densities recorded

344 for early and late post-fire stages, whereas the basal area depression lasted for 20

345 years between 10 and 32 years post-fire (Figure 2). Intermediate-sized trees

346 dominated within the first decade post-fire while their densities rapidly decreased

347 with a minimum by about 10 to 32 years post-fire. Thin and intermediate-sized trees

348 increased in densities 32 years post-fire, and tall trees were present throughout the

349 whole observation period.

350 In comparison to low and moderate burn severity, tree densities in high severity sites

351 rapidly decreased throughout all DBH classes within the first decade post-fire and

352 dropped by a factor of 2.3 from 10 to 20 years post-fire (Figure 2). After 20 years

353 post-fire, the new regeneration characterized by thin (DBH $<$ 24 cm in particular)

354 trees increased and their densities doubled with each post-fire age class, peaking after

355 32 years post-fire.

356

357 [**Fig. 2** Tree densities (DBH $\geq$ 8 cm) for living and dead (shaded bars) trees in

358 different DBH-classes (grey color gradient) for low, moderate and high (burn)

359 severity sites and the corresponding unburnt beech forests, grouped by years post-fire]

360 **3.2   Surface unevenness**

361 Most burnt plots were located on a plane (46%) surface followed by small depressions

15

362 (31%), and convex (23%) microrelief. The average coverage of rocks in a burnt plot

363 was 2%, ranging from zero to maximum 30%. Early post-fire colonizers grew

364 frequently after fires of moderate and high burn severity. They reached average

365 coverages of 28% in moderate and 56% in high severity sites (Figure 3). Over the

366 years post-fire, they increased in coverage within the first decade post-fire and peaked

367 (~30%) by around 20 years post-fire in moderate severity sites. In high severity sites

368 they reached a maximum coverage (~ 60%) after 30 years post-fire. This contrasts to

369 plots burnt of low burn severity, where early post-fire colonizers never exceeded

370 25%. There was no clear temporal tendency, which was similar to the pattern of early

371 post-fire colonizers in the unburnt plots. Here coverages tended to be close to zero.

372

373 [**Fig. 3** Temporal trends for the cover of early post-fire colonizers (sum of *Pteridium*

374 *aquilinum, Cytisus scoparius*, *Molinia arundinacea*) visualized by loess-smoothing

375 curves (black dotted lines) including confidence intervals (grey) for the different burn

376 severity classes and the corresponding unburnt forests]

377

378 Pattern in the volume of lying dead branches and brushwood were similar in the

379 different burn severity sites with peaks at around 15 years post-fire (Figure 4).

380 Afterwards volumes steadily decreased reaching similar values recorded for the

381 unburnt forests. When considering different burn severities, the volume of lying

382 branches and brushwood scored highest average values (106 m^3) in high severity sites;

383 here it was 1.5-times higher than in moderate (75 m^3) and low (60 m^3) severity sites,

384 respectively. Contrastingly, no clear temporal trend was detected in the unburnt

385 forests where volumes of lying branches and brushwood never exceeded 25 m^3 ha^{-1}.

386

16

387 [**Fig. 4** Temporal trends in the volumes [m^3 ha^{-1}] of lying dead branches and

388 brushwood visualized by loess-smoothing curves (black dotted lines) including

389 confidence intervals (grey) for the different burn severity classes and the

390 corresponding unburnt forests]

391   3.3   Temporal trends in the protective capacity of forests

392 The Rockfor.net model results highlight the mid-term (first 40 years post-fire)

393 evolution of the protective capacity of burnt beech stands as a function of different

394 burn severities, rock sizes, forested slope lengths, and slope inclinations. The average

395 protective capacity aggregated over the years post-fire decreased with increasing rock

396 size, slope inclination, and shortness of the forested slope length (Table 2). The

397 protective capacity of low severity sites did not significantly differ from the unburnt

398 forests for most of the scenarios. However, for moderate and high burn severity sites

399 the protective capacity significantly differed from the unburnt forests in more than

400 half (67%) of the scenarios (Table 2).

401

Table 2: Mean protection capacity [%] for the different scenario specifications grouped by low, moderate and high burn severity and the corresponding unburnt forests. Similarities (Mann-Whitney-Wilcox tests) in the protection capacity between unburnt and burnt forests of different severities are shown in the superscript.

Forested slope length		75 m			150 m		
Mean slope gradient		27°	30°	35°	27°	30°	35°
rock size	burn severity	Mean protective capacity [%]					
0.05 m^3	unburnt	97	95	91	95	95	95
	low	96 (ns)	92 (ns)	87 (ns)	92 (ns)	92 (ns)	92 (ns)
	moderate	89 (ns)	85 (*)	76 (**)	88 (*)	87 (*)	87 (*)
	high	73 (*)	68 (**)	61 (**)	74 (*)	73 (**)	69 (**)
0.2 m^3	unburnt	94	84	69	95	94	89
	low	87 (*)	83 (ns)	71 (ns)	94 (ns)	91 (ns)	84 (ns)
	moderate	77 (**)	66 (ns)	57 (*)	89 (ns)	85 (*)	71 (*)
	high	55 (***)	49 (**)	40 (***)	73 (*)	67 (**)	53 (*)
1 m^3	unburnt	62	48	30	94	75	58
	low	61 (ns)	54 (ns)	37 (ns)	93 (ns)	76 (ns)	56 (ns)
	moderate	47 (**)	37 (ns)	28 (ns)	86 (ns)	59 (*)	39 (*)
	high	33 (***)	28 (**)	23 (ns)	65 (**)	41 (***)	29 (**)

Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05 '•' 0.1 'ns' 1

Low and moderate severity sites yielded a protective capacity above 50% (more than adequate) for small and intermediate-sized rocks regardless of the forested slope length (Figure 5-6). Only in scenarios with rocks of 0.2 m^3, slope inclination $\geq$ 30° and forested slopes length shorter than 75 m the protective capacity decreased below 50%, mostly between 20 and 30 years post-fire (Figure 6 a). In similar scenarios, the protective capacity in high severity sites ranged between ~10% (inadequate) and 45%, and was at a minimum in scenarios combining intermediate-sized rocks with steep and short forested slopes (Figure 6 a).

For scenarios with rocks of 1 m^3 and 150 m forested slopes, the protective capacity of the forests was above 50% (adequate protection) for the unburnt and low severe burnt forests without any clear temporal trend (Figure 7 b). In case of shorter forested slopes, the protective capacity of those forest types ranged only between 25% (satisfying) and 75% (adequate) (Figure 7 a). Contrastingly, the protective capacity in moderate and high severity sites younger than 15 years post-fire rapidly decreased

423 below 50%, reaching its minimum (~10% that is inadequate) around 20 years post-

424 fire.

425 The linear regression models applied to detect temporal trends in the protective

426 capacity of the burnt and unburnt forests showed significant correlations between the

427 protective effect and the linear and quadratic term of the number of post-fire years for

428 most of the moderate and high burn severity scenarios. Such a significant correlation

429 was missing for low severity sites and the unburnt forests (Appendix 3).

430 [**Fig. 5** Temporal trends in the protective effect [%] of beech stands hit by low,
431 moderate and high burn severity and the corresponding unburnt beech forests against
432 small rocks [0.05 m^3], 75 m (a) and 150 m (b) forested slopes

433 **Fig. 6** Temporal trends in the protective effect [%] of beech stands hit by low,
434 moderate and high burn severity and the corresponding unburnt beech forests against
435 intermediate-sized rocks [0.2 m^3], 75 m (a) and 150 m (b) forested slopes

436 **Fig. 7** Temporal trends in the protective effect [%] of beech stands hit by low,
437 moderate and high burn severity and the corresponding unburnt beech forests against
438 large rocks [1 m^3], 75 m (a) and 150 m (b) forested slopes]

439

4 Discussion

441 The protective effect of forest stands against rockfall highly depends on species

442 composition, stand structure, and sustainability of the forest regeneration capacity

443 (Motta and Haudemand 2000; Dorren et al. 2004a; Dorren and Berger 2005).

444 Disturbances such as forest fires abruptly and substantially change the forest

445 structures, which may temporarily affect the protective capacity of the concerned

446 forest stand (e.g. Dorren et al. 2004a).

447 Our results show that in beech dominated stands, episodic surface fires cause little

448 changes in the tree species composition. Beech directly re-grows (Maringer et al.

449 subm.) after single fire events, resulting in stable and locally adapted forests on the

450 long-term (Dorren et al. 2004a; Rigling and Schaffer 2015).

451 However, the post-fire vertical and horizontal stand structures, as well as the amount

19

452 and timing of regeneration, depends strongly on the burn severity. The forest structure

453 in low severity sites is mostly comparable to those of the unburnt forests (Keyser et

454 al. 2008). The small, fire related changes in tree density, canopy layer, and

455 regeneration dynamics do no seem to affect the overall protective effect. This

456 contrasts to moderate and high severity sites, where significant structural changes

457 occur after fire, what may cause failures in the protective effectiveness against

458 rockfall depending on the forested slope length, the mean slope gradient and the rock

459 size. Structural changes in moderate severity sites are mostly due to the dieback of

460 small and intermediate-sized trees, which goes in line with post-fire observations in

461 conifer stands (Keyser et al. 2008). Surviving tall beeches maintain to some extent the

462 protective capacity (Volkwein et al. 2011) and provide at the same time seeds for new

463 regeneration (Ascoli et al. 2015). The gradual canopy opening of the dominant tree

464 layer leads to emerging beech regeneration, so that the forest protective effect

465 increases again after 20 years post-fire. In the long-term, the mixture of surviving tall

466 and emerging small and intermediate-sized trees results in a multi-layer stand

467 structure that may better meet the protective function standards than mono-layered

468 stands (Dorren et al. 2005b; O`Hara 2006). Nevertheless, the temporary deficit in the

469 protective effectiveness of the forests seem to occur between 10 and 35 years post-

470 fire, especially in case of forested slopes limited in length.

471 Tree mortality in high severity sites happens immediately and concerns all tree sizes.

472 This is similar to crown fires in conifer stands (Keyser et al. 2008; Brown et al. 2013)

473 and to wind-throw areas, where most trees die immediately after the disturbance

474 event. In those areas, standing and lying dead trees mostly maintain the forest

475 protective effect (Frey and Thee 2002; Schönenberger et al. 2005; Bebi et al. 2015),

476 although their resistance decreases with time, as shown by tensile tests (Frey and

477 Thee 2002; Bebi et al. 2012; Bebi et al. 2015). The dead wood quantity and quality

478 might be also lower in fire sites than in wind-throw areas (Wohlgemuth et al. 2010;

479 Priewasser et al. 2013), especially in case of tree species such as beech displaying a

480 rapid decaying wood (Maringer et al. subm. a). As shown by our results, the amount

481 of dead wood consistently decreases from 15 years post-fire on, contributing little in

482 the long-term to the forest protective capacity (Frey and Thee 2002). Such a loss in

483 protective capacity has to be compensated by the upcoming regeneration, which

484 might be delayed due to a lack of seed providing trees and/or a thick layer of

485 competing, fast growing early post-fire colonizers. The latter are able to prevent

486 immediate post-fire beech regeneration (Herranz et al. 1996; Ascoli et al. 2013;

487 Maringer et al. subm.), inhibiting the forest re-growth for several decades (Koop and

488 Hilgen 1987). At the same time our results indicate significantly increase in the

489 coverage of early post-fire colonizer and lying dead branches, which may contribute

490 to some extent to the protective capacity against falling rocks with volumes smaller

491 than 0.2 m^3 in the first 20 years post-fire. However, to date their effective contribution

492 is hard to quantify in process-orientated models.

5 Conclusion and practical consequences for forest managers

494 In this paper we analyze the temporal trends in the forest protection capacity against

495 rockfall of burnt beech stands in the Southern Alps. Based on our results, standing or

496 lying dead trees should in general be left at the burnt site because they contribute

497 temporally to the forest protective effect and provide shade, moisture and nutrients to

498 the emerging tree regeneration (Maringer et al. subm.). In particular, burnt beech

499 forests hit by low severity fires provide nearly similar protective effects as unburnt

500 forests. Hence, silvicultural measures are generally not necessary, whereby the

501 protective capacity has to be assessed on an individual basis.

502 In case of moderate to high severe fires stands may experience a temporal deficit in

503 their protective capacity between 10 to 30 years post-fire depending on the effective

504 burn severity, the rock sizes, the length of the forested slopes and the mean slope

505 gradient. The cumulative effect of dieback of pre-fire trees and slow re-growth of the

506 regeneration may drop the protective capacity below 50%, especially in case of large

507 falling rocks on steep slopes. Consequently, silvicultural and/or technical measures

508 may be necessary in such critical scenarios depending on the risk for humans and

509 their assets in relation to the cost-benefit ratio. Beside the installation of rockfall nets

510 or walls, small-scale felling of standing dying trees and obliquely positioning of the

511 resulting logs offers a possibility to mitigate the loss in protective capacity. However,

512 directional felling has to be conducted within a particular time frame, because (i) the

513 time-lag between salvage logging and a beech mast year affects the regeneration

514 process, and (ii) beech wood decays relatively fast with progressive time (Ascoli et al.

515 2013; Maringer et al., submit. a). As mentioned by Ascoli et al. (2013; 2015), salvage

516 logging should be carried out the following winter after a beech mast year—because

517 the success of beech regeneration highly depends on quantitative seed input—, and

518 within the first five year post-fire to protect established beech saplings. Moreover,

519 weed control combined with artificial beech seed dispersal could reduce the inter-

520 species competition and may accelerate the establishment of a new beech generation.

521 We were not able to quantify the contribution of brushwood and coverage of early-

522 post-fire colonizers in the rockfall modeling. Hence further research is needed in

523 order to quantify the dissipative energy of dense shrub vegetation and their

524 implementation in process-based models.

525

Appendix

Appendix 1: Investigated fire sites sorted by the date of fire. Further listed: slope [°], elevation (elev. [m a.sl.]), number of plots, mean stem density [stems ha^{-1}], mean basal area [m^2 ha^{-1}], species (F.s.= *Fagus sylvatica*, Broad. = other broadleaf species, P.a. = *Picea abies*, Conif. =other conifer species, species proportion of living trees [%], number of plots in the corresponding unburned forest (control).

| Location | Site characteristics | | | | burnt forests characteristics | | | | control |
Municipal	Date of fire	Slope	Elev.	Nr. plots	Mean stem density	Mean basal area	Species	Species proportion	Nr. plots
Gordevio	09.03.73	24	1460	1	1900	10	F.s.	97	0
							Broad.	3	
Moghegno	27.11.73	40	1100	3	883	38	F.s.	50	0
							Broad.	50	
Arbedo	20.03.76	31	1300	13	912	36	F.s.	76	1
							Broad.	22	
							P.a.	3	
Sparone	28.12.80	22	1100	16	753	27	F.s.	62	1
							Broad.	37	
							Conif.	1	
Astano	01.01.81	22	1050	2	750	35	F.s.	70	0
							Broad.	30	
Indemini	01.01.81	31	1200	12	613	13	F.s.	71	1
							Broad.	29	
Intragna	04.01.87	27	1150	3	583	18	F.s.	100	0
Aurigeno	01.08.89	35	900	2	1500	25	F.s.	84	1
							Broad.	16	
Corio	15.02.90	19	1080	10	295	26	F.s.	60	2
							Broad.	40	
Mugena	23.03.90	19	900	6	108	29	F.s.	100	1
Novaggio	10.03.90	35	1300	2	225	8	Broad.	38	1
							F.s.	62	
Rosazza	19.01.90	40	1000	5	460	49	F.s.	91	0
							Broad.	9	
Pollegio	09.04.95	22	1200	3	117	22	F.s.	56	2
							Broad.	44	
Tenero	21.04.96	37	950	3	200	15	Broad.	18	0
							F.s.	82	
Arola	04.06.97	40	800	13	646	37	F.s.	66	0
							Broad.	34	
Magadino	15.04.97	33	1200	24	427	28	F.s.	72	3
							Conif.	2	
							Broad.	26	
Ronco s. A.	15.03.97	22	1300	6	417	23	F.s.	100	1
Sonvico	03.04.97	24	1000	5	380	13	F.s.	49	2
							Broad.	51	
Indimini	19.12.98	33	1300	1	100	30	F.s.	50	1
Gordevio	24.04.02	24	1400	5	490	31	F.s.	100	4
Maggia	11.03.98	14	1380	3	617	32	F.s.	100	1
Bodio	17.03.99	33	1050	3	167	48	F.s.	62	1
							Broad.	38	
Dissimo	05.04.99	40	1000	3	900	27	F.s.	97	1
							Broad.	3	
Someo	05.08.99	27	1450	3	433	35	F.s.	100	1
Varallo	10.08.99	29	1300	11	323	26	F.s.	96	1
							Broad.	4	
Villadossola	15.03.01	37	1250	11	1009	27	F.s.	79	1
							Broad.	21	
Cugnasco	02.04.02	22	700	4	575	21	Broad.	53	1
							F.s.	47	

23

Ronco s.A.	22.04.03	3	1300	2	350	35	F.s.	100	1
Condove	01.03.08	19	1100	11	573	50	F.s.	98	1
							Broad.	2	
Drugno	26.03.12	29	1100	12	963	20	F.s.	90	1
							Broad.	10	
Giaglione	03.03.12	39	1300	8	994	44	F.s.	77	1
							Conif.	21	

532

533 **Appendix 2: Estimates and standard error of the mixed-effect model for stem densities modeled**
534 **against slope inclination.**

535

Variable	Estimate	Standard error
Intercept	**5.9**	**<0.0001**
Slope	**0.009**	**0.25**
random intercept	**Variance**	**StdDev.**
	0.33	**0.6**

536

537

538   Slopes of the plots were measured in degree and implemented as explanatory variable

539   in a mixed effect model with negative binomial distribution (Bolker et al., 2013).

540   Stem densities served as response variable, and because of the high intra-class

541   correlation fire sites were implemented as random effect in the model. The result

542   shows that slope inclination was not significant at the 0.05-level (Appendix 3), and

543   thus it was possible to use standardized slope inclination in the Rockfor.net tool.

544   Against this background, the 1st (26.7°) and 3rd quantile (35°) as well as the mean

545   (29.7°) was used as standardized slope inclinations.

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Appendix 3: Linear regression models for temporal trends in the years post-fire (AGE) of the protective capacity of burned beech stands differing in burn severity (low, moderate, high) and the corresponding unburned forests. Models were separately conducted for scenarios differing in rocks size (0.05 m^3, 0.2 m^3, 1 m^3), forested slope length (75 m, 150 m) and slope inclination (27°, 30°, 35°). The sign and significance level of the predictor are displayed.

Scenario						
Rock size [m^3]	Forested slope length [m]	Slope inclination [°]	Burn severity	Intercept	AGE	AGE^2
0.05	75	27	Unburned	(+)***	ns	ns
			Low	(+)**	ns	ns
			Moderate	(+) •	ns	ns
			High	(+)***	(-)**	(+)**
0.05	150	27	Unburned	(+)***	ns	ns
			Low	(+)***	ns	ns
			Moderate	(+)***	(-)•	(+)•
			High	(+)***	(-)***	(+)***
0.05	75	30	Unburned	(+)***	ns	ns
			Low	(+)***	ns	ns
			Moderate	(+)***	(-)•	(+)•
			High	(+)***	(-)***	(+)***
0.05	150	30	Unburned	(+)***	ns	ns
			Low	(+)***	ns	ns
			Moderate	(+)***	(-)•	(+)•
			High	(+)***	(-)***	(+)***
0.05	75	35	Unburned	(+)**	ns	ns
			Low	(+)***	ns	ns
			Moderate	(+)***	(-)*	(+)•
			High	(+)***	(-)***	(+)***
0.05	150	35	Unburned	(+)***	ns	ns
			Low	(+)***	ns	ns
			Moderate	(+)***	(-)•	(+)•
			High	(+)***	(-)***	(+)***
0.2	75	27	Unburned	(+)***	ns	ns
			Low	(+)***	ns	ns
			Moderate	(+)***	(-)**	(+)**
			High	(+)***	(-)***	(+)***
0.2	150	27	Unburned	(+)***	ns	ns
			Low	(+)***	ns	ns
			Moderate	(+)***	(-)*	(+)*
			High	(+)***	(-)***	(+)**
0.2	75	30	Unburned	(+)**	ns	ns
			Low	(+)***	ns	ns
			Moderate	(+)***	(-)***	(+)***
			High	(+)***	(-)***	(+)***
0.2	150	30	Unburned	(+)***	ns	ns
			Low	(+)***	ns	ns
			Moderate	(+)***	(-)*	(+)*
			High	(+)***	(-)***	(+)***
0.2	75	35	Unburned	(+)***	(-)**	(+)**
			Low	(+)*	ns	ns
			Moderate	(+)***	(-)**	(+)*
			High	(+)***	(-)***	(+)***
0.2	150	35	Unburned	(+)**	ns	ns
			Low	(+)***	ns	ns
			Moderate	(+)***	(-)***	(+)**

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			High	(+)***	(-)***	(+)***
1	75	27	Unburned	ns	ns	ns
			Low	ns	ns	ns
			Moderate	(+)**	(-)*	(+)•
			High	(+)***	(-)***	(+)***
1	150	27	Unburned	(+)***	ns	(-)*
			Low	(+)***	•	ns
			Moderate	(+)***	(-)*	(+)*
			High	(+)***	(-)***	(+)***
1	75	30	Unburned	ns	ns	ns
			Low	ns	ns	ns
			Moderate	(+)*	(-)**	•
			High	(+)***	(-)***	(+)***
1	150	30	Unburned	(+)***	(-)**	(+)**
			Low	(+)*	ns	ns
			Moderate	(+)***	(-)**	(+)**
			High	(+)***	(-)***	(+)***
1	75	35	Unburned	ns	(-)•	ns
			Low	(+)**	ns	ns
			Moderate	(+)*	(-)**	(+)•
			High	(+)**	(-)***	(+)***
1	150	35	Unburned	ns	ns	ns
			Low	ns	ns	ns
			Moderate	(+)*	(-)**	(+)•
			High	(+)***	(-)***	(+)***

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References

Ambrosi C, Thüring M (2005) Statistical analysis of rockfall frequency - volume relationship in Ticino (Switzerland) based on historical data. Swiss Geoscience meeting, Zürich

Arpa Piemonte. http://www.arpa.piemonte.it/banca-dati-meteorologica. Accessed 01 February 2015

Ascoli D, Castagneri D, Valsecchi C, Conedera M, Bovio G (2013) Post-fire restoration of beech stands in the Southern Alps by natural regeneration. Ecol Eng 54: 210–217. doi: 10.1016/j.ecoleng.2013.01.032

Ascoli D, Vacchiano G, Maringer J, Bovio G, Conedera M (2015) The synchronicity of masting and intermediate severity fire effects favors beech recruitment. Forest Ecol Manag 353:126–135. doi: 10.1016/j.foreco.2015.05.031.

Bebi P, Teich M, Schwaab J, Krumm F, Walz A, Grêt-Regamey A (2012) Entwicklung und Leistung von Schutzwäldern unter dem Einfluss des Klimawandels. Schlussbericht im Rahmen des Forschungsprogramms "Wald und Klimawandel", Bern

Bebi P, Putallaz J, Frankhauser M, schmid U, Schwitter R, Gerber W (2015) Die Schutzfunktion in Windwurfflächen. Swiss Forestry Journal 166:168–176

Berger F, Dorren L (2007) Principles of the tool Rockfor.net for quantifying the rockfall hazard below a protection forest. Schweizer Zeitschrift für Forstwesen 158:157–165

Bolker B, Skaug H, Magnusson A, Nielsen A (2012) Getting started with the glmmADMB package. R Core Team. http://glmmadmb.r-forge.r-project.org/glmmADMB.html. Accessed 25 January 2015

Brändli U-B, Huber M (2015) Schweizerisches Landesforstinventar LFI, Ergebnisse zur Erhebung 2004-06. Spezialanfertigung vom 25.11.2015. Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft (WSL), Birmensdorf

Brang P, Schönenberger W, Frehner M, Schwitter R, Thormann J, Wasser B (2006) Management of protection forests in the European Alps: an overview. For. Snow Landsc. Res. 80: 23–44

Brauner M, Weinmeister W, Agner P, Vospernik S, Hoesle B (2005) Forest management decision support for evaluating forest protection effects against rockfall. Forest Ecol Manag 107: 75–85. doi: 10.1016/j.foreco.2004.10.018

Brown J (1974) Handbook for inventorying downed woody material. USDA Forest Service General Technical Report INT - 16 – Rocky Mountain Research Station, Utah. http://www.fs.fed.us/rm/pubs_int/int_gtr016.pdf. Accessed 1 November 2015

Brown MJ, Kertis J, Huff MH (2013) Natural tree regeneration and coarse woody debris dynamics after a forest fire in the Western Cascade Range. USDA Forest Service – Research Paper PNW-RP-592. Pacific Northwest Research Station, Portland. http://www.fs.fed.us/pnw/pubs/pnw_rp592.pdf. Accessed 1 Nobember 2015

Camerano P, Gottero F, Terzuolo P, Varese P (2004) Tipi forestali del Piemonte. Blu Edizioni, Torino

Ceschi I (2006) Il bosco nel Canton Ticino. Armando Dadó Editore, Locarno

Chambers JM, Hastie TJ (1992) Statistical Models in S. Local regression models. CRC Press LLC, Boca Raton (USA)

Collet C, Piboule A, Leroy O, Frochot H (2008) Advance *Fagus sylvatica* and *Acer pseudoplatanus* seedlings dominate tree regeneration in a mixed broadleaved

603   former coppice-with-standards forest. Forestry 81: 135–150. doi:
604   10.1093/forestry/cpn004

605 Conedera M, Lucini L, Holdenrieder O (2007) Pilze als Pioniere nach Feuer. Wald
606   und Holz 11: 45–48

607 Conedera, M., Lucini, L., Valese, E., Ascoli, D., Pezzatti, G. (Eds.) 2010 Fire
608   resistance and vegetative recruitment ability of different deciduous tree species
609   after low- to moderate-intensity surface fires in southern Switzerland. In: Viegas,
610   D.X. (ed) VI International Conference on Forest Fire Research, 15-18 November
611   2010, Coimbra, Portugal. [CD-ROM]. Portugal, ADAI/CEIF University of
612   Coimbra

613 Conedera M, Tonini M, Oleggini L, Orozco CV, Leuenberger M, Pezzatti G (2015)
614   Geospatial approach for defining the Wildland-Urban Interface in the Alpine
615   environment. Computers, Environment and Urban Systems 52: 10–20

616 Deepayan S (2008) Lattice: multivariate data visualization with R. Springer, New
617   York (USA)

618 Dorren L, Berger F, Imeson AC, Maier B, Rey F (2004a) Integrity, stability and
619   management of protection forests in the European Alps. Forest Ecol Manag
620   195:165–176

621 Dorren L, Maier B, Putters US, Seijmonsbergen AC (2004b) Combining field and
622   modelling techniques to assess rockfall dynamics on a protection forest hillslope
623   in the European Alps. Geomorphology 57: 151–167. doi: 10.1016/S0169-
624   555X(03)00100-4

625 Dorren L, Berger F (2005) Stem breakage of trees and energy dissipation during
626   rockfall impacts. Tree Physiol 26: 63–71

627 Dorren L, Berger F, Hir C, Mermin E, Tardif P (2005a) Mechanisms, effects and
628   management implications of rockfall in forests. Forest Ecol Manag 215: 183–195.
629   doi: 10.1016/j.foreco.2005.05.012

630 Dorren L, Berger F, Maier B (2005b) Der Schutzwald als Steinschlagnetz.
631   LWFaktuell 50: 25–27

632 Dorren L, Berger F, Frehner M, Huber M, Kühne K, Métral R, Sandri A, Schwitter R,
633   Thormann J, Wasser B (2015) Die neue NaiS-Anforderungsprofil Steinschlag.
634   Swiss Forestry Journal 166: 16–23

635 ESRI: ArcGIS Desktop: Release 10. (Environmental Systems Research Institute:
636   Redlands, CA)

637 Frehner M, Wasser B, Schwitter R (2005) Nachhaltigkeit und Erfolgskontrolle im
638   Schutzwald. Wegleitung für Pflegemassnahmen in Wäldern mit Schutzfunktion.
639   Bundesamt Umwelt Wald Landschaft, Bern

640 Frey W, Thee P (2002) Avalanche protection of windthrow areas: A ten year
641   comparison of cleared and uncleared starting zones. Forest Snow and Landscape
642   Research 77: 89–107

643 Herold A, Ulmer U (2001) Stand stability in the Swiss National Forest Inventory:
644   assessment technique, reproducibility and relevance. Forest Ecol Manag 145: 29–
645   42. doi: 10.1016/S0378-1127(00)00572-7

646 Herranz J, Martinez-Sanchez J, Las Heras J de, Ferrandis P (1996) Stages of plant
647   succession in *Fagus sylvatica* L. and *Pinus sylvestris* L. in forests of Tejera Negra
648   Natural Park (Central Spain), three years after fire. Israel Journal of Plant Science
649   44: 347–358

650 Hood SM, Smith SL, Cluck DR (2007) Delayed conifer tree mortality following fire
651   in California. USDA Forest Service, pp. 261–283.

http://www.fs.fed.us/psw/publications/documents/psw_gtr203/psw_gtr203_019ho od.pdf. Accessed 1 February 15

Isotta FA, Frei C, Weilguni V, Perčec Tadić M, Lassègues P, Rudolf B, Pavan V, Cacciamani C, Antolini G, Ratto S, Munari M, Micheletti S, Bonati V, Lussana C, Ronchi C, Panettieri E, Marigo G, Vertačnik G (2014) The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data. Int J Climatol 34: 1657–1675. doi: 10.1002/joc.3794

Kajdiž P, Diaci J, Rebernik J (2015) Modelling facilitates silvicultural decision-making for improving the mitigating effect of beech (*Fagus sylvatica* L.) dominated alpine forest against rockfall. Forests 6: 2178–2198. doi: 10.3390/f6062178

Keller M (Eds.) (2005) Schweizerisches Landesforstinventar. Anleitung für die Feldaufnahmen der Erhebung 2004-2007. Druckzentrum Schütz AG, Birmensdorf

Keyser TL, Lentile LB, Smith FW, Shepperd WD (2008) Changes in forest structure after a large, mixed-severity wildfire in Ponderosa Pine Forests of the Black Hills, South Dakota, USA. Forest Science 54: 328–338

Koop H, Hilgen P (1987) Forest dynamics and regeneration mosaic shifts in unexploited beech (*Fagus sylvatica*) stands at Fontainebleau (France). Forest Ecol Manag 20: 135–150

Kramer K, Brang P, Bachofen H, Bugmann H, Wohlgemuth T (2014) Site factors are more important than salvage logging for tree regeneration after wind disturbance in Central European forests. Forest Ecol Manag 331:116–128

Kupferschmid Albisetti A (2003) Zerfall und Verjüngung eines Schutzwaldes nach dem Absterben der Fichten durch Buchdruckerbefall. GAIA 12: 271–274

Maringer J, Conedera M, Ascoli D, Schmatz DR, Wohlgemuth T (submitted) Resilience of European beech forests (*Fagus sylvatia* L.) after fire in a global climate change context. Int J Wildland Fire

Maringer J, Ascoli D, Küffer N, Conedera M (submitted a) What drives European beech (*Fagus sylvatica* L.) to death after forest fires of varying severities? Forest Ecol Manag

MeteoSwiss (2015) Swiss climate. Federal Office of Meteorology and Climatology. Zürich, Switzerland. http://www.meteoschweiz.admin.ch/home.html?tab=overview. Accessed 1 February 15

Morgan P, Keane RE, Dillon GK, Jain TB, Hudak AT, Karau EC, Sikkink PG, Holden ZA, Strand EK (2014) Challenges of assessing fire and burn severity using field measures, remote sensing and modeling. Int J Wildland Fire 23: 1045-1060. doi: 10.1071/WF13058

Motta R, Haudemand J (2000) Protective forests and silvicultural stability: an example of planning in the Aosta Valley. Mountain Research and Development 20: 180–187

O`Hara K (2006) Multiaged forest stands for protection forests: concepts and applications. Forest Snow and Landscape Research 80: 45–55

Olmedo-Manich I (2015) Etude expérimentale et numérique de l'efficacité d'ouvrages ligneux de génie biologique pare-pierres. Dissertation, INSA Lyon

Olschewski R, Bebi P, Teich M, Wissen Hayek U, Grêt-Regamey A (2012) Avalanche protection by forests - A choice experiment in the Swiss Alps. Journal of Forest Policy and Economics 15:108–113

701 Perzl F (2009) Die Buche - eine Baumart des Objektschutzwaldes. BFW –
702   Praxisinformation 12:29–31
703 Pezzatti G, Bajocco S, Torriani D, Conedera M (2009) Selective burning of forest
704   vegetation in Canton Ticino (Southern Switzerland). Plant Biosystems 143: 069-
705   620. doi: 10.1080/11263500903233292
706 Pezzatti G, Reinhard M, Conedera M (2010) Swissfire: Die neue schweizerische
707   Waldbranddatenbank. Swiss Forestry Journal 161: 465–469
708 Pfiffner AO (2015) Geologie der Alpen, 3rd edn. Haupt-Verlag, Bern
709 Priewasser K, Brang P, Bachofen H, Bugmann H, Wohlgemuth T (2013) Impact of
710   salvage-logging on the status of deadwood after windthrow in Swiss forests. Eur J
711   Forest Res 2:231–240. doi: 10.1007/s10342-012-0670-1
712 R Development Core Team (2014) R: A language and environment for statistical
713   computing, Vienna, Austria
714 Regione Autonoma Valle d'Aosta (2010) Regione Piemonte Foreste di protezione
715   Diretta. Disturbi naturali e stabilità nelle Alpi occidentali, Arezzo
716 Rigling A, Schaffer HP (2015) Waldbericht 2015. Zustand und Nutzung des
717   Schweizer Waldes. Eign. Forschungsanstalt für Wald, Schnee und Landschaft,
718   Birmensdorf
719 Schmidt O (2005) Zur Gefährdung der Hauptbaumarten aus Sicht des biotischen
720   Waldschutzes. LWFaktuell 49:1–2
721 Schönenberger W, Noack A, Thee P (2005) Effect of timber removal from windthrow
722   slopes on the risk of snow avalanches and rockfall. Forest Ecol Manag 213: 197–
723   208. doi: 10.1016/j.foreco.2005.03.062
724 Spinedi F, Isotta FA (2005) Il clima del Ticino negli ultimi 50 anni. Dati statistiche e
725   società 4:4–39
726 Volkwein A, Schellenberg K, Labiouse V, Agliardi F, Berger F, Bourrier F, Dorren L,
727   Gerber W, Jaboyedoff M (2011) Rockfall characterisation and structural
728   protection - a review. Nat Hazard Earth Sys 11: 2617–2651. doi: 10.5194/nhess-
729   11-2617-2011
730 Wagner S, Collet C, Madsen P, Nakashizuka T, Nyland R, Sagheb-Talebi K (2010)
731   Beech regeneration research: from ecological to silvicultural aspects. Forest Ecol
732   Manag 259: 2172–2182. doi: 10.1016/j.foreco.2010.02.029
733 Wehrli A, Dorren L, Berger F, Zingg A, Schönenberger W (2006) Modelling long-
734   term effects of forest dynamics on the protective effect against rockfall. Forest
735   Snow and Landscape Research 80: 57–76
736 Wickham H, Chang W (2015) Package `ggplot2`. https://cran.r-
737   project.org/web/packages/ggplot2/ggplot2.pdf. Accessed 1 December 2015
738 Wohlgemuth T, Brigger A, Gerold P, Laranjeiro L, Moretti M, Moser B, Rebetez M,
739   Schmatz DR, Schneiter G, Sciacca S, Sierro A, Weibel P, Zumbrunnen T,
740   Conedera M (2010) Leben mit Waldbrand. Merkblatt für die Praxis 46: 1–16
741 Zinggeler A, Krummenacher B, Kienholz H (1991) Steinschlagsimulation in
742   Gebirgswäldern. Berichte und Forschungen des Geographischen Instituts der
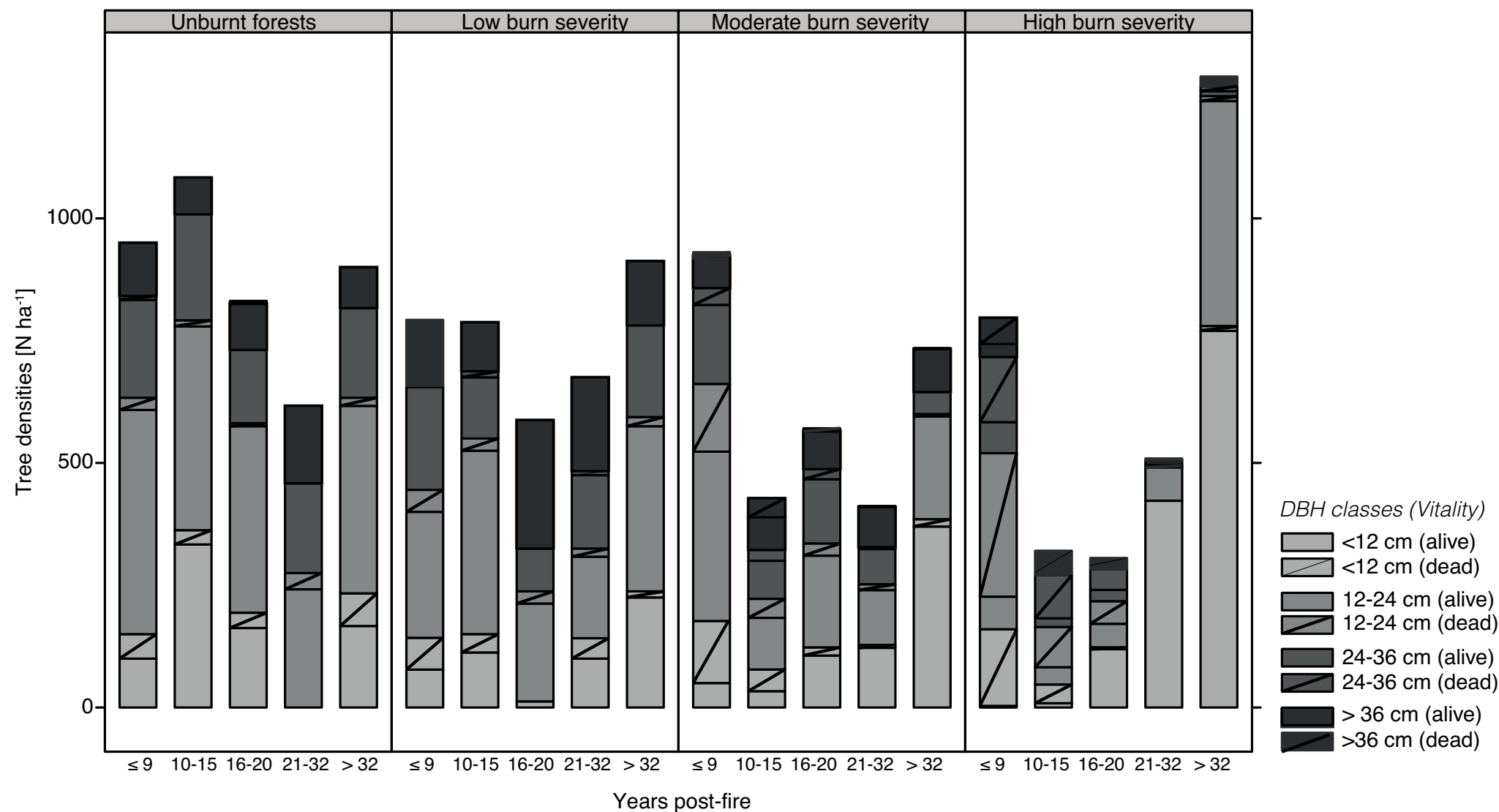743   Universität Fribourg, Universität Fribourg
744

Figure

1550 m a.s.l.

Starting point

1500 m a.s.l.

10 m

30 m

50 m

1450 m a.s.l.

Beech forest

Chestnut forest
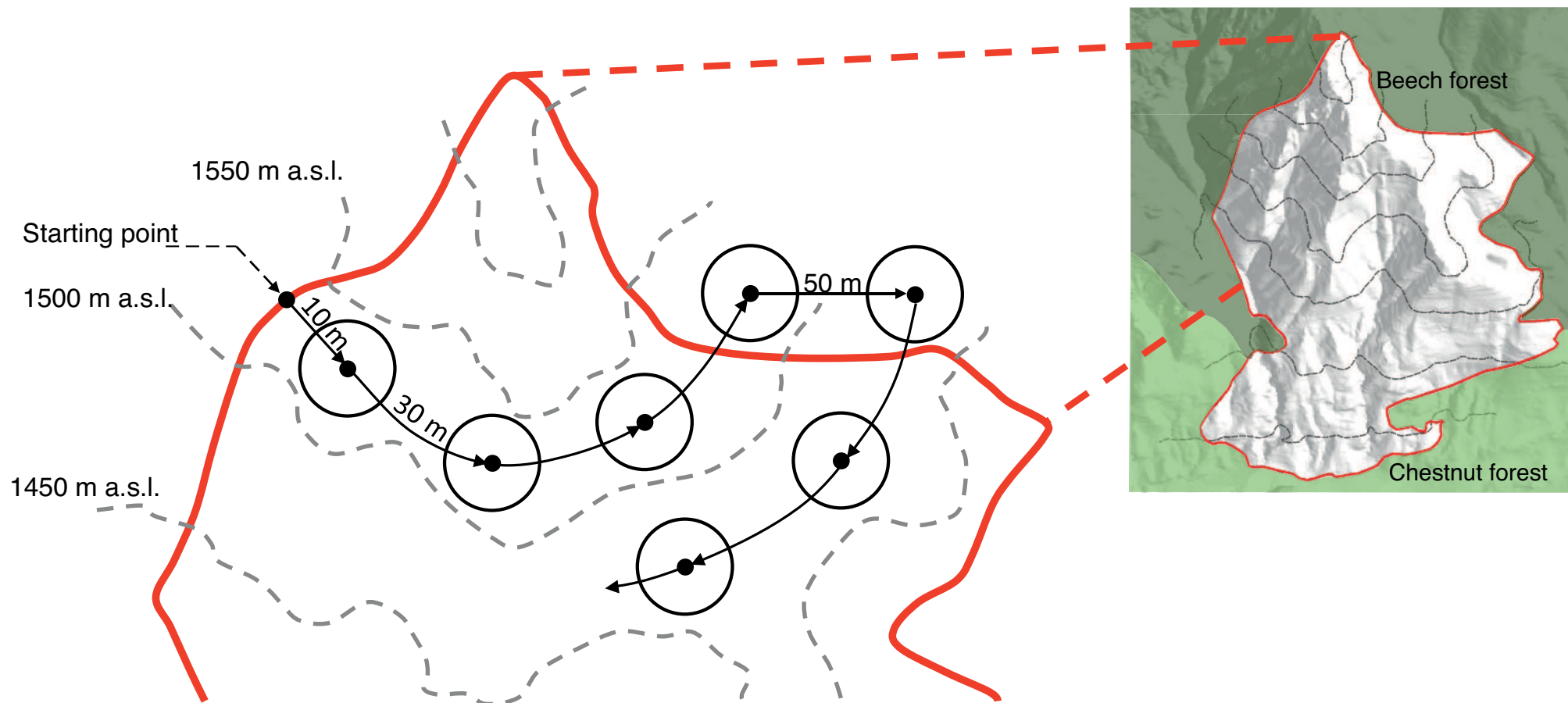
Low fire severity
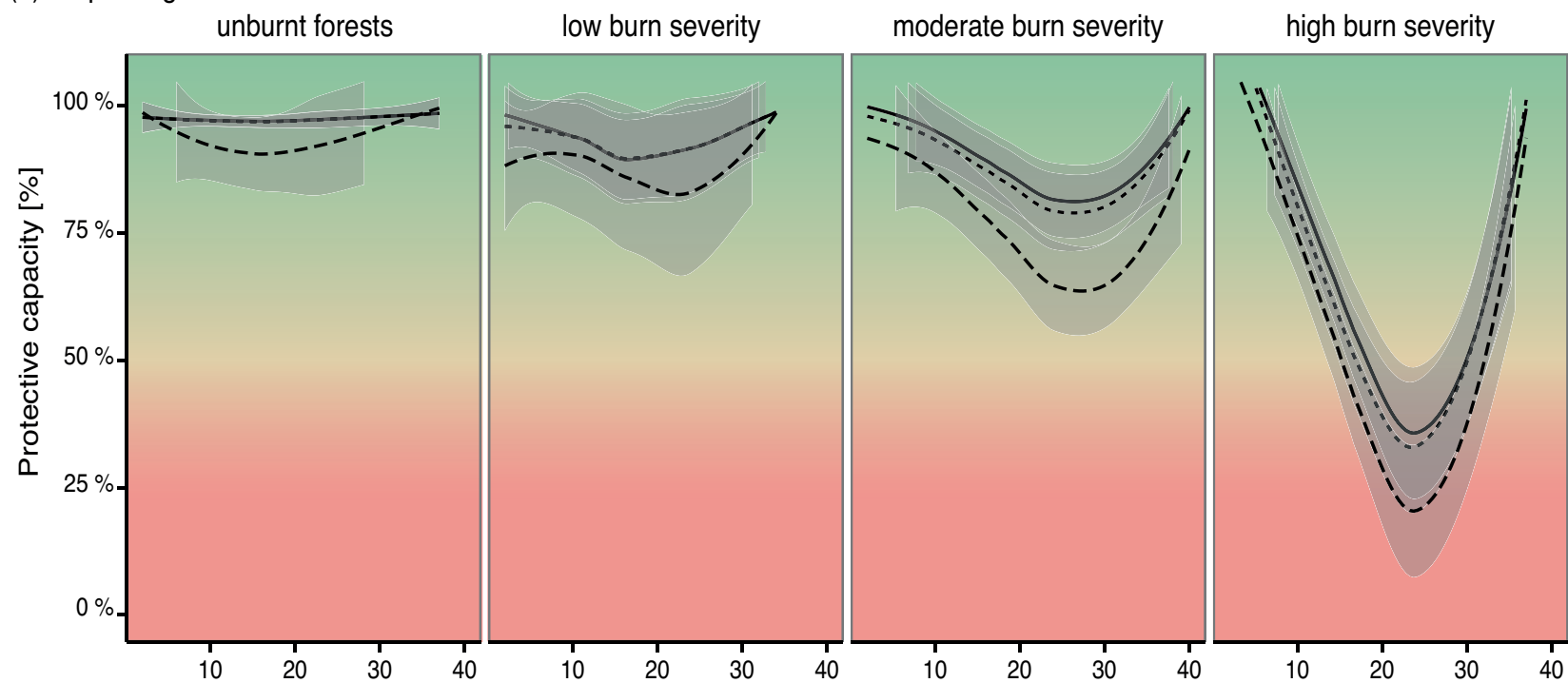
Moderate fire severity

High fire severity

Figure

Figure
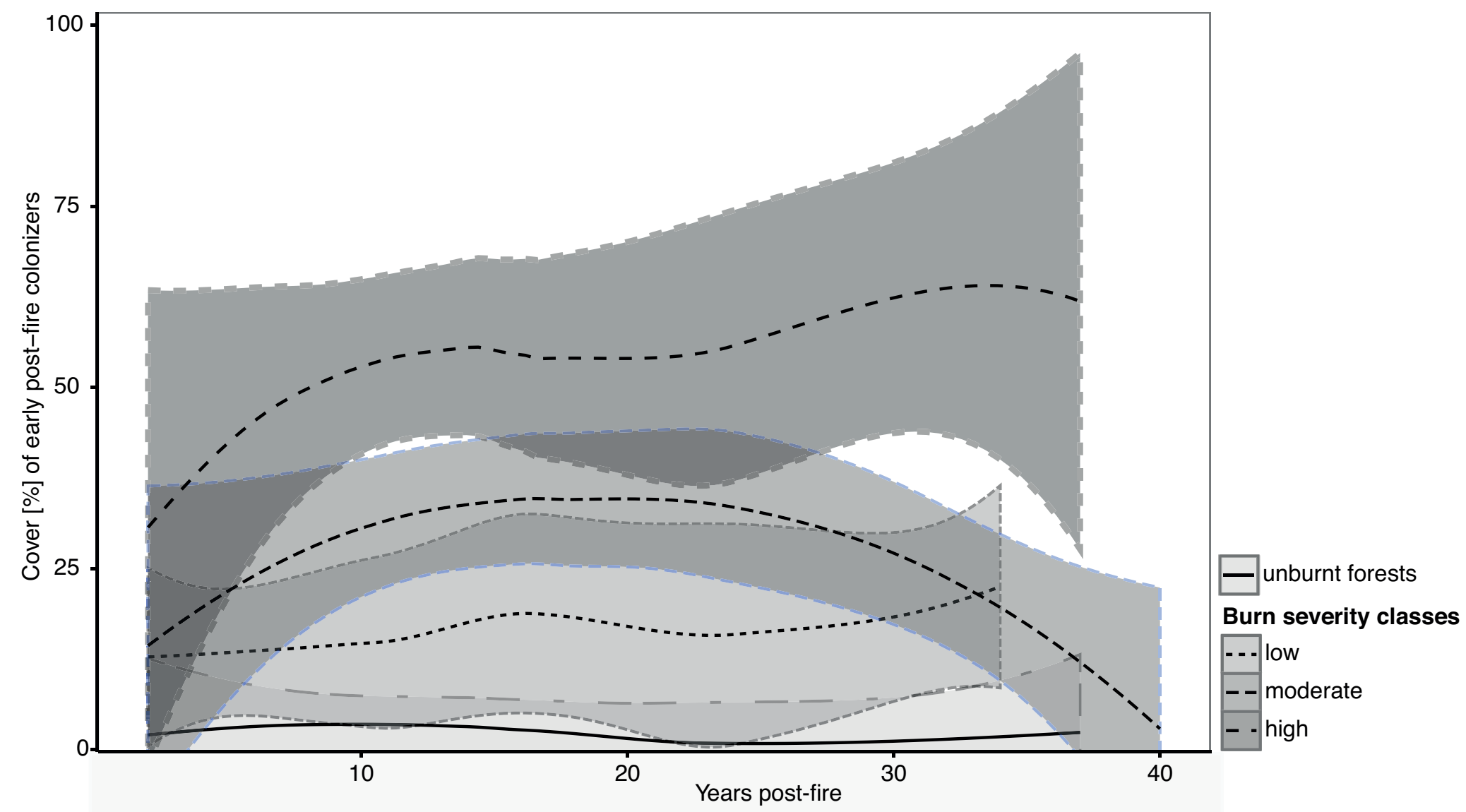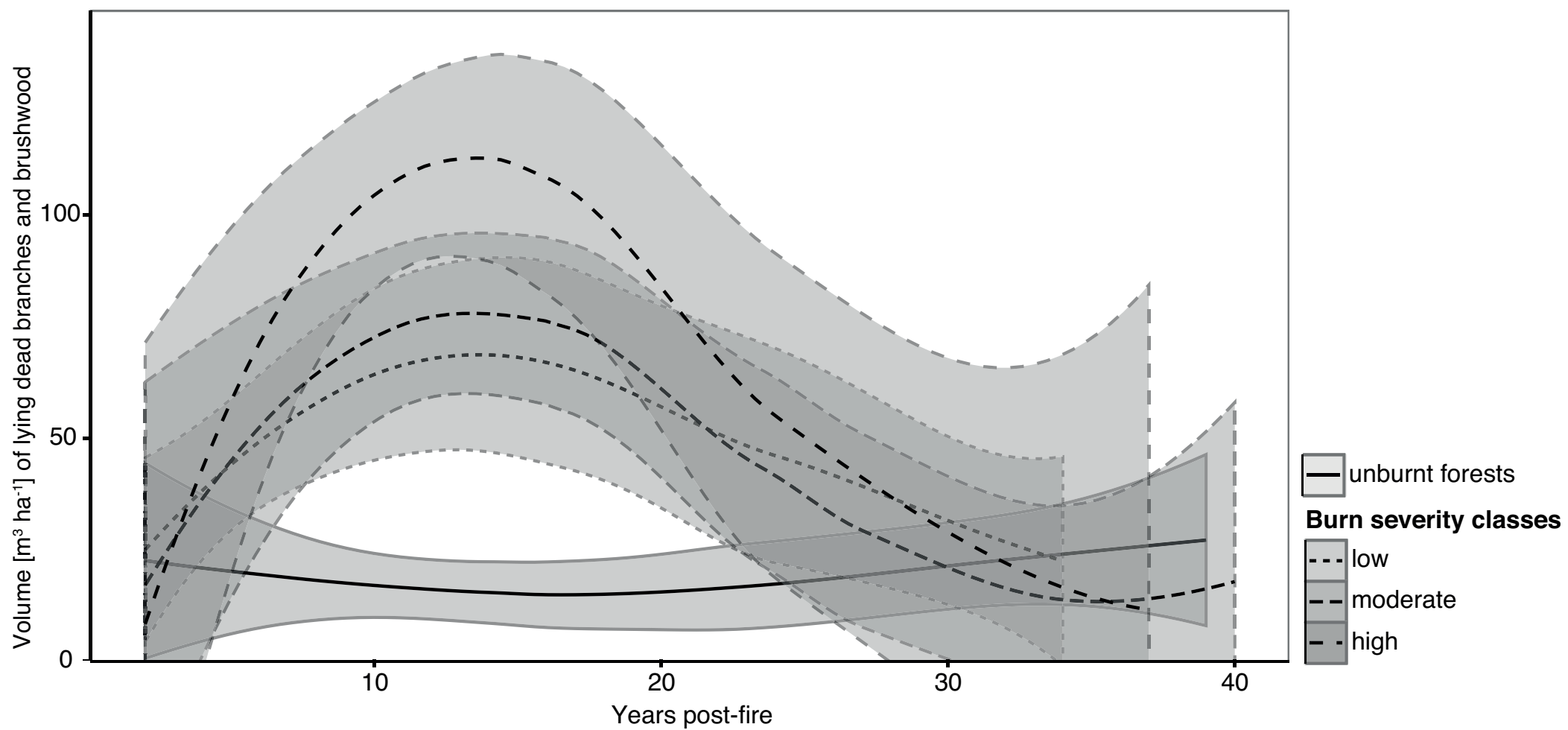
Scenario: Stone = 0.05 m³;   Slope: —— 27° ···· 30° – – 35°
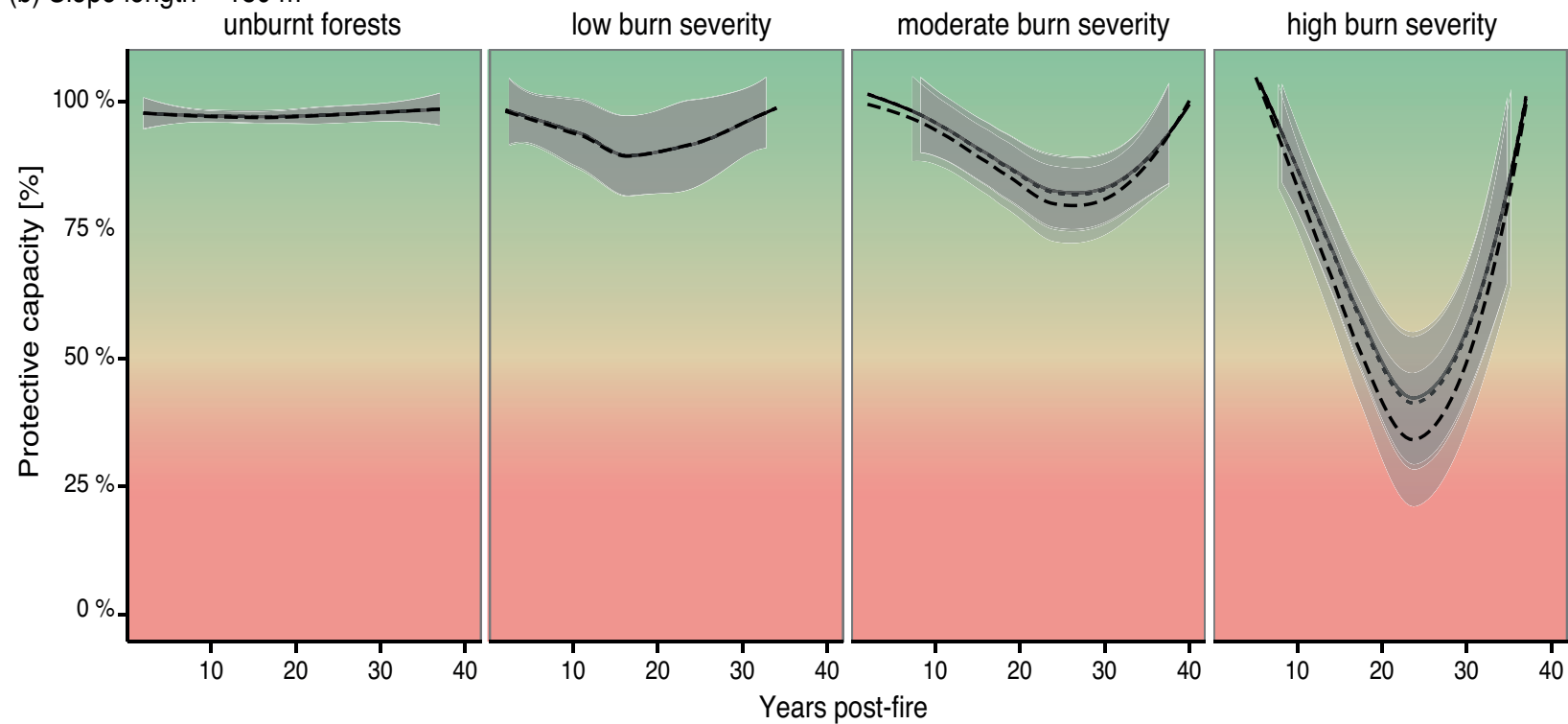
(a) Slope length = 75 m

Figure

Scenario: Stone 0.2 m³; Slope: —— 27° ···· 30° – – 35°

(a) Slope length = 75 m

| unburnt forests | low burn severity | moderate burn severity | high burn severity |

(b) Slope length = 150 m

| unburnt forests | low burn severity | moderate burn severity | high burn severity |

Protective capacity [%]

Years post-fire
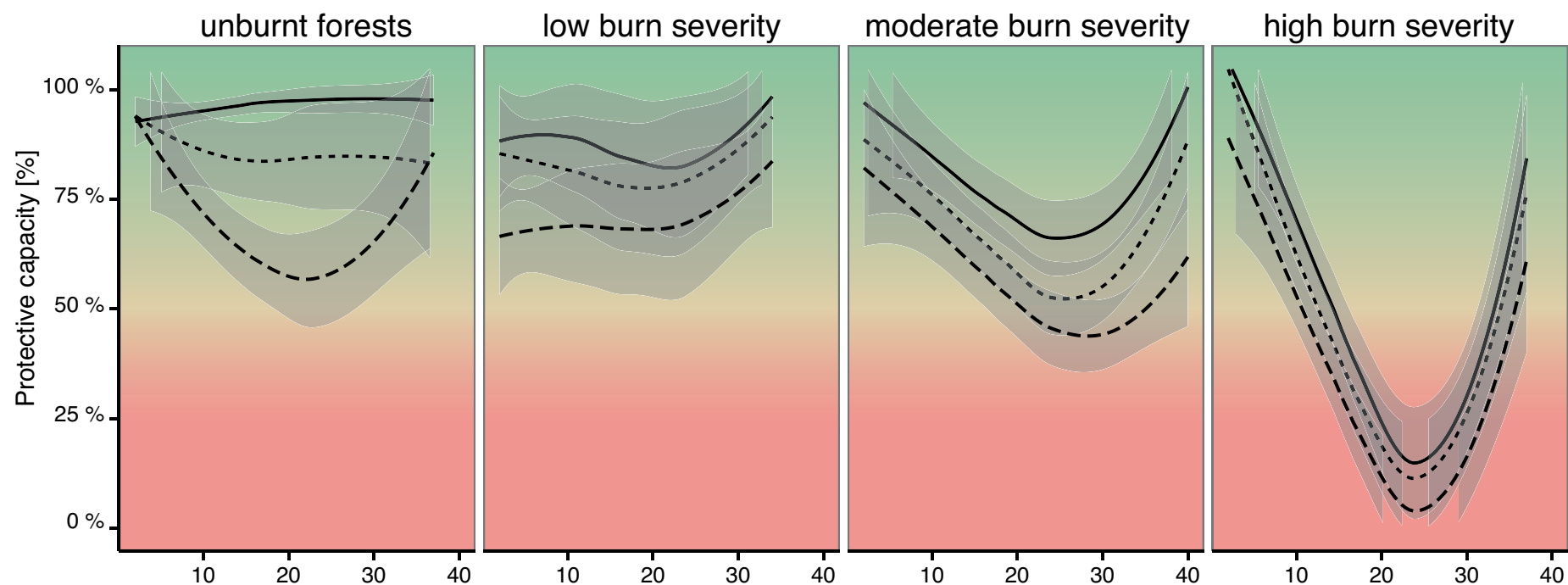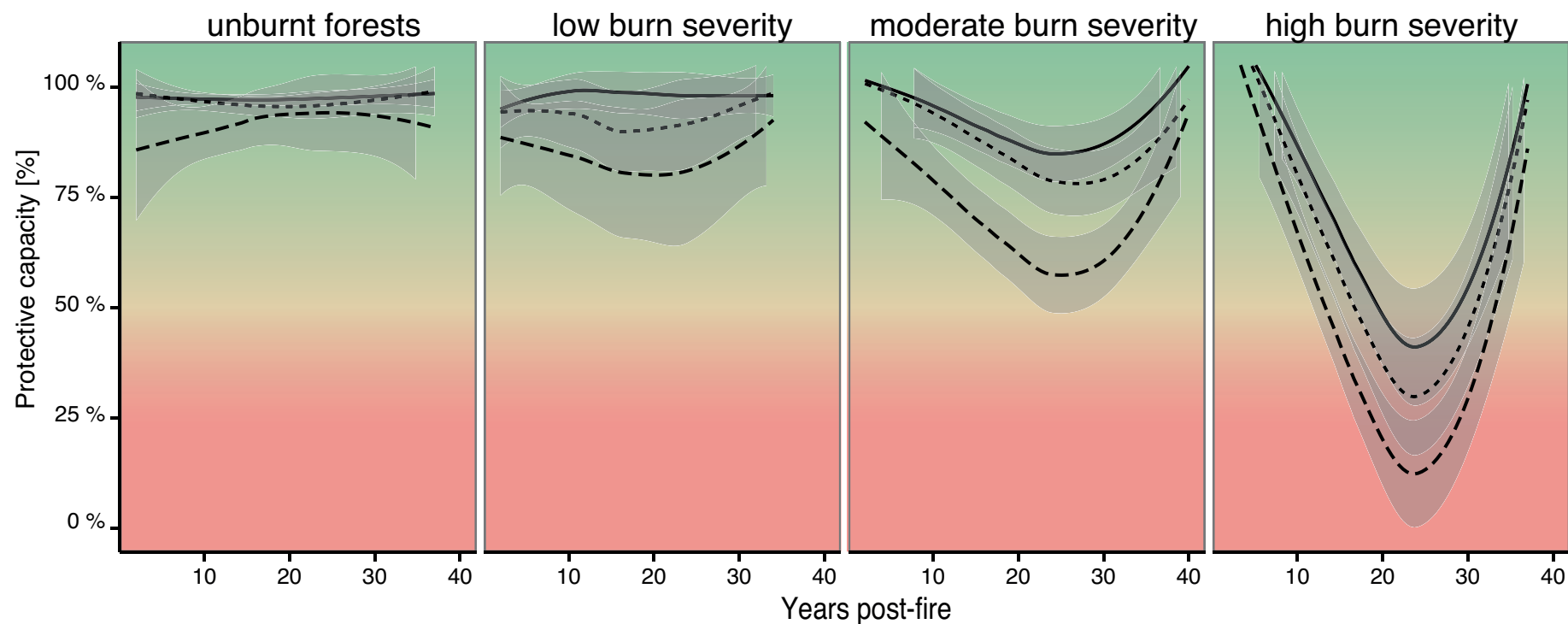
Figure

Scenario: Stone 1 m³; Slope: —— 27° ···· 30° –– 35°

(a) Slope length = 75 m

unburnt forests | low burn severity | moderate burn severity | high burn severity

Protective capacity [%]

(b) Slope length = 150 m

unburnt forests | low burn severity | moderate burn severity | high burn severity

Protective capacity [%]

Years post-fire