Fuel modelling and fire hazard assessment based on data from the Portuguese National Forest Inventory

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Abstract: Fire management activities can greatly benefit from the description of wildland fuel as a fire behaviour predictor. A forest typology developed from the Portuguese National Forest Inventory that combines cover type (the dominant overstorey species) and forest structure defined as a combination of generic stand density (closed or open) and height (low or tall) was translated into fuel models. Fire behaviour simulations that accounted for the fire environment modification induced by stand structure resulted in an objective and quantitative fire hazard classification for 19 forest types. We found that potential fire behaviour is primarily driven by stand structure, rather than by cover type. The results reveal four basic fire hazard groups. Surface fire spread rate is low to moderate, surface fire intensity is low and the crown fire hazard is insignificant in the open and tall forest types, as well as in dense and tall *Quercus suber* and diverse forests. Moderate surface fire potential and high to very high crowning potential characterizes dense and low woodland of deciduous oaks, *Quercus suber* and diverse forests, closed and tall *Pinus pinaster* stands, and open and low eucalypt stands. Open and low types of *P. pinaster*, *Q. suber* and *Q. rotundifolia* have very high or extreme spread and crowning potential, while surface fire intensity ranges from high to very high. In closed and low stands of *P. pinaster*, eucalypts and acacias, spread rate is moderate, but fireline intensity varies from high to extreme, and the potential for crowning is extreme. Practical applications for the hazard classification are suggested and exemplified.

Keywords: Fuel modelling, fuel characteristics, Mediterranean-type ecosystems, fire hazard, fire behaviour simulation

1. Introduction

Fuel properties determine fire behaviour and fire effects, which makes the fuel description of wildland vegetation of paramount importance to the overall process of fire management. Fuel beds are highly variable in nature, composition and structure, and the fuel complex often is stratified into several fuel beds. Systematic schemes of fuel classification are therefore needed such that fuels are consistently described without oversimplification and for a variety of users and objectives (Sandberg et al., 2001).

Typologies of fuel complexes depend on the input requirements of the models used to estimate fire behaviour characteristics. Rothermel (1972) designed the fuel model concept to feed his semi-physical fire spread model with quantitative fuel data, considering four possible vectors for surface fire propagation (litter, herbs, shrubs, slash) and resulting in the 13 NFFL stylised fuel models (Anderson, 1982). Further technological developments have allowed users to build and test custom fuel models to obtain more realistic estimates of fire characteristics for their specific fuel types and complexes (Burgan and Rothermel, 1984; Andrews et al., 2004). A quite expanded set of standard fuel models for the U.S. is now available (Scott and Burgan, 2005).

Vegetation and fuel types in southern Europe are frequently assigned a NFFL fuel model, e.g. ICONA (1990). This is understandable, given the existence of ready to use technology, gaps in knowledge and expertise, and because the fuel models are usually employed to assess possible or potential, rather than actual, fire situations. The need to address the specificities of Mediterranean well-aerated, heterogeneous and very fine fuel complexes is nevertheless well recognised, and has prompted several research efforts on the properties of fuel particles and fuel beds for the more widespread species and vegetation cover types.

Custom fuel models in Europe have been developed to describe local conditions, usually for fuel hazard mapping or for research purposes, namely to investigate the effects of fuel management activities (e.g. Fernandes and Botelho, 2004). Loureiro et al. (2002) simulated fire growth in *Pinus pinaster* landscapes with a set of fuel models describing fuel accumulation with time and calibrated with observed fire behaviour data. Other European studies have proposed fuel models for broader regional or national application, namely in Switzerland (Allgöwer et al., 1998), Greece (Dimitrikapoulos, 2002) and Portugal (Cruz, 2005).

Forest inventory data has proved helpful in fuel modelling (e.g. Cruz et al., 2003) and hazard classification and mapping (e.g. Hardy et al., 2001). In this study we translate a forest classification based on the Portuguese National Forest Inventory (NFI) into fuel models, which are then used to evaluate and compare the fire hazard potential between forest types defined by their composition and structure.

2. Fuel modelling

The NFI includes variables that describe the vertical structure and composition of Portuguese mainland forests on 2258 sampling plots (DGF, 2001). The NFI field assessments aimed at describing forest composition and vertical structure consisted of percentage cover estimates by species or groups of analogous species per height class. Seven layers are considered, respectively <0.5 m, 0.5-1 m, 1-2 m, 2-4 m, 4-8 m, 8-16 m, and >16 m.

A cluster analysis of the NFI database by Godinho-Ferreira et al. (2005) identified 10 main cover types, as defined by the dominant species: *Quercus pyrenaica*, other deciduous oaks, *Arbutus unedo*, *Cistus ladanifera*, *Cytisus* spp., *Acacia* spp., *Quercus suber*, *Pinus pinaster*, *Eucalyptus globulus*, and diverse forests. The existing variability in stratification resulted in the discrimination of 22 forest types that reflect the combination of composition and structure, categorized as open and tall, open and low, closed and tall, or closed and low. The correspondence between cover and structure types is displayed in Table 1.

The fuel modelling process consisted in the estimation of fuel parameters for each forest type. Shrub-dominated cover types with scattered trees (*Arbutus*, *Cytisus* and *Cistus*) were ruled out, since our main interest was to assess fire hazard in forested ecosystems. Additional information about the depth and cover of litter in the NFI plots was retrieved and averaged for each forest type. The following methodological sequence was followed to develop the fuel models:

1. Literature review on the fuel properties of the species identified by the NFI that generate the forest floor and comprise the understorey and canopy strata: surface area to volume ratio, heat content, fine fuel bulk density, fine fuel partition dead or live condition, and dead fuel moisture of extinction. Cohen et al. (2003) was the main source for fuel particle characteristics.
2. Combination of the information gathered by the literature review with the NFI synthesized data for each forest type in order to:
 - estimate fine fuel load for each species and dead or live condition from the respective volumes of occupation on each layer up to a 2-m height;
 - estimate means for the remaining fuel characteristics (surface area to volume ratio, heat content, dead fuel moisture of extinction) for each layer, where each species values were weighted by their relative importance;
3. Data synthesis according to the input requirements of the software Behave Plus 3.0 (Andrews et al. 2004) and development of a fuel model for each structural forest type. Fuel depth was computed as the sum of litter depth and understorey depth *H*, with *H* determined as $h - h[(100-C)/100]$, where h = mean understorey height and C = uderstorey cover %.

Coarse (thicker than 6 mm) fuel loadings were not estimated, because the NFI lacked the information to do so. We have considered the use of literature-based estimates for the 10-h and 100-h time lag classes, but reliable information was restricted to a few vegetation types. No attempts were made to adjust the fuel models parameters.

3. Fire hazard assessment

Fire hazard assessment took into account not just the physical properties of the surface fuel complex, expressed as a whole in the fuel model, but also the effect of stand structure on the meteorological fire environment (wind speed and dead fuel moisture), as well as the implications of species composition on the moisture content of live fuels.

In order to quantify wind reduction by the canopy, wind adjustment factors (WAF) that convert wind speed at a standard 6-m height above the vegetation to the so-called midflame wind speed were calculated in Behave Plus from the mean height, crown ratio and crown cover of each forest type. WAF values are included in Table 1 and range from 0.10 to 0.44.

Estimation of dead fuel moisture contents according to Rothermel et al. (1986) resorted to the FIRE2 program of Behave 4.1, using as inputs a relative humidity of 20%, an ambient temperature of 35 ^{o}C, and a 6-m windspeed of 30 km h^{-1}; fuel moisture differentiation between forest types was a function of the WAF and several tree and stand structure descriptors. Calculated dead fuel moistures varied in the relatively narrow range of 3.8 to 5.3%.

Live fuel moisture values representative of the summer peak burning period were collected in the literature for the various species. Means weighted by species importance were calculated for the understorey fine fuels and tree foliage. The 75-106% interval covered the overall variation in live fuel moisture of the understorey, with the extreme corresponding to low and closed *Quercus suber* stands and deciduous oak woodland.

The evaluation of fire hazard for the 19 forest types was based on three fire behaviour descriptors, respectively rate of spread, fireline intensity, and crown fire potential. The surface fire rate of spread was estimated with the Behave Plus 3.0 software for each fuel model, with a 6-m windspeed of 30 km h^{-1}, the moisture contents estimated for each fuel model, and a slope terrain of 30% as inputs. Fireline intensity *sensu* Byram (1959) was then calculated by multiplying the rate of spread estimate, fuel load (i.e. assuming total fuel consumption), and heat content corrected for losses due to moisture content.

The critical fire intensity for crown fire initiation was determined following Van Wagner (1977). The corresponding spread rate value was calculated and plotted over a reasonable wind speed range of 0-70 km h^{-1} in Behave Plus to find the 6-m wind speed threshold for crowning. This index of crowning potential differs from the Torching Index of Scott and Reinhardt (2001) because fireline intensity is calculated differently.

Fire behaviour data was converted to relative indices given by 100 x_i / x_{max}, where x_i is the value of variable x in forest type i and x_{max} is the maximum value of variable x, which resulted in scores on intervals of]0-100] for surface fire spread and intensity, and [0-100] for crowning (0 meaning a crown fire is unlikely).

Table 1. Fuel model parameters for the 19 forest types.

Cover and structural type		Depth, cm	Fine fuel load, t ha^{-1} 1-h	live	SVR, m^{-1}	HC, kJ kg^{-1}	Mx, %	WAF
Acacia spp.	CL	43	5.17	3.47	5214	20236	32	0.17
Eucalyptus globulus	OT	16	1.10	0.49	3645	19865	27	0.14
	OL	51	0.83	1.18	5764	21080	30	0.23
	CT	28	5.16	2.15	5752	20908	28	0.10
	CL	57	3.73	4.02	5579	20969	30	0.13
Quercus pyrenaica	CL	69	1.60	2.48	5497	20894	26	0.12
Diverse	OT	17	2.05	0.42	7119	19826	26	0.19
	OL	39	1.73	1.17	4720	20535	28	0.36
	CT	39	2.55	1.41	4772	20494	28	0.13
	CL	58	1.91	3.56	5318	20448	32	0.17
Other deciduous oaks	CL	43	6.37	4.89	5039	20436	25	0.14
Pinus pinaster	OT	8	4.32	0.90	4551	19608	38	0.17
	OL	36	1.36	2.36	4303	21189	36	0.44
	CT	24	7.36	3.04	4986	20223	37	0.12
	CL	46	6.66	6.35	4950	21379	36	0.16
Quercus suber	OT	41	1.38	0.56	5994	21475	28	0.16
	OL	50	1.28	1.00	5304	21225	32	0.36
	CT	17	3.29	1.19	5583	21280	22	0.12
	CL	39	4.75	4.39	4666	20406	25	0.15

CL = closed and low stands; CT = closed and tall stands; OL = open and low stands; OT = open and tall stands.
SVR = surface area to volume ratio; HC = heat content; Mx = dead fuel moisture of extinction; WAF = wind adjustment factor.

4. Results and discussion

Table 1 displays the parameters for the fuel models, while Figure 1 presents the three components of relative fire hazard arising from the simulations. The fuel models can be thought of as "incomplete" due to the absence of coarse fuels. However, and unless silvicultural and fuel treatment operations create slash fuels, the significance of 10-h and 100-h fuels is usually reduced in Mediterranean forests. The loading of fine fuel appears suspiciously low, but the estimates are the end product of a methodology that was uniformly applied to the forest types. These shortcomings should not affect the objectives of the study.

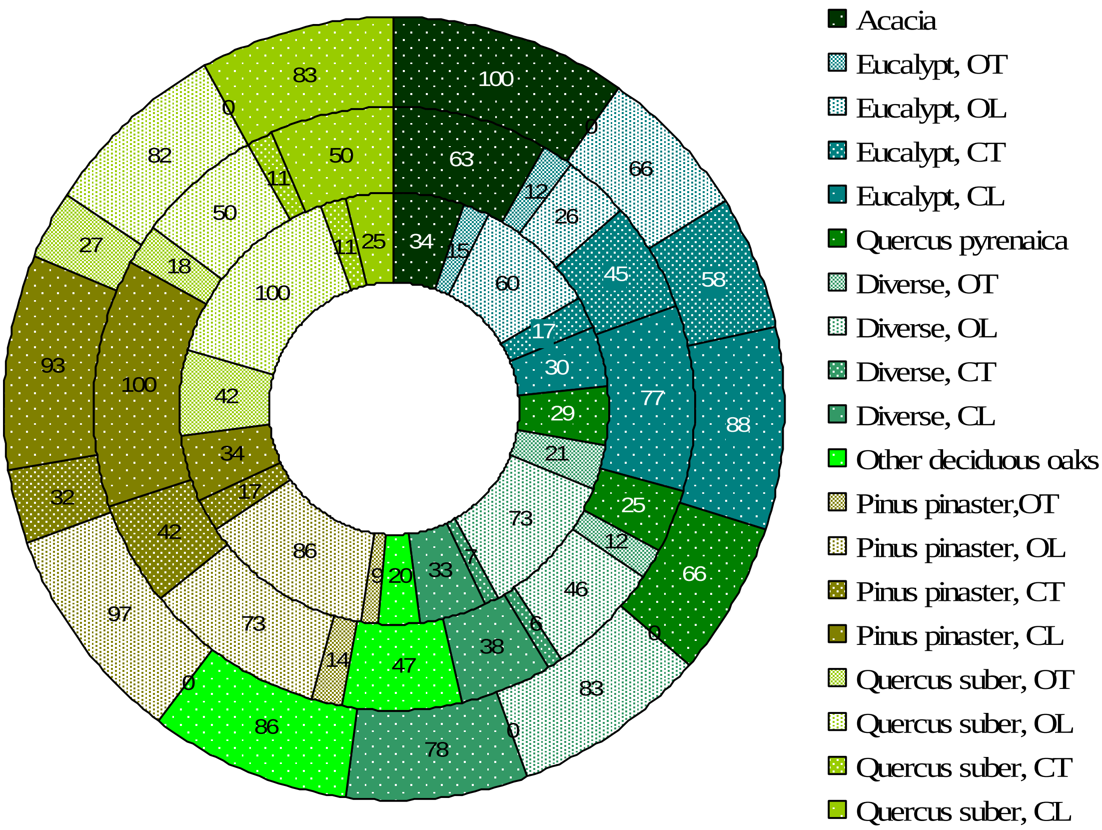

Figure 1. Fire hazard scores (0-100) for the 19 Portuguese forest types. The inner, middle and outer rings respectively indicate the relative potential for surface fire spread, surface fire intensity and crowning.

A wide variation in fire potential is apparent within the 19 forest types group. Individual flammabilities seem however to be a function of structure, rather than cover type, which is readily apparent for the most important species (*Pinus pinaster*, *Eucalyptus globulus*, *Quercus suber*) and contradicts simplistic but frequent assertions that are made about the hazard posed by certain cover types. Fire potential descriptors, stand variables and most fuel descriptors are in fact not statistically different (p>0.05) between cover types. *Pinus pinaster* fuel models are significantly higher (p<0.05) in heat content and moisture of extinction due to their litter and understorey shrub species characteristics. Understorey height and live fuel moisture tend to be higher in deciduous *Quercus*.

Table 2 summarizes stand, fuel and fire hazard descriptors for each type of forest structure and reinforces the impression left by Figure 1 in that structure is more relevant to fire hazard than cover type. Open structures have a lower and less expressive understorey layer and less fuel loading. This contradicts the normal expectation, and probably reflects fuel dynamics – younger eucalypt plantations and older stands are included – and the type and intensity of management that southern Portugal woodlands of *Quercus suber* and *Quercus rotundifolia* are subjected to. The height of understorey vegetation decreases with stand height (p=0.030) and crown base height (p=0.0214), and understorey cover shows the same trend, which is significant (p=0.0096) for crown base height only.

Table 2. Stand, fuel and fire hazard descriptors by structural forest type (mean ± std. dev.).

Type	Crown cover, %	Stand height, m	Crown base height, m	WAF	Understorey	
					height, m	cover, %
CL	60 ± 18 ab	6.0 ± 0.4 b	2.9 ± 0.7 b	0.15 ± 0.02 b	1.1 ± 0.2 a	49 ± 12 a
CT	84 ± 10 a	9.8 ± 2.0 a	5.3 ± 0.9 a	0.12 ± 0.01 b	0.9 ± 0.3 ab	24 ± 9 b
OL	22 ± 10 c	5.8 ± 0.7 b	3.0 ± 1.1 b	0.35 ± 0.09 a	0.8 ± 0.1 b	19 ± 10 b
OT	44 ± 10 bc	10.4 ± 1.9 a	6.3 ± 0.8 a	0.16 ± 0.02 b	0.6 ± 0.1 b	9 ± 4 b

Type	Fine fuel		Fuel depth, cm	Fire hazard score		
	load, t ha^{-1}	dead fraction		spread	intensity	crowning
CL	8.5 ± 3.1 a	0.49 ± 0.09 b	51 ± 11 a	29 ± 5 b	57 ± 25 a	85 ± 11a
CT	6.6 ± 3.0 ab	0.70 ± 0.04 a	27 ± 9 bc	13 ± 5 b	26 ± 20 ab	23 ± 28 b
OL	2.7 ± 0.8 b	0.48 ± 0.11 b	44 ± 8 ab	80 ± 17 a	49 ± 19 ab	82 ± 13 a
OT	2.8 ± 1.6 b	0.77 ± 0.07 a	21 ± 14 c	22 ± 14 b	14 ± 3 b	7 ± 13 b

Means that in a column are followed by the same letter are not significantly different according to the HSD Tukey test.

Open and low stands have drier dead fuels and are more exposed to wind, showing the highest potential for fire spread. Tall stands have higher crown base as expected, which greatly reduces crown fire hazard. The high and low extremes of the surface fire intensity and crown fire potential spectrum are understandably occupied by dense and low stands and tall open forests, understorey development and fuel accumulation being superior in the former; the spread potential is nevertheless similar between these two structural types, which do not differ in WAF and 1-h moisture content.

An analysis of the relative importance of fuel and weather variables on fire hazard might be interesting to define fuel management guidelines and priorities. This can be achieved by a regression of fire behaviour estimates as a function of the fire environment variables; standardized regression coefficients (β) indicate the weight of each significant (p<0.05) factor. A simple linear regression – our limited sample size of n=19 does not warrant a more sophisticated approach – explains 91% of the variation in spread rate and indicates dominance by the WAF (β=0.87), with a comparatively minor influence of fuel depth (β=0.30). In regards to fireline intensity (R^2=0.82) fuel load prevails (β=0.87) over rate of spread (β=0.69). Finally, crown base height was the single significant variable in explaining variation in crowning potential (R^2=0.81).

Four basic hazard groups emerge from the results, from the lowest to the highest fire potential:

1. Open and tall forest types, and closed and tall *Quercus suber* and diverse forests (mostly *Pinus pinea*, *P. sylvestris*, *Castanea sativa* and deciduous oaks). Surface fuel accumulation is low to moderate and the canopy layer is distant from the ground. Rate of fire spread is low to moderate, fireline intensity is low and the potential for crown fire development is nil or weak.

2. Closed, low woodlands of deciduous oaks, *Quercus suber* and diverse forests (*Quercus rotundfolia*, *Pinus pinea*, *P. sylvestris*, *Castanea sativa*, among others), closed and tall *Pinus pinaster* stands, and open and low eucalypt stands. This is the group with more heterogeneous fuel conditions, especially in understorey cover and fuel loading. Surface fire potential is moderate, but the spread rate component is high in eucalypts. Crowning potential is high or very high, but in pine stands is only moderate.
3. Open and low types of *Pinus pinaster*, *Quercus suber* and diverse forests (essentially *Quercus rotundifolia*). The spread and crowning hazards are very high or extreme, due to wind exposure and poor vertical discontinuity. With a fuel loading similar to group 1, albeit in a more flammable arrangement, surface fire intensity ranges from high to very high.
4. Closed and low stands of *Pinus pinaster*, *Eucalyptus globulus* and *Acacia* spp. Spread rate is only moderate, but fireline intensity ranges from high to extreme due to a well-developed shrub layer and high fuel loading. The lowest vertical discontinuity among groups contributes to an extreme crowning potential.

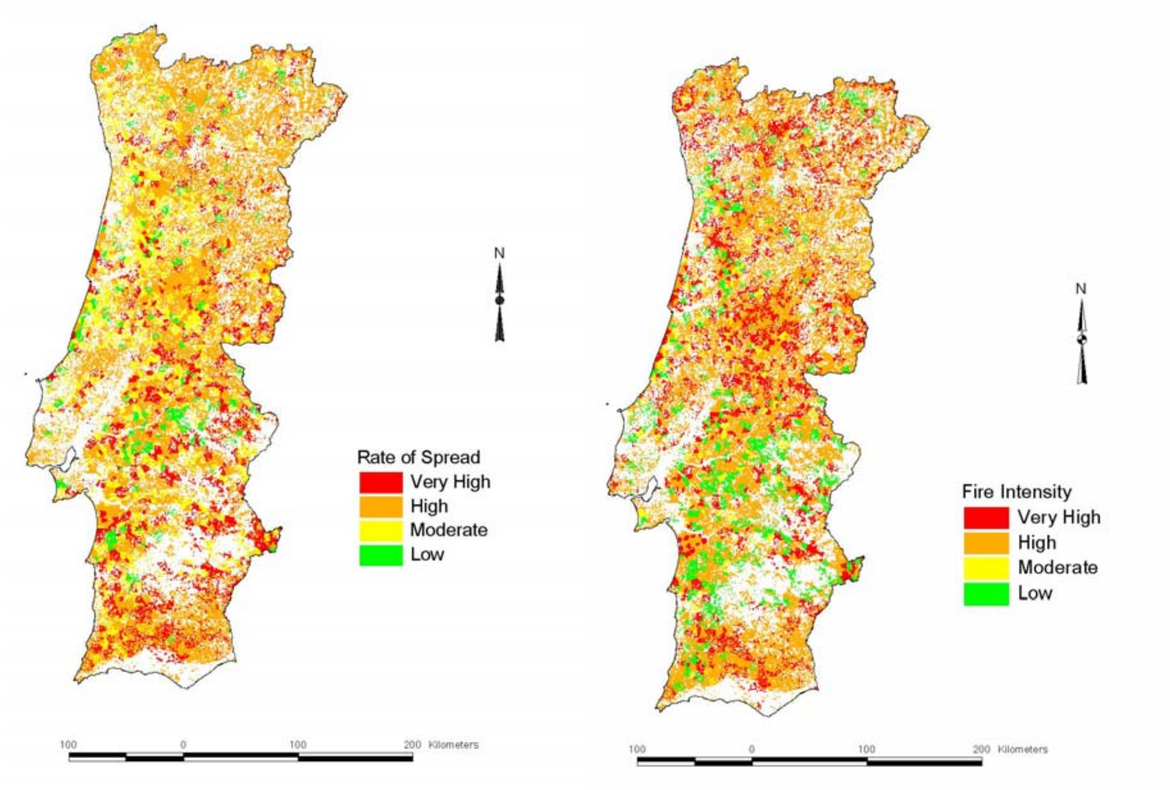

Figure 2. Mapping of the potential surface fire spread and intensity classes for Portugal.

Godinho-Ferreira et al. (2005) refer the areas occupied by the 19 forest types, which allows estimates of the relative importance of each fire hazard group: 22.6, 31.7, 20.7 and 25% of the forested Portuguese area, respectively for groups 1, 2, 3 and 4. By using the companion cartography to Godinho-Ferreira et al. (2005) we have mapped the surface spread and intensity potential for Portugal (Figure 2), a demonstrative exercise which does not account for terrain or weather influences. For this purpose the fire hazard scores of each forest type were subjectively classified as low (0-25), moderate (25-50), high (50-75), or very high (75-100); shrubland areas are also included in the map, and are rated high or very high depending of their nature.

Finally we illustrate how fuel modelling can be used to look at the effectiveness and trade-offs of distinct scenarios of fuel management and cover type replacement. In Figure 3 – a worked output of a Behave Plus simulation – the relative reduction in burned surface is plotted versus the percentage of area randomly substituted by a preferred, less flammable fuel type. This is exemplified for three Portuguese regions each with a preferred forest type (see Figure's 3 legend). The individual landscapes are assigned a "mean" fuel model whose parameters are weighted averages of the fuel models corresponding to the forest types that compound the typical regional landscape. This is of course a simple and crude approach that can be made much more complex and detailed in the settings examined, results obtained and conclusions reached, by using real landscapes and a spatial fire growth simulator.

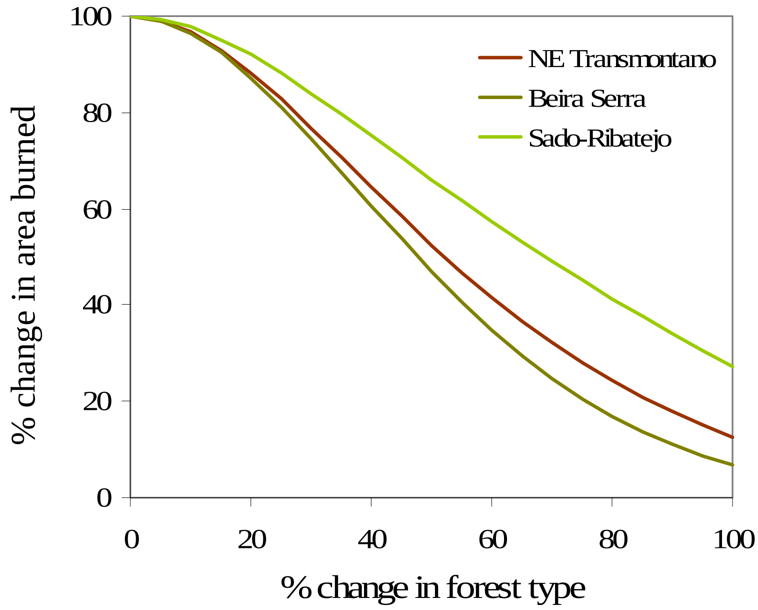

Figure 3. Burned area decrease as a function of random changes in forest type for three regions of Portugal. The forest types replacing the current landscape are closed and tall diverse forest (NE Transmontano), open and tall *Pinus pinaster* stands (Beira Serra), and closed and tall *Quercus suber* woodland (Sado-Ribatejo).

5. Conclusion

The availability of fuel models describing relevant vegetation types can contribute to the promotion of decision-making improvements in both planning and operational fire situations. A wide-ranging and flexible fuel modelling classification for Portugal is currently under development. The first and exploratory step was to build a set of fuel models for forest types defined as a combination of overstorey species dominance and stand structure, forming a baseline for the project's future development.

The 19 fuel models were derived from simple and incomplete data. Although we recognize weaknesses in the procedures used to establish the fuel models we believe the approach served well the goal of comparing the relative fire hazard potential of Portuguese forest types on a quantitative and objective basis.

A major implication of this study's results is that fire hazard cannot be automatically inferred from forest composition. Stand structure is clearly more important to fire behaviour than the tree species that comprise the stand. Low stands correspond to the highest fire hazard, whether they are dense or open (in part for different reasons). Individual descriptors of stand structure and the general four structural types (closed, low or tall; open, low or tall) show some correlation with surface fuel characteristics, have a strong influence on in-stand wind speed and dead fuel moisture, and are critical in the transition of surface to crown fire. This places the emphasis on fuel and stand dynamics and, consequently on proactive stand and fuel management.

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