Temporal and spatial dynamic of stool uprooting in abandoned chestnut coppice forests

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Abstract

Chestnut (*Castanea sativa* Mill.) coppice is a man-made forest type that has been managed for centuries in short rotations to rapidly produce woody biomass. These forests, which nowadays cover significant areas within Europe, experience a general neglect and are subsequently being abandoned. Most of them are now over-aged, very dense, and highly monotone. Little is known about their development. The increasing frequency of uprooting events of stools (i.e., a whole stump including the shoots that originated after coppicing), is raising concern among forest managers who fear a progressive expansion of the phenomenon.

Our objective was i) to describe the temporal and spatial patterns of the ongoing uprooting processes, ii) to identify causes and iii) to estimate future developments. We have analysed the stool uprooting dynamics in a 100-ha abandoned chestnut coppice and have built an empirical, predictive model to estimate the uprooting probability based on topographic, stand and stool characteristics. Finally, detailed uprooting dynamics were reconstructed at the single gap level for three case studies to characterise the process of gap expansion. Tree-rings were used to date the relevant events.

We found that uprooting is primarily caused by precarious tree statics rather than external forcing agents. The empirical model clearly predicts that tall stools located in hollows and gullies the most likely to uproot. In fact, in this particular situation a non-extreme environmental event suffices to disturb the equilibrium between the higher tree-induced gravitational loads and the weaker root anchorage, resulting in a collapse. Since the stool uprooting is mainly an endogenous process, we expect a progressive increase of this phenomenon with the ageing of abandoned coppices.

From the forest manager's perspective, this situation favours a progressive rejuvenation and diversification of the forest structure. On steep slopes, however, where the forests also play an important role in protecting infrastructure, uprooting events might entail some additional risks. Our results have important management implications for foresters.

Key-words: *Castanea sativa*, treefall gaps, stand dynamics, empirical modelling, tree-ring, insubric ecosystems.

Introduction

50 Succession is the process through which a plant community evolves and changes into another (Clements, 1916; Gleason, 1917; 1927; Crawley, 1985). In the specific case of forests, these changes are mostly driven by processes of canopy replacement. Disturbance resulting in death of canopy trees has the effect of releasing growing space which is available for other plants. Future canopy composition not only depends on the species, size and abundance of individuals and
55 species that occupy the newly available spaces, but also on the type and number of overstorey trees removed from the canopy (Oliver and Larson, 1996). Catastrophic disturbances, such as windstorms or fires, usually remove large portions of the canopy, leading to complete stand regeneration. Although these disturbances can have a natural origin, their impact can be substantial depending on a forest's function. For protection forests, for instance, such unpredicted
60 disturbances are highly undesirable since they expose settlements and infrastructure to unacceptable risks. Succession can also be progressively achieved through small-scale disturbances involving the death of only a single or few trees. In this case, changes are mainly based on the processes of gap creation and filling; and thus, forest cover is present even throughout the transition phase (e.g. Poulson and Platt, 1989; Lertzman, 1992).

65 Understanding the dynamics of forest replacement helps to clarify management objectives: active forest management based on model predictions can mitigate the occurrence of catastrophic disturbances. Although our understanding of canopy gap dynamics and replacement processes in undisturbed forests is substantial (e.g. Uhl et al., 1988; Brokaw and Scheiner, 1989; Manrubia and Solé, 1997; Dubé et al., 2001; Gagnon et al., 2004; King and Antrobus, 2005), these processes
70 have yet to be studied in secondary and abandoned man-made forests, which are more exposed to major disturbances because of their monotonic structure.

Sweet chestnut (*Castanea sativa* Mill.) is a tree species that has been intensively cultivated for centuries as a monoculture (coppices and orchards), even at the limits of its potential ecological range (Pitte, 1986; Bernetti, 1987). Chestnut forest ecosystems still represent an important landscape component in the mountainous regions around the European Mediterranean basin and in the Southern Alps, covering more than 2.2 million ha (Conedera et al., 2004). Since the early 1950s, however, changes in the socio-economic structure of the rural areas and the spread of chestnut diseases such as chestnut blight (*Cryphonectria parasitica* (Murr.) Barr.) and ink disease (*Phytophthora* spp.) have caused a decline in the cultivation of sweet chestnut forests in many European regions (Pitte, 1986). As a result, both coppices and orchards were abandoned and gave way to a more natural forest development (Arnaud et al., 1997; Conedera et al., 2001). Chestnut coppices, which for millennia have been regularly and intensively managed for fast timber production, have long exceeded their usual rotation length (< 20 years). Today, they are over-aged and highly monotonic in structure. These stands are mainly located on steep slopes, where they are starting to manifest first signs of decline. Over-aged chestnut stools (i.e., whole stumps including the shoots that originated after coppicing) lose vitality and competitive power (Fonti et al., 2006). Meanwhile, openings within the forest canopy, especially when resulting from stool uprooting events, are becoming more frequent. This novel situation is raising concern among forest managers who fear a general loss in stability of abandoned stands, which may compromise their important protection function.

The aim of this study is to gain a better understanding of the ongoing successional processes occurring in abandoned chestnut coppices in order to evaluate the magnitude of risk involved. In particular, this study intends (1) to describe the temporal and spatial pattern of stool uprooting dynamics at the stand scale and at the forest gap level, (2) to identify the main factors causing uprooting, and (3) to build an empirical predictive model in order to estimate the probability of chestnut stool uprooting.

Materials and methods

Study sites

We performed analyses on stool uprooting on various abandoned forest plots belonging to the non-native chestnut forest belt of the Southern Swiss Alps, specifically in Ticino. The main study area, a 100-ha chestnut (*Castanea sativa* Mill.) forest, was selected to describe the stand level occurrence of uprooting and to collect the data necessary to build an empirical model. The area, located between the villages of Gravesano, Manno, Cademario and Bosco Luganese (lat. 46°02'00'' N, long. 8°51'50'' E), ranges from 330 to 820 m a.s.l. and is exposed prevailing East–Northeast. The slopes are steep, with 52% of the area exhibiting slopes $> 30^\circ$ and another 38% between 20° and 30° . The area is completely forested and dominated by chestnut coppices abandoned for more than 50 years. Other hardwood species such as oak (*Quercus* spp.), common alder (*Alnus glutinosa* Gaertn.), ash (*Fraxinus excelsior* L.), sweet cherry (*Prunus avium* L.), and beech (*Fagus sylvatica* L.) occur sporadically. Some abandoned chestnut orchards are located on the gentle slope zones close to villages. The forest has a closed and single layer canopy and regeneration is rare.

In addition to the main area, we selected three small plots (approx. 0.1-0.2 ha) with at least 15 uprooted stools within other abandoned chestnut coppices in order to study the dynamics of uprooting in single forest gaps. The plots are located next to Locarno, Bellinzona, and Gravesano.

Survey within the main study area

During the early spring of 2005, an inventory of all tree-fall events was completed through ground reconnaissance. We considered only live uprooted trees *sensu* Schaetzel et al. (1989). Groups of fallen trees were assigned to a single event. Only that tree which was supposed to be the origin of the collapse was counted and measured. For each event we annotated the location, species, and the forest management type (coppice or orchard).

To identify differences between uprooted and standing stools, we surveyed a set of topographic, stand and stool parameters relevant for stool stability (Schaetzl et al. 1989) (see Table 1). Since we were especially interested in processes occurring in chestnut coppice, only chestnut coppice stools were measured. A total of 45 uprooted stools were randomly selected from a subset of stools that
125 were unaffected by ivy (*Hedera helix* L.) and that had been uprooted in the last 5-7 years. We used the presence of bark and fine roots as visual selection criteria. Consequently, an equal number of standing coppice stools were randomly selected using a 50-m wide sampling grid. All grid points located at least 25 m away from the inventoried uprooted stools were considered for the draw. Our ultimate selection was the standing chestnut stool closest to the chosen grid point. Due to the
130 relatively homogeneous density of the coppice, this procedure did not result in a biased selection (see Crawley 2002, pp 53-55).

We used tree-ring analyses to describe the growth of the selected stools as well as to date the overturning events to the exact year. For each selected stool, either a core or a wood disc was taken from the dominant shoot. Wood samples were taken at about 1 m height in order to avoid
135 root influences. Wood discs and cores were sanded and tree-ring widths measured to the nearest 0.01 mm with a standard tree ring measuring device (Measuring table Dendrotab Walesch, Effretikon, Switzerland). Ring-width data were visually crossdated with TSAPWIN v0.53 (Frank Rinn, Heidelberg, Germany) and subsequently checked with COFECHA v6.06p (Holmes, 1983; Grissino-Mayer, 2001). Since in some cases fallen stools did not die immediately, we counted the
140 internodes of freshly sprouted epicormic shoots to determine uprooting year.

Model construction and statistical analyses

We used logistic regression modelling (Hosmer and Lemeshow, 2000) to find the relevant predictor variables as well as to predict the probability for an uprooting event to occur. We evaluated model performance in terms of model calibration and model discrimination by
145 calculating Nagelkerke's R^2_N as well as the AUC-value (area under the receiver operating characteristic curve, Fielding and Bell, 1997; Harrell, 2001). In the case of multiple models, classification rate, sensitivity (i.e. the proportion of correctly classified events) and specificity (i.e.

the proportion of correctly classified non-events) were calculated for an optimal cut-off probability according to Schröder (2004). To receive unbiased estimates of model performance, we internally
150 validated the models via bootstrapping (Verbyla and Litvaitis, 1989; Reineking and Schröder, 2003) and then corrected for optimism (see Peppler-Lisbach and Schröder, 2004, Oppel et al., 2004).

First, we considered only those predictors that achieved AUC-values exceeding 0.7 and R^2_N greater than 0.2 in the univariate case. Additionally, we checked for unimodal relationships by
155 testing significance of quadratic terms as well as two-way interactions (Hosmer and Lemeshow 2000). We reduced multicollinearity among selected predictors by carrying out non-parametric bivariate correlation analyses and applying a threshold of $r_s = 0.7$ for removing one out of a pair of correlated predictors from the analyses according to Fielding and Haworth (1995).

Following these steps, a backward stepwise variable selection was applied to determine the final
160 set of predictor variables from the previously selected subset. We used Akaike's Information Criterion (AIC) to choose the most parsimonious model that offered the highest accuracy with the least variables (Burnham and Anderson, 1998; Reineking and Schröder, 2006). All these analyses were carried out with S-Plus 6.1. For model estimation and bootstrapping (2000 replicates) we applied the libraries *Hmisc* and *Design* provided by Harrell (2001,
165 <http://stat.cmu.edu/S/Harrell/library/splus6/>). To facilitate understanding and visual interpretation of the relationships between environmental conditions (tree-level and stand-level) with stool uprooting events, we produced three-dimensional response surfaces.

In a last step, we were interested in the amount of variability in uprooting events explained by the different predictors considered in the final model. We therefore applied hierarchical partitioning to
170 estimate the independent and joint effects of the predictors (Mac Nally, 2000) using the library *hier.part* provided by Mac Nally and Walsh (2004) for R 2.0.1 (R Development Core Team 2005, <http://www.r-project.org>).

Reconstruction of gap level uprooting dynamic

We compiled detailed maps of standing and uprooted stools for each of the three selected plots in order to reconstruct their specific uprooting history. The gap perimeter was defined by the position of the standing stools around the collapsed ones. Each stool in the perimeter was labelled and briefly characterised (species, tree height, number and circumference of shoots). In addition, we performed a specific survey with regard to the falling direction, the superposing pattern among uprooted stools, as well as the presence and count of internodes of recent epicormic vertical shoots for all uprooted stools. Finally, the stool's dominant shoot was cored and tree-ring analyses were performed to date the year of the falling events. At last, we analysed all this information to reconstruct the sequence of stool uprooting within the gaps.

Results

Rate and frequency of collapse

Within the 100-ha study area, we observed 137 places with at least one uprooted stool, which corresponds to a rate of 1.37 events/ha. Chestnut trees were at the origin of a gap in 119 cases (115 as coppice stools and four as chestnut orchard trees). Among the events triggered by chestnut stools, 35 cases involved more than one individual. In the remaining 18 cases, other tree species uprooted, such as oak, common alder, ash, sweet cherry, and beech. The largest event observed involved a group of 40 individuals.

The dating of the 45 randomly selected uprooted stools shows that the events occurred regularly. Except for two uprooting events prior to 1999, the events of the last 5 years are well distributed in time: 8 in 1999, 7 in 2000, 11 in 2001, 6 in 2002, 6 in 2003, and 5 in 2004. We can therefore estimate a frequency of about 20 events per 100 ha per year.

Characteristics of uprooted stools

Uprooted stools are distributed all over the study area, although they are mainly found in association with hollows and gullies. As shown in Table 2, uprooted stools are large compared to

chestnut coppice standards (Manetti et al., 2001). Exposed root plates were shallow (0.85 m) with an average area of 5.54 m². This type of uprooting pattern corresponds to the “simple falls” (*sensu* 200 Schaetzel et al., 1989), indicating that the fall results in a tree-tipping rotation with no backward displacement at the base of the stool. Except for a few rare cases, uprooted stools are oriented downslope. As depicted in Figure 1, multiple falls are caused by successive events of groups of contemporaneously uprooting stools. In general, this process mainly results in upslope gap enlargement.

205 ***Predicting the probability of falling***

The comparative analysis highlights some significant differences between standing and uprooted stools concerning topography as well as stand and stool characteristics (Table 2). To predict the uprooting probability of individual stools, we estimated logistic regression models. Table 3 shows the estimated model coefficients obtained by univariate logistic regressions for all significant 210 predictor variables. To test for unimodal relationships, all quadratic terms were checked for significance. At this point, we excluded variables with $p > 0.05$, $AUC < 0.7$ and $R^2_N < 0.2$.

The resulting set of selected significant candidate predictor variables was the preliminary input into the multiple logistic regression model. Stool height and stand height were highly correlated ($r_s = 0.786$). To avoid multicollinearity, we selected the parameter that is easier to measure for 215 management purposes which was stand height in this case. Table 4 summarizes the characteristics and performance of the final model. The regression coefficients indicate that the tree-fall probability increases with steeper slopes, concave curvatures and increasing tree-height. Figure 2 provides a graphical representation of the final model by means of response surfaces. Critical slopes and stand heights depend on curvatures. As indicated by the high performance criteria after 220 internal validation ($R^2_N = 0.775$ and $AUC = 0.966$), the model displays a very high explanatory and predictive power. Applying a critical threshold probability $P_{fair} = 0.52$, the overall correct classification rate, sensitivity and specificity is 91.1%.

The hierarchical partitioning analysis shows that all predictors reveal comparatively high independent effects on the probability of tree-fall events lying between 28% (profile curvature)

and 21% (stand height; cf. Fig. 3). In the case of plan curvature, almost half of the overall effect is joint but not independent from other predictors. For profile curvature and stand height, this joint effect is smaller (1/3 of total effect), for slope it is negligible.

Discussion

Uprooting determinants

Our results clearly show that uprooting in abandoned chestnut coppices does not occur simply by chance. The observed uprooting pattern suggests that specific topographic conditions together with stool characteristics significantly affect the likelihood of uprooting. As attested by our final model, particularly tall stools located in hollows and gullies are most likely to uproot. These results are in accordance with many other field observations and uprooting experiments performed in various types of forests and climate: Schaetzl et al. (1989) in their broad review on tree uprooting determinants already mentioned that wet and gleyed soils, steep slopes and larger trees were frequently associated with uprooting. More recently, tensile-strength experiments of soil-root systems on a variety of species (e.g. Peltola et al., 2000; Meunier et al., 2002), soils (e.g. Moore, 2000; Cucchi et al., 2004; Achim et al., 2005) and topographic situations (Nicoll et al., 2005) also support our findings.

From a mechanical point of view, uprooting occurs when lateral forces applied to the tree overcome root anchorage (Putz et al., 1983). In our study case, however, in comparison with similar studies on windthrow risks (e.g. Greenberg and McNab, 1998; McNab et al., 2004; Cucchi et al., 2005; Scott and Mitchell, 2005), the determinants for uprooting seem to be primarily driven by tree mechanical instability rather than by an external forcing agent. The first evidence supporting this claim is that the phenomenon almost exclusively affects stools that are the most unstable due to their static condition and topographic location. As we have shown, uprooting occurs preferentially in hollows and gullies. In these locations, coppice stools have better access to water and nutrients so that they can grow faster and taller in competition for light, but at the same time, they are often also tilted and have asymmetric crowns. In addition, steep slopes are subject to

erosion and mass-movement phenomena, and shear strength of the soil is reduced by high water content. As a result, the root plate is too weak to counteract the tree-induced gravitational load. Such stools are therefore more susceptible to uprooting. The falling patterns provide additional evidence for the endogenous origin of this phenomenon due to the diachronic occurrence of the events, their small extent, the patchy gap distribution, the almost complete absence of stool-falling on wind exposed crests, as well as the systematic downslope falling direction irrespective of the main wind direction.

Thus, we interpret uprooting in abandoned chestnut coppices as a consequence of precarious stool stability: Root anchorage cannot compensate for an aboveground biomass that is too large and unbalanced. In these cases, a slightly unusual environmental event, for instance high wind or wet snow, can be enough to trigger local uprooting.

Potential risks

The rate and frequency of uprooting events is not extreme. The estimated rate of about 20 collapsing events per 100 ha (that according to our definition might involve more trees) is far below the 200-450 fallen trees in an equal area reported by Falinski (1978) for a primeval forest in Poland, the 840 events estimated for an evergreen oak forest in Japan (Naka 1982) or the 100-210 events observed in a beech maple forest in the US (Brewer and Merritt, 1978). The endogenous origin of the processes underlying stool uprooting, however, allows us to predict a progression of this phenomenon along with time. Now, 30-40 years beyond the regular rotations, these strongly anthropogenic forests stands show a very dense and monotone structure. Therefore, stools will keep growing in size and thereby increase the risk of destabilization if no silvicultural intervention occurs. Moreover, roots have only very limited room for further expansion due to the high stool density (Fonti and Giudici, 2001). They are therefore unable to compensate for the increased instability by improving anchorage. But then, once an opening in the canopy occurs, the phenomenon tends to expand, probably as a consequence of increased instability, as the analysis of the falling dynamics in gaps has demonstrated. Remaining border stools have more room to bend,

they are more exposed to wind, and they are likely to occupy the available space with a more asymmetric crown formation.

From the forest manager's perspective, a mosaic spatial distribution of little canopy openings due to falling trees may have a positive consequence. Canopy gaps regulate diverse aspects of forest ecology. They are crucial for germination of seeds and growth of seedlings, which can influence the establishment of the species composition and regulate forest structure in a variety of forest ecosystems (e.g. Qinghong and Hakan, 1991; Gale, 2000; Clinton and Baker, 2000; Degen et al., 2005; King and Antrobus, 2005). Since abandoned chestnut coppices have a closed canopy and tend to be poorer in diversity (e.g. Fuller and Moreton, 1987; Cutini, 2001), such openings are opportunities for these anthropogenic forests to rejuvenate, to increase diversity and stability, and thereby to move towards a more natural species composition (Conedera et al., 2001). In some cases, however, especially on steep slopes where the forest also plays an important role in protecting human infrastructure, such uprooting events entail potential risks. For example, the fallen trunks and root plates could dam the bottom of small gorge stream. After an intense and long rainfall the accumulated and eroded material might be abruptly released as debris flow causing damages along the way.

A new tool in forest management

Our study, based on the analysis of uprooting patterns observed in a 100 ha forest, has highlighted that the uprooting is a phenomenon that is closely related to the abandonment and over-aging of chestnut coppices. Understanding the predisposing factors and the mechanisms leading to uprooting is a prerequisite for successful forest management. The empirical predictive model estimating the risk of uprooting provides an important management tool for foresters. For the future, we hope that the combination of this model with related spatial information about chestnut coppice distribution, potential tree heights (e.g. inferred by site fertility maps) and potential damaging objects will allow the elaboration of risk maps.

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Tables and Figures

440 Table 1: Description of all variables recorded

Variable	Unit	Description
Topographic parameters^I		
Slope	grad	Terrain inclination at the tree
Aspect	-	sin (Exposition), cos (Exposition)
Profile curvature	cat	Vertical shape of terrain (1-concave, 2-straight, 3-convex)
Plan curvature	cat	Horizontal shape of terrain (1-concave, 2-straight or convex)
Stand parameter^{II}		
Stand density	# / ha	Number of stools in the stand
Shoot density	# / ha	Total number of shoots in the stand
Stand height	m	Average height of the three tallest stools in the stand
Shoot circumference ^{III}	cm	Average circumference of the three largest shoots in the stand
Stool parameter		
Stool status	cat	Response variable: standing (0); uprooted (1)
Shoot number ^{III}	#	Number of all living shoots
Stool height	m	Height of the tallest shoots
Average shoot circumference ³	cm	Averaged circumference of all living shoots on the stool
Growth ₉₀₉₅	mm	Sum of the tree ring radial increment for the years 1990 to 1995 of the dominant shoot
Falling direction	-	Direction of collapse relative to the slope
Root plate surface	m ²	Surface of the eradicated root plate (area of the circle)
Root plate depth	m	Depth of the eradicated root plate
Root plate volume	m ³	Volume of the calotte

^ITopographic parameters are measured close to the concerned stool.

^{II} Stand parameter refers to a circle of 8 m radius around the concerned stool.

445 ^{III} Only shoots with a circumference > 20 cm were considered.

Table 2: Univariate comparative analyses between standing and uprooted stools.

Continuous predictor variables: median $\pm$ MAD and Mann-Whitney U-tests;

450 categorical predictors: crosstables and χ^2 -tests for independence.

Variable	Standing (n = 45)	Uprooted (n = 45)	Mann-Whitney U-test or χ^2 -test	
			test statistic	p-value
Topographic parameters				
Slope [°]	35.5 $\pm$ 13.4	43.5 $\pm$ 5.9	4.008	<0.0001
Sin (Exposition)	0.866 $\pm$ 0.150	0.643 $\pm$ 0.507	-2.414	0.016
Cos (Exposition)	-0.34 $\pm$ 0.510	0 $\pm$ 0.953	-0.275	0.784
Profile curvature			31.036	<0.0001
concave	2	19		
straight	23	25		
convex	20	1		
Plan curvature			35.280	<0.0001
concave	6	34		
straight/convex	39	11		
Stand parameters				
Stand density [# / ha]	250 $\pm$ 74	200 $\pm$ 148	-1.991	0.046
Shoot density per stool	1.60 $\pm$ 0.59	1.57 $\pm$ 0.64	0.462	0.644
Stand height [m]	18.3 $\pm$ 3.1	21.4 $\pm$ 3.0	5.052	<0.0001
Shoot circumference [cm]	100 $\pm$ 23	110 $\pm$ 20	2.026	0.043
Stool parameters				
Shoot number [#]	2 $\pm$ 1.48	2 $\pm$ 1.48	-0.227	0.821
Stool height [m]	17.7 $\pm$ 2.8	20.8 $\pm$ 2.7	5.804	<0.0001
Average shoot circumference [cm]	82 $\pm$ 26	97 $\pm$ 25	2.324	0.020
Growth9095 [mm]	1.22 $\pm$ 0.71	1.29 $\pm$ 0.66	-0.129	0.897
Root plate surface [m ²]	-	5.54 $\pm$ 3.13	-	-
Root plate depth [m]	-	0.85 $\pm$ 0.30	-	-
Root plate volume [m ³]	-	2.39 $\pm$ 1.70	-	

Table 3: Results of univariate logistic regression models for all significant predictor variables. We

455 present only regression slopes to show the direction of relationships; although all intercepts were significant they are omitted here.

Predictor	Regression slope	S.E.	p-values	R²_N	AUC
Slope	0.095	0.026	< 0.001	0.244	0.745
Profile curvature straight	-2.168	0.798	0.007	0.450	0.807
convex	-5.247	1.266	< 0.001		
Plan curvature convex	-3.000	0.559	< 0.001	0.462	0.871
Shoot density	-0.747	0.219	< 0.001	0.246	0.732
Stand height	0.391	0.094	< 0.001	0.358	0.809
Stool height	0.603	0.142	< 0.001	0.51	0.855

Table 4: Results of the final, multiple logistic regression model: a) estimates; b) model performance after internal validation by means of bootstrapping (2000 replicates); c) confusion matrix. P_{fair} corresponds to the threshold probability with equal sensitivity and specificity, P_{opt} and P_{Kappa} are optimised to yield the highest correct classification rate (CCR) and Cohen's Kappa, respectively.

a)

Predictor	Coefficient	SE	p-value
Intercept	-10.532	4.536	0.0202
Slope	0.244	0.076	0.0013
Profile curvature			
straight	-5.623	2.992	0.0602
convex	-7.849	3.288	0.0170
Plan curvature			
convex	-2.625	1.019	0.0100
Stand height	0.407	0.156	0.0091

b)

P_{crit}	Sensitivity	Specificity	CCR	Kappa
$P_{opt} = P_{Kappa} = 0.48$	0.933	0.911	0.922	0.844
$P_{fair} = 0.52$	0.911	0.911	0.911	0.822
$P_{0.5} = 0.5$	0.911	0.911	0.911	0.822
Nagelkerke's $R^2 = 0.775$		AUC = 0.966		

c)

Confusion matrix for P_{fair}		predicted	
		fallen	standing
observed	fallen	41	4
	standing	4	41

Figure 1: Uprooting dynamic within the three selected gaps.

Dashed line delimits the gap area, arrows refer to shoots of uprooted stools, circles to intact standing trees and triangles to damaged standing trees. The top of the map refers to upslope.

480 **Figure 2: Response surfaces according to the final model.**

Each response surface represents the predicted probabilities of tree fall events (z-axis) for different values of slope (y-axis) and stand height (x-axis) and different categories of plan and profile curvatures. Filled circles refer to uprooted stools, open circles to standing stools.

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Figure 3: Hierarchical partitioning of the final model. The bars show the relative independent effect of each predictor variable on the probability of uprooting events.