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ORIGINAL PAPER

Comparison of postfire mortality in endemic Corsican black pine (*Pinus nigra* ssp. *laricio*) and its direct competitor (*Pinus pinaster*)

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Abstract
· ***Introduction*** Laricio pine (*Pinus nigra* J.F. Arn. ssp. *laricio* (Poiret) Maire var Corsicana Hyl.) is a form of black pine endemic to Corsica, that may now be under threat due to current fire regimes and competition with maritime pine (*Pinus pinaster* Aiton).
· ***Material and methods*** This study aimed to compare postfire mortality in laricio and maritime pine in a mixed stand in northwest Corsica. Diameter at breast height, bark char, bole length charred, and tree mortality were measured in 661 trees 9 months after a severe fire. Logistic regressions were used to determine mortality probabilities which, to compare the two species, were expressed in relation to species, age, and species-independent severity indicators.
· ***Results*** For all ages considered, laricio pine mortality was up to threefold that of maritime pine. The differences between the species were most significant in pines less than 60 years old and exposed to severe conditions. This was mainly due to differences in growth rate between the two species.
· ***Conclusion*** Considering life history traits, maritime pine appears to be better adapted than laricio pine to the risk of fire. As the frequency of major fires in Corsica is on the increase, constituting a real threat for endemic species, we provide a few management guidelines for conservation of the laricio pine.

Keywords Fire impact · Pine · Postfire mortality · Survival · Logistic regression

1 Introduction

Current fire regimes in the Mediterranean area may be a threat to high-elevation pines, depending on their ability to regenerate or survive after a fire (Pausas et al. 2008). In Corsica, large stands of laricio pine (*Pinus nigra* J.F. Arn. subsp. *laricio* (Poiret) Maire var Corsicana Hyl.) recently sustained severe damage during 10 forest fires in 2000 and 2003. Laricio pine often forms mixed stands with maritime pine (*Pinus pinaster* Aiton), its main competitor (Zaghi 2008). Both pines are shade-intolerant and thrive on poor, acid soils. Laricio and maritime pines both played a significant role in the Corsican landscape during the late Holocene. After the last ice age, laricio pine was the first to undergo extension (2500 BP), followed by maritime pine (between 2000 and 1000 BP). Charcoal fragments suggest that fire and slash-and-burn agriculture favor the expansion of maritime pine (Carcaillet et al. 1997), and its postfire regeneration is far denser than that seen with *P. nigra* (Pausas et al. 2008). Maritime pine currently covers 18% of Corsican forest, compared with 31% for laricio pine (French National Forestry Inventory—FNI). But the range of the laricio pine may decrease in coming years due to increasing fire frequency, and to better understand this potential recession, we undertook to investigate, and report here, the survival ability of these two species.

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The laricio subspecies of the black pine is endemic to Corsica (Afzal-Rafii and Dodd 2007) and is included in annex I to Council Directive 79/409/EEC on the Conservation of Natural Habitats. Mature and overmature laricio stands are the habitat of several endemic bird species, including the Corsican nuthatch (*Sitta whiteheadi*), (Prodon and Thibault 2002a, b). Because of the rarity, beauty, and ecological importance of old pines, forest managers go to great lengths to conserve damaged stands. But the presence of many dead trees increases the risk of healthy trees being attacked by bark beetles (Jenkins 1990; Ryan and Amman 1994; Sullivan et al. 2003), and foresters are also looking to mitigate the visual impact of damaged forest. Thus, the conservation of laricio pine in its competition with maritime pine requires tools that can be used to assess the likelihood of mortality in damaged trees, coupled with pertinent forest management prescriptions.

The ability of a tree to survive a fire depends on crown shape, bud size, bark thickness (related to diameter at breast height, DBH) and root structure. Crown injury is related to the intensity of the surface fire and to flame length. Stem injury is related to both fire residence time in surface fuels and bark thickness (Ryan 1982; Rego and Rigolot 1990). Logistic models of postfire mortality in pines have been developed for several species (see Fernandes et al. 2008 for a review in European pines). Model variables consist of dendrometric parameters (height, diameter at breast height) and several indicators of fire severity (crown scorch volume, bole length charred, bark char). Mortality generally occurs 2 or 3 years after the fire, but may be observed in old pines 13 years later (Rigolot 1992; McHugh and Kolb 2003; Sullivan et al. 2003).

Although some mortality data are available for *P. nigra* (Ordonez et al. 2005), no model has been developed for laricio pine. Also, no comparison has yet been made between laricio and maritime pines. In the study reported here, we used logistic regressions to model individual short-term mortality in relation to tree size and fire severity in the two pines. These models can help managers by predicting pine mortality but cannot be used directly for a satisfactory comparison between the two species as a given fire will not produce the same damage in the two trees. In addition, comparing trees of a given diameter makes no sense in terms of an analysis of population dynamics. In order to compare more rigorously their resistance to fire, additional variables were used, to understand how the two species will be threatened in a context of competition under increasing fire occurrence.

2 Materials and methods

Tree diameter, fire severity characteristics, and tree mortality were measured in Corsica in 2004 in a mixed stand of laricio and maritime pines 9 months after a major wildfire, and the results were used to compute logistic mortality models for each species.

2.1 Study sites

The study area consisted of a mixed stand of laricio and maritime pines in the Cinto–Rotondo forestry zone. Two sites were selected on the south-facing slope of the Tartagine valley and on the north-facing slope of the Melaja forest (Haute Corse; 42°29′00 N, 9°11′00 E). The wildfire occurred in late August caused by lightning during the heat wave and severe drought of 2003, and burned 1,836 ha (i.e., 52% of the Tartagine and Melaja forests). The fire was very severe (stand-replacing fire) over most of the area but patchy because of the uneven terrain with many rocky outcrops. This resulted in unburned patches from place to place, offering a wide range of severities. No major fires had been recorded in the area prior to 2003, and most of the forest could be considered as old growth.

Table 1 Tree sampling design and variables measured

	Range	Sampling classes
DBH		
Maritime pine	5–65 cm	6 classes
Laricio pine	5–75 cm	7 classes
BLC	0–100%	0–20%: low severity
		20–30%: medium severity
		30–60%: high severity
		>60%: very high severity
BC	0: bark not blackened 1: slightly or not completely blackened	No sampling class for this variable
	2: moderate uniformly but moderately blackened	
	3: deeply charred	

DBH diameter at breast height, *BLC* bole length charred, *BC* bark char

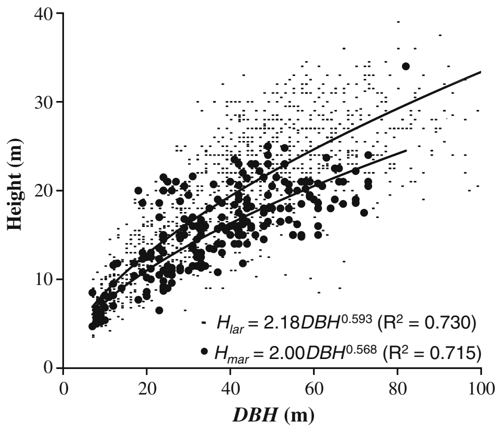

Fig. 1 Relationship between height and diameter at breast height (*DBH*) for the two pine species (FNI data: Cinto–Rotondo area)

2.2 Data collection

Sampling was stratified according to both DBH and bole length charred (BLC) to avoid correlations between tree size and thermal damage in the dataset (Table 1). DBH was measured to within 1 cm and trees grouped into classes 10 cm apart. Bark thickness (BT, in cm) at breast height was computed from DBH (in cm), using FNI relationships valid for the Cinto–Rotondo zone ($BT = 0.0667DBH + 0.0104$ for maritime pine and $BT = 0.044DBH + 0.0117$ for laricio pine). Bark factor (BF) was computed according to Ryan et al. (1994): $BF = 1 - e^{-BT(cm)}$.

BLC, i.e., the greatest percentage of bole height charred by the fire, was measured using a Suunto dendrometer. Severities were divided into four BLC classes: low, medium, high, and very high fire severities (Table 1). These BLC classes were derived from mortality probabilities obtained by a preliminary sampling of 50 trees, and corresponded to 0–25%, 25–50%, 50–75%, and 75–100% dead trees. BLC was our only indicator of flame height and canopy damage (Hely et al. 2003; Sidoroff et al. 2007). Even if crown scorch volume is often the most accurate predictor (Ryan and Reinhardt 1988; McHugh and Kolb 2003), it cannot be measured a few months after a fire because scorched needles cannot be distinguished from needles yellowed by the postfire decaying of the tree, and because most have already fallen to the ground.

Bark char depth was estimated on each quadrant of the bole 0.5 m above ground level and ranged from zero when the bark was not blackened, to three when it was deeply blackened. Mean bark char (BC) was computed as the mean of the four bark char depth values.

Tree status M (alive=0, dead=1) was also estimated, the tree being considered dead in the absence of green needles and buds ready to open (Rigolot 2004).

2.3 Data analysis

Logistic regressions of tree status were computed in relation to BF, BLC, and BC using "R" software (Ihaka and Gentleman 1996; Eq. 1). The regression coefficients were tested using Wald's χ^2.

$$P_{mortality} = \frac{1}{1 + e^{-\left(\sum_i a_i \times X_i\right)}} \quad (1)$$

where X_i is the different variables and a_i their coefficient.

The significance of the explanatory variables was evaluated from deviance ratio χ^2 tests. Models were selected on the basis of the Akaïke criterion (McCullagh and Nelder 1989). Data sparseness (due to the fact that the tree was either dead or alive) could have led to underestimated deviance, and thus to an overestimation of the model's joint significance (McCullagh and Nelder 1989). The original dataset was therefore resampled on the basis of the linear predictor $\sum a_i \times X_i$ obtained from the original logistic regression in eight tree classes. We compared the average mortality probabilities in these groups, and this nonsparse dataset was used to evaluate deviance and thus provide an unbiased joint significance (McCullagh and Nelder 1989). The concordance index CI (Regelbrugge and Conard 1993) was used to evaluate model efficiency and consists in systematically comparing the predicted mortality probability for each pair of trees, one dead and the other alive. When the mortality probability of the live tree was lower than for the dead tree, the pair was said to be *concordant*. Otherwise, the pair was said to be *discordant*. The CI was computed as:

$$CI = \frac{NC}{T} \quad (2)$$

where T is the total number of pairs, and NC is the number of concordant pairs.

Table 2 Outline of measured variables

	Number of trees	DBH mean, [min–max]	BLC mean, [min–max]	BC mean, [min–max]	Mortality
Maritime pine	330	35 cm, [5–65 cm]	36%, [0–100]	1.85, [0–3]	30%
Laricio pine	331	40 cm, [5–75 cm]	41%, [0–100]	1.96, [0–3]	40%

DBH diameter at breast height, *BLC* bole length charred, *BC* bark char

Table 3 Logistic models of mortality for maritime and laricio pine

	Intercept	BF	BLC	BC	Deviance	DF	CI
Mar1	−0.759±0.76	−9.32±1.29***	0.0499±0.89***	2.71±0.49***	224 (Null 403) AIC 232	326	0.908
Mar2	0.773±0.62	−5.39±0.85***	0.0679±0.0080***		268 (Null 403) AIC 274	327	0.864
Mar3	−0.527±0.738	−9.04±1.21***		3.53±0.47***	262 (Null 403) AIC 268	327	0.873
Lar1	0.222±0.800	−9.95±1.32***	0.103±0.014***	1.20±0.47*	189 (Null 446) AIC 197	327	0.948
Lar2	1.13±0.69	−8.78±1.17***	0.118±0.014***		196 (Null 446)AIC 202	328	0.943
Lar3	−0.376±0.721	−8.47±1.04***		3.10±0.40***	291 (Null 446) AIC 297	328	0.857

BF bark factor, *BLC* bole length charred, *BC* bark char, *D* deviance, *AIC* Akaïke criterion, *DF* degrees of freedom, *CI* concordance index

Mar1, *Mar2*, and *Mar3* are models for maritime pine, with three or two variables. *Lar1*, *Lar2*, and *Lar3* are models for laricio pine, with three or two variables

***P<0.001; **P<0.001; *P<0.1 (χ^2 test)

2.4 Comparing mortality in the two pines

A given damage level results in a species-dependent mortality probability. But damage itself is species-dependent. Any comparison of species-specific mortality must therefore include species-specific damage differences, which in practice is difficult because fire conditions around a given tree are unknown. We chose to rely on damage indices (referred to later as *independent indices*) scaled identically for both species. For example, crown scorch volume cannot be considered as an *independent index*, because it depends on crown structure. On the other hand, BLC can be seen as an independent indicator of flame height for identical DBH and height. But, for a given DBH, laricio pine is slightly higher than maritime pine (Fig. 1), so BLC is not an independent index. We therefore introduced $BLC_{mod}(DBH) = \frac{\text{Flame}Height}{H_{mar}(DBH)}$, as an independent index of flame height:

$$\begin{aligned} BLC_{\text{mod}}(DBH) &= BLC, \text{for maritime pine} \\ BLC_{\text{mod}}(DBH) &= BLC\frac{H_{lar}(DBH)}{H_{mar}(DBH)}, \text{ for laricio pine} \end{aligned} \quad (3)$$

where H_{lar} and H_{mar} are mean heights of laricio and maritime pines, respectively.

As the insulating property of bark does not vary substantially between species (van Mantgem and Schwartz 2003), BC may be assumed to be an independent index of residence time. Here, bark structure differences were assumed to be negligible. We then fitted logistic models in relation to the species (maritime=0, laricio=1), BF, BC, and BLC_{mod}.

DBH depends on species growth, so comparing tree mortality on the basis of diameter does not provide any valuable information with regard to population dynamics. As a life history trait, mortality should be analyzed in relation to tree age (A). Age/DBH relationships were derived from FNI data available for the forestry zone:

$$\begin{aligned} &\text{Maritime pine}: \ DBH = 3.02A^{0.588}(r^2 = 0.405; 54\,pines) \\ &\text{Laricio pine}: \ DBH = 1.93A^{0.639}(r^2 = 0.564; 276\,pines) \end{aligned}$$

As the study sites with basal areas between 18 and 25 m^2/ha and densities between 180 and 250 stems/ha were representative of the forestry zone, these relationships were assumed to be valid at these sites.

Finally, mortality probability was modeled in relation to species, age (A), and two independent indices (flame height and residence time) to compare species resistance.

Table 4 Deviance and joint significance after resampling linear predictors (no sparseness effect)

	Deviance	Null deviance	DF (Null DF)	Significance
Mar1	8.1	181	6 (7)	***
Mar2	4.6	133	6 (7)	***
Lar1	5.92	257	6 (7)	***

***P<0.001; **P<0.001; *P<0.1 (χ^2 test)

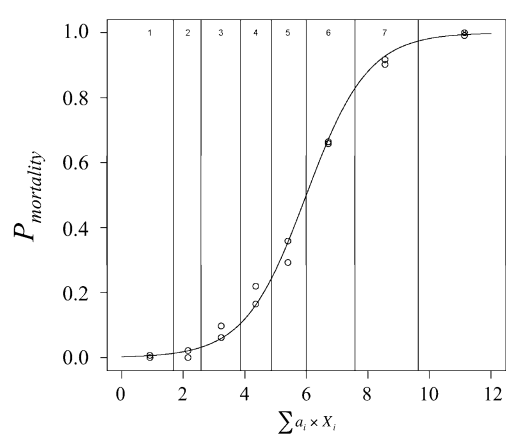

Fig. 2 Logistic regression of laricio mortality probability after resampling (i.e., without any sparseness effect) for the *Lar1* model

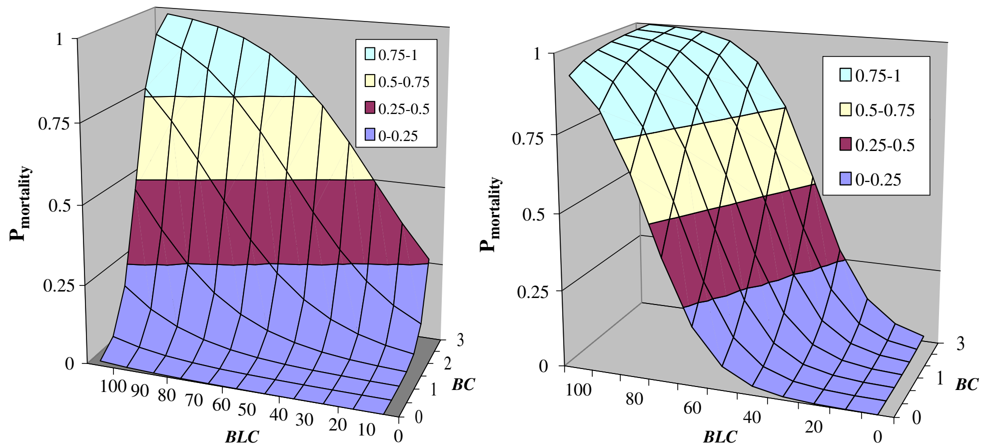

Fig. 3 Mortality probability (for a diameter at breast height of 35 cm in relation to bole length charred (*BLC*) and bark char (*BC*)) in maritime (*left*) and laricio (*right*) pines (*Mar1* and *Lar1* models)

3 Results

In all, 331 laricio and 330 maritime pines were sampled, covering a broad range of tree dimensions and thermal damage. Overall, laricio pine showed a higher mortality rate than maritime pine; about 40% of laricio pines died compared to 30% of maritime pines (Table 2).

3.1 Species-specific mortality models

The three best models for each pine species are presented in Table 3. *Mar1* and *Lar1* used three explanatory variables (BF, BC, and BLC). *Mar2* and *Lar2* used two explanatory variables (BF and BLC), as did *Mar3* and *Lar3* (BF and BC). Significance values were all very high (likelihood ratio test $P \leq 0.0001$) with concordance indices of more than 0.85. Model fits were better for laricio than for maritime pine, especially with BLC (*Lar1*, *Lar2*, *Mar1*, and *Mar2*). BC was indecisive for laricio pine (*Lar2* was almost as good as *Lar1*), but was significant for maritime pine since the performance of *Mar2* was poorer than that of *Mar1*. As expected, the resampling used to avoid the sparseness effect decreased joint significance (Table 4), which was initially biased. But significance remained satisfactory, and the models were well fitted (e.g., *Lar1* model in Fig. 2).

Figure 3, derived from models *Lar1* and *Mar1*, shows mortality probabilities for the two pines at median diameters (DBH=35 cm). Maritime mortality was sensitive to BC decreasing with this index. Laricio pine was less sensitive to BC. As a result, mortality at low BC was far higher in laricio than in maritime pines. Small laricio pines (DBH=25 cm) were more vulnerable to fire than maritime pines. In contrast, large and medium laricio pines were less vulnerable than maritime pines (Fig. 4).

3.2 Model common to both species

A model that included both species selected using the Akaïke criterion (Table 5), *MarLar1*, showed significant differences between the two species, mostly explained by BC. The BF × Species interaction was not significant, consistent with the hypothesis that BF is a species-independent indicator of bark insulating properties. The

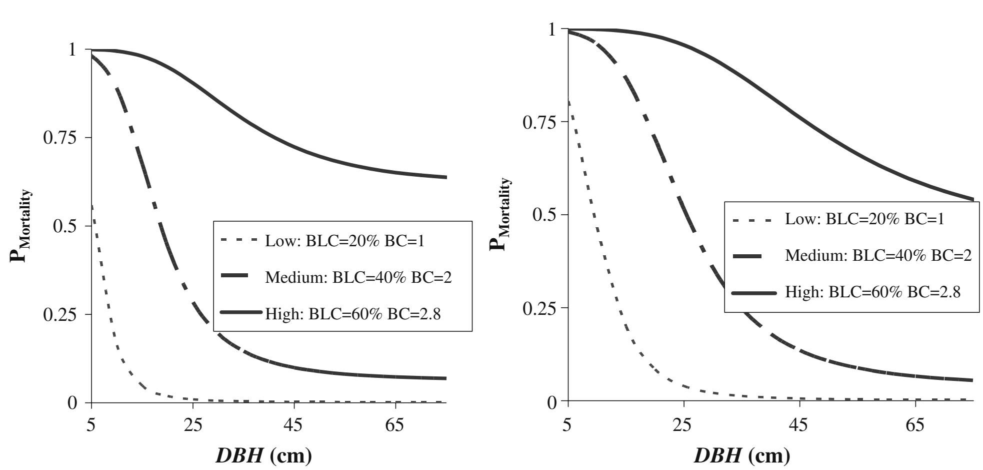

Fig. 4 Mortality probability in relation to diameter at breast height (*DBH*), in maritime (*left*) and laricio (*right*) pines (*Mar1* and *Lar1* models)

Table 5 Logistic models common to both species (*MarLar1*)

Intercept	BF	BLC_{mod}	BC	BLC_{mod} × Species	BC × Species	Deviance	DF	CI
−0.225± 0.54	−9.71± 0.92***	0.0498± 0.0087***	2.62± 0.372***	0.0352± 0.0141*	−1.26± 0.35***	415 (Null 857) AIC 427	655 (Null 660)	0.930

BF bark factor, BLC_{mod} bole length charred (modified), *BC* bark char, *D* deviance, *AIC* Akaïke criterion, *DF* degrees of freedom, *CI* concordance index

***$P<0.001$; **$P<0.001$; *$P<0.1$ (χ^2 test)

species index was significant (through variables BLC_{mod} × Species and BC × Species), showing different behavior between the pines in terms of postfire mortality. For a given bark factor, similar damage to the crown (BLC) caused higher mortality in laricio than maritime pine. Similar damage to bark (BC) caused lower mortality in laricio than maritime pine. Using BLC_{mod} instead of BLC did not significantly alter the results, but was more satisfactory for species comparisons. A significant correlation was found in the dataset between BC and BLC_{mod} ($r^2=0.576$), due to probable correlations between residence time (associated with BC) and flame height (associated with BLC_{mod}). For the sake of simplicity, this correlation between measured variables was used to establish a single independent fire damage variable FD (%):

$$\begin{aligned} &\text{For a given } FD, \quad -BLC_{mod} = FD \\ &-BC = 1.35 + 0.013 \times FD \end{aligned} \tag{4}$$

Laricio mortality was higher under almost all fire conditions, frequently up to 30% and even 100% for young pines experiencing intense fire. Differences between the species were less significant in old pine stands experiencing minor fire damage (Fig. 5). The vulnerability of young laricio may be explained by their smaller size and poorer self-pruning capacities, resulting in more low branches than in maritime pine.

4 Discussion and conclusion

4.1 Model evaluation

As expected, short-term tree mortality decreased with BF and increased with BLC and BC. Model fits were very good even without using crown scorch volume as a predictive variable given that this probably correlates with bole length charred (bole length charred itself has no physical meaning in terms of indicating damage). Taking into account a possible sparseness effect (artificial decrease in deviance) by resampling had little effect on the results. The fact that only short-term mortality was modeled may also go some way to explaining the very good fit obtained with the models as short-term mortality is directly related to the fire's physical characteristics (Hely et al. 2003; Sidoroff et al. 2007). Delayed mortality, often due to indirect factors such as bark beetles or local drought conditions, is known to introduce more variability into model predictions (Ryan and Amman 1994) and should be taken into account in management applications.

The relative insensitivity of laricio mortality to BC at low and high BLC is surprising (Fig. 3, laricio pine). This could mean that its cambium is well protected under the bark even when severe damage is sustained, but the relatively thin bark of the laricio pine does not support this hypothesis. Another opposing hypothesis is that laricio pine is already very sensitive to the lowest levels of bark damage (BC=1), meaning that the BC scale is not a good linear

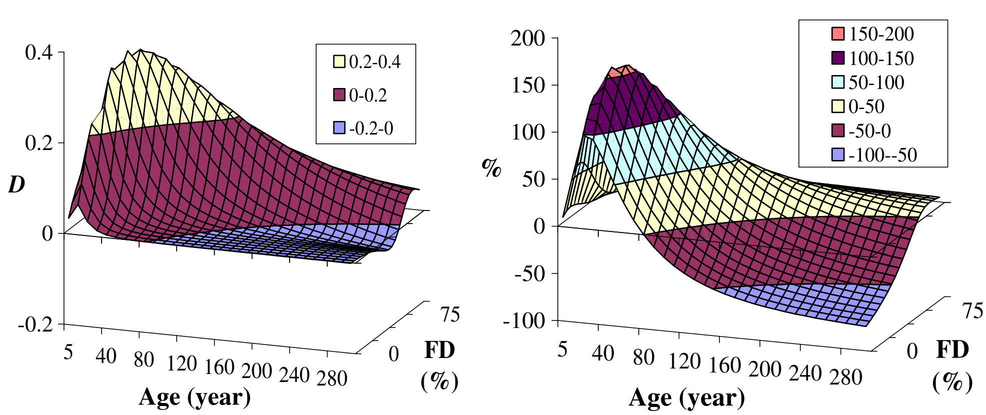

Fig. 5 Absolute and relative differences in mortality probabilities between maritime (*left*) and laricio (*right*) pine in relation to age and fire damage *FD* (%; *MarLar1* model)

predictor of mortality in a logistic regression. But the model's very good fit does not support this second hypothesis. An explanation may be found in BC/BLC correlations. In the dataset, cases with low BC and high BLC (and vice versa) were rare because severities near the ground and in the canopy were correlated; consequently, the model is probably less accurate in these cases. This does not raise a serious problem for operational use because the model will be used within the parameter range that provides a very good fit. But this slightly weakens interpretations in terms of species resistance to fire damage.

4.2 Comparison between resistance in the two species

At all given ages, the probability of laricio mortality was far higher than that of maritime pine at the same level of bole damage. It was higher for almost all ages and fire damage percentages (Fig. 5), especially for young trees. These differences may for the most part be explained by diameter and height growths, which were significantly lower in laricio pine, but also by the fact that laricio bark was thinner for a same DBH and it had more low branches. In addition, maritime pine bark is more fissured and laminated than in laricio, which favors desquamation when burning (Fernandes and Rigolot 2007) and limits heat flux on the maritime pine bole.

The interspecies differences in short-term mortality suggest that more frequent fires place laricio pine at a disadvantage with respect to maritime pine. The postfire regeneration of laricio pine is unknown, but other *P. nigra* generally lack regeneration, especially when compared to maritime pine (Pausas et al. 2008). These results are consistent with Carcaillet et al. (1997), who explain that the extension of maritime pine and the decrease in laricio pine were caused by an increase in fire frequency during the Holocene.

4.3 Management guidelines

Although the *Lar1* and *Mar1* models can only predict short-term mortality, they can nevertheless be used by forest managers looking to assess individual tree mortality in the year following a fire.

First, as the disadvantage of the laricio pine is more marked in its young stages, forest managers should concentrate their efforts in pure laricio or mixed stands less than 60–80 years old, even if the value of old growths is higher. Second, given that laricio pine is more vulnerable to bark damage and flame height, residence time and fire intensity must be reduced, especially near the ground, by removing surface fuel. Litter and understorey can be controlled by mechanical clearing or prescribed burning in sufficiently old stands. Ladder fuel can be diminished by pruning, and this can reduce crowning and protect the seedlers required for regeneration. The selective thinning of maritime pine can also reduce competition with laricio. Moderate thinning is recommended even in pure laricio stands to enhance radial growth which increases tree resistance (through thicker bark), but also to reduce crown fire risk. Dreyfus (1990) recommends moderate thinning of *P. nigra* stands combined with brush clearing in 30–40-year-old stands where growth is maximal. When postfire logging is absolutely necessary for safety or esthetic reasons, we recommend cutting the fewest pines possible because even seriously injured trees with low survival probabilities can provide a suitable habitat for the endemic Corsican nuthatch (Moneglia et al. 2009).

The recent increase in fire occurrence and severity coupled with the maritime pine's better adaptation to dry conditions and its postfire resistance suggest that the laricio pine's situation in Corsica could deteriorate rapidly. The inclusion of postfire regeneration capacities and survival abilities in population dynamics models (Franc et al. 2000) would allow the future of Corsican forests to be predicted under different fire regimes and management scenarios, enhancing the conservation of this important ecosystem in the long term.

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