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Regional variations in wildfire susceptibility of land-cover types in Portugal: implications for landscape management to minimize fire hazard

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Abstract. Patterns of wildfire occurrence at the landscape level were characterised during the period 1990–94 in Portugal. Based on land-cover information within 5591 burned patches (larger than 5 ha) and in the surrounding landscape, selection ratio functions were used to measure fire preference or avoidance for different land-cover types in 12 regions of the country. Shrublands were the most fire-prone land cover, whereas annual crops, permanent crops and agro-forestry systems were the most avoided by fire. In terms of forest types, conifer plantations were more susceptible to fire than eucalyptus, and broadleaved forests were the least fire-prone. There were regional variations in land-cover susceptibility to fire, which may be explained by differences in climate, management, ignition patterns, firefighting strategies, and regional availability. A cluster analysis of regional variations in selection ratios for all land covers allowed the identification of three main geographical areas with similar fire selection patterns. These results can be used for planning landscape-scale fuel management in order to create landscapes with a lower fire hazard.

Additional keywords: fuel breaks, Mediterranean, selection patterns.

Introduction

Understanding how landscape structure affects the spatial spread of disturbances is a key issue for understanding their ecological implications and the role disturbances play in landscape dynamics (Baker 1989; Turner and Dale 1990; Forman 1997; Farina 1998). Fire is a major disturbance affecting Mediterranean landscapes (e.g. Rundel 1998), and in the last decades, fire occurrence has increased dramatically in southern Europe (Rego 1992; Moreno *et al*. 1998). The major driving forces of this increase include land abandonment and subsequent shrub encroachment, as well as afforestation of former agricultural land, both leading to increased fuel accumulation (e.g. Ales *et al*. 1992; Moreira *et al*. 2001; Lloret *et al*. 2002; Romero-Calcerrada and Perry 2002; Mouillot *et al*. 2005; Viedma *et al*. 2006). The result is increased fire hazard (as in Hardy 2005), defined here as the degree of ease of ignition and potential fire behaviour resulting from the existing spatial arrangement of fuel load at the landscape level. However, more studies are necessary to understand the inter-relationships between fire and landscape dynamics, namely how changes in landscape structure have affected fire occurrence patterns and how fires themselves have contributed to these changes (e.g. Lloret *et al*. 2002; Gustafson *et al*. 2004; Viedma *et al*. 2006).

Fire initiation and spread result from a complex interaction among ignition sources, weather, topography and land cover (related to vegetation structure and fuel arrangement) (e.g. Rothermel 1983; Mermoz *et al*. 2005). Land cover is a key variable, and at the landscape level, fire spreads from a local epicentre (ignition spot) with a propagation rate enhanced or retarded by landscape heterogeneity (Turner and Dale 1990). Certain land-cover types (e.g. shrublands or conifer plantations) in a landscape are more susceptible to fire than others (e.g. wetlands, agricultural areas or recently burned patches) (Forman 1997; Moreira *et al*. 2001; Mermoz *et al*. 2005), because of differences in vegetation structure, moisture content, and fuel load composition (Rothermel 1983). This causes differential combustibility, fire intensity and rate of fire spread across different land-cover types.

The final configuration of burned patches provides useful information on the differential use of the land-cover types previously available (e.g. Moreira *et al*. 2001; Mermoz *et al*. 2005). If the different land-cover categories of a given landscape were equally fire-prone, then we would expect fires to occur randomly in the landscape with an equal proportion of burned and available (before the fire) categories. Alternatively, if fire preferentially burns some categories and avoids others, this knowledge could have practical application for landscape management to decrease fire hazard, by promoting less fire-prone land covers. This knowledge can be applied in landscape-scale fuel breaks, designed to (i) effectively break up the continuity of hazardous fuels across a landscape, with the objective of reducing the occurrence of large wildfires; (ii) reduce the intensity of wildfires, providing broad zones within which firefighters can conduct suppression operations more safely and efficiently; (iii) provide strips to facilitate subsequent area-wide fuel treatments; and (iv) provide various non-fire-related benefits (e.g. habitat diversity, landscape scenery) (Weatherspoon and Skinner 1996; Agee *et al*. 2000; Cumming 2001; Rigolot 2002; CNR 2005).

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In a previous study, Nunes *et al*. (2005) studied fire selection patterns in Portugal during the 1991 fire season and found that they were selective, with a marked preference for shrublands, followed by forest. Although they made a preliminary analysis of regional variations in fire selection patterns, their sample sizes, statistical methods used and typology of land covers did not provide detailed information on the best landscape management options, at the regional level, for reducing wildfire hazard.

In the present study, we used a different analytical approach and a larger sample of fires to address the following specific questions: (i) Can we identify similar fire selection patterns in different regions of Portugal? (ii) For a given land-cover type, are there regional variations in susceptibility to fire? (iii) In the context of intensive silviculture, what are the regional variations in susceptibility to fire of the more common species used (eucalyptus and conifers)? (iv) To what extent does the use of native broadleaved species, in pure or mixed stands, contribute to decrease fire susceptibility? (v) Which are the best options, both for landscape management and, more specifically, forest management, for reducing wildfire hazard?

Methods

Study area

The study area is the whole Portuguese mainland. The population is ∼10 million inhabitants, and is concentrated in the north and central coastal areas (INE 2003). Altitude ranges from sea level to ∼2000 m, with the main elevations concentrated in the northern half of the country. Mean annual temperature and precipitation follow a gradient of increasing temperature and decreasing rainfall from north to south and coastal to inland areas. Mean annual temperature ranges from 7 to 18°C, and annual rainfall from 400 to 2800 mm (IA 2003).

In terms of land cover, forests and woodlands cover over one-third of the country. Pine stands (mostly *Pinus pinaster*) are located mainly in the northern half of the country, whereas eucalyptus (*Eucalyptus globulus*) plantations are more common along the western half of Portugal. Evergreen oak woodlands, mainly cork oak (*Quercus suber*) and holm oak (*Quercus rotundifolia*), predominate in the southern half of Portugal. Shrublands cover approximately one-quarter of the country, and are located mostly in the northern third of the country area. They are dominated by the genus *Cytisus* (legume family, Fabaceae), predominating in soil derived from granite bedrock, and *Cistus* (rockrose family, Cistaceae), more common in schist (Nunes *et al*. 2005). In the northern third of Portugal, the most abundant shrubs are from the genus *Erica* and *Calluna* (heather family, Ericaceae), also with *Ulex*, *Cytisus* and *Pterospartium* (legume family, Fabaceae). In the southern half of Portugal, *Cistus* shrublands (in particular *C. ladanifer*) predominate (Pena and Cabral 1996; Nunes *et al*. 2005). Agricultural areas cover one-third of the area of Portugal. In central and northern Portugal, land ownership is very fragmented, and the agricultural landscape is a fine-grained mosaic of small parcels of diverse crops, vineyards, and olive groves. The agricultural landscapes of south and eastern Portugal are more extensive and homogeneous, dominated by dryland farming of cereal crops (Nunes *et al*. 2005).

Land-cover map

Our base map was a 1990 land-cover map for Portugal (scale 1 : 25 000) developed by the Centro Nacional de Informação Geográfica (CNIG 1990). As that map is incomplete for a few parts of Portugal (∼5%), the gaps were filled with CORINE (Coordination of Information on the Environment) land-cover data (scale 1 : 100 000), based on 1986 Landsat imagery. The legends of both maps were simplified to a common nine-class legend considered adequate for the approach used and purposes of the present study:

(1) Annual crops. Twenty-six percent of the area of the country; mainly composed of dry crops (58% of the total area of this land-cover type) and irrigated crops (13%), but also including diverse agricultural mosaics dominated by annual crops, and pastures.
(2) Permanent crops. Nine percent of the area of the country; mainly consisting of olive groves (44%), vineyards (18%) and orchards (12%).
(3) Agro-forestry systems. Seven percent of the area of the country; consisting of annual crops combined with trees, mainly holm oak (*Quercus rotundifolia*) and cork oak (*Quercus suber*) (38%), or olives (17%).
(4) Shrublands. Eighteen percent of the area of the country; mostly low shrublands (58%) but also tall shrublands, degraded forests and clear-cut or recently burned areas.
(5) Conifer forests. Ten percent of study area; mainly maritime pine (*Pinus pinaster*) (86%) and combined maritime pine and stone pine (*Pinus pinea*) (5%).
(6) Eucalyptus forests. Five percent of the area of the country; mostly with blue gum (*Eucalyptus globulus*).
(7) Broadleaved forests. Fourteen percent of the area of the country; mainly cork oak (34%), holm oak (32%), mixed cork oak–holm oak (16%), other oaks (mostly *Quercus robur* and *Q. pyrenaica*; 6%) and other broadleaved species.
(8) Mixed conifer and eucalyptus forests. Three percent of the area of the country; mainly stands with maritime pines dominant over eucalyptus (68%) or eucalyptus dominant over maritime pines (31%).
(9) Mixed forests of broadleaves with conifers or eucalyptus. Four percent of the area of the country; mainly mixed broadleaved and conifers (93%), with the remainder mixed broadleaves and eucalyptus; main combinations of the former category are maritime pine and cork oak and maritime pine and other oak.

Urban areas, dunes and water bodies, considered non-combustible, were excluded from the analysis. For each region, the proportion of the area covered by each land-cover class is shown in Table 1.

Fire data

The location and size of areas burned during the period 1990–94 were estimated by semi-automated processing of Landsat 5 Thematic Mapper satellite images, with a minimum mapping unit of 5 ha (Pereira and Santos 2003). With this method, a fire is equivalent to a burned patch, although this patch may have resulted from different fires that merged into a single final patch.

Table 1. Proportion (%) of the area of each ecological region covered by different land-cover types
Land cover includes annual crops (ac), permanent crops (pc), agro-forestry (agf), shrublands (shr), conifer forests (con), eucalyptus forests (euc), broadleaved forests (brl), mixed conifer and eucalyptus forests (mx) and mixed forests of broadleaved and conifer, or broadleaved and eucalyptus (mxb)

Region	ac	pc	agf	shr	con	euc	brl	mx	mxb
Noroeste	28.0	1.0	4.9	18.2	11.5	4.6	2.1	13.9	4.3
Alto Portugal	19.3	7.5	4.9	39.5	13.2	<1	6.9	<1	5.5
Nordeste	28.3	16.4	5.7	28.5	5.9	<1	9.0	0.0	3.6
Beira Douro	17.9	9.0	3.7	36.7	14.4	4.2	2.4	4.9	3.8
Beira Litoral	23.8	9.9	3.3	6.7	30.8	3.9	1.0	7.7	2.0
Beira Alta	19.4	3.1	6.4	21.4	23.6	12.4	1.4	4.9	3.3
Beira Serra	18.3	2.4	5.1	36.7	21.7	5.1	4.7	<1	2.9
Estremadura	25.6	17.5	8.1	13.1	8.4	7.8	1.3	4.9	2.6
Beira Baixa	20.3	11.0	6.9	18.2	11.5	12.1	16.1	<1	1.3
Sado e Ribatejo	23.4	5.7	7.0	3.3	9.4	6.8	25.6	<1	12.2
Alentejo	37.5	8.8	11.3	6.9	<1	2.3	30.4	<1	<1
Algarve	18.1	18.9	4.4	22.4	3.5	8.1	15.6	<1	2.3

A total of 5591 burned patches larger than 5 ha were considered for analysis. As we were interested in regional variations in fire selection patterns, we classified each fire into one of 12 ecological regions based on climatic, geologic and topographic features (Albuquerque 1985). If an individual fire patch overlapped more than one ecological region, it was assigned to the region holding the largest proportion of the burned patch.

Estimating fire selection patterns

The overall approach was to compare land-cover composition previous to burning in a buffer surrounding (and including) each burned patch area (land-cover availability) with the land cover composition within the patch (land-cover use). If fires occurred in the landscape independently of land cover, we would expect similar land-cover composition within burned patches and in the buffer. In contrast, if one or more land-cover types were burned more or less than their relative availability, different composition would be expected in the burned patch and in the buffer, and fire would be considered selective.

We used selection ratios to characterise land-cover selection patterns by fire (Manly *et al*. 1993; Moreira *et al*. 2001). The selection ratio (w_i) for a given land-cover type i is an index of selection estimated as $w_i = o_i/\pi_i$ (Manly *et al*. 1993), where o_i is the proportion of burned patches with land cover i (estimated from the area consumed by fire for several land-cover types) and π_i is the proportion of available land cover in category i (estimated from the area of the several land-cover types occurring in the surrounding buffer). If a given land cover is used in proportion to its availability, then $w = 1$. If $w > 1$, the land cover is used more than expected by chance (preferred). If $w < 1$, the land cover is used less than expected by chance (avoided). Selection ratios range from 0, if the land cover was available but not consumed by fire, to a large value (in theory ∞), in the situation where a fire occurred exclusively in the single tiny patch of a given type in the surrounding buffer. Selection ratio for a given land cover cannot be estimated if it was not available for a given fire. For each different fire patch, we estimated land-cover types used and available as described below.

Estimating land cover use and availability

We departed from the built land cover map of 1990, and described fire selection patterns using wildfires occurring during the period 1990–94. This time-frame was a compromise between having a larger sample size and minimizing the time effect on land-cover changes. We assumed that major land-cover changes during these 5 years were due to wildfires, so each year we updated the land-cover map by assigning previously burned areas to the shrubland category (the most likely vegetation physiognomy in burned patches, during the first years after fire). The implication of this assumption is that the value for the selection ratios for this land cover may have been artificially lowered, if fires avoid previously burned areas and these had been categorized as shrublands.

As mentioned before, for each fire patch, land-cover use was estimated based on the proportion of its total area covered by the different cover types (before fire). For determining availability, we created circular buffers centred on the patch centroid coordinates and with an area equal to the maximum fire size in the respective ecological region (Table 2). This maximum size was presumed as an indicator of the size a burned patch could potentially attain in that region. We assumed a circular buffer because, in the absence of fuel, climate and topography effects, the shape of a burned area would be a circle (Ventura and Vasconcelos 2006), so this would be the best shape for testing against the null hypothesis of no land-cover effects on fire selection patterns. A similar approach was used in a previous study using simulated fires (Mermoz *et al*. 2005). This resulted in circles with ~2–6 km radius around each fire patch, according to the region. Therefore, all fires occurring in one region had the same value of available area independently of their shape. The only exceptions were a few burned patches ($n = 72$) for which the shapes did not fit entirely in their respective buffer circle. In these situations, buffers were expanded to be tangential to the more distant point of the burned perimeter, so that the whole burned perimeter was within the availability buffer.

Statistical analysis

For each of the 5591 fires, we estimated the selection ratio for the nine land-cover types. Box-plot examination of selection ratios for different land-cover types in each region resulted in the detection of a few extreme values (outliers) observed for some fires, corresponding to atypical situations of very high selection ratios (Table 2). These fires ($n = 98$) corresponded mainly to situations where a small fire had burned a single land cover that was rare in the buffer (thus $o_i = 1$ but π_i was quite small, resulting in extreme w_i values), and were excluded from further analyses. Confidence intervals (95%) for each land-cover type were estimated at the country level and separately for each region. Owing to the geographic overlap of fire buffers, the resulting selection ratios could not be assumed independent; thus differences between land-cover types were not tested for significance. However, it was assumed that confidence intervals that did not overlap represented significantly different selection ratios. Confidence intervals that did not include $w = 1$ represented land covers that were significantly preferred (if the interval was above 1) or avoided (if the interval was below 1) by fire.

To identify regions with similar fire selection patterns, based on the average selection ratio per land cover and region ($n = 12$), we performed a cluster analysis using the Spearman rank correlation and the centroid clustering method (Legendre and Legendre 1998; SPSS 2005). Mixed conifers and eucalyptus forests were not included as they did not occur in one of the regions (see Table 1). Differences in selection ratios between clusters were then tested using the Kruskal–Wallis non-parametric test (Siegel and Castellan 1988).

To study the potential influence of regional availability of a given land-cover type in the obtained mean selection ratio, we first estimated availability by pooling the area of all the buffers corresponding to fires in a given region and estimating the proportion of that area covered with that type. The best fit for the relationship between the regional abundance and the mean selection ratio for a land-cover type was determined by comparing different curve estimation regression models (linear, logarithmic, quadratic, power, growth and exponential) (SPSS 2005) and selecting the one explaining the largest proportion of variability in selection ratios.

Results

Fire occurrence patterns

During the period 1990–94, a total of 5591 fires larger than 5 ha occurred in Portugal, burning a total of 441 493 ha. The number of fires per region ranged from 110 in Beira Litoral to 960 in Alto Portugal (Table 2).

Average fire size was greatest in Beira Serra (190 ha) and smallest in Alentejo (30 ha). However, fire size distribution patterns were highly skewed to the right, and maximum fire ranged from 459 ha in Alentejo to 12 000 ha in Beira Serra. The year with the highest number of fires was 1990 (1667) whereas the minimum was registered in 1993 (353 fires).

Overall fire selection pattern

Shrublands were the only land cover burned more than expected based on availability at the national scale, i.e. they were preferred by fire (Fig. 1).

Forests as a whole rank second, although with a trend for eucalyptus and other broadleaves to have lower preference compared with conifers and both types of mixed stands. Crops (both annual and permanent) and agro-forestry systems were the land covers less preferred by fire.

A cluster analysis of fire selection patterns across regions allowed the identification of three geographically distinct groups (Fig. 2) for which there were significant differences (Kruskal–Wallis test) in selection indices for annual crops ($\chi^2 = 7.6$, $P = 0.022$), permanent crops ($\chi^2 = 6.8$, $P = 0.034$), broadleaves ($\chi^2 = 6.4$, $P = 0.041$), shrublands ($\chi^2 = 6.4$, $P = 0.041$), and nearly significant for agro-forestry systems ($\chi^2 = 5.8$, $P = 0.053$). The first group included four regions in north-western Portugal where fire showed a low preference for annual crops, permanent crops, agro-forestry systems and broadleaved forests, and a high preference for shrublands. In contrast, in a second group of three regions in southern Portugal, fire had the highest preference for annual and permanent crops, agro-forestry systems and broadleaved forests, and the lowest

Table 2. Descriptive statistics of fire sizes (for fires larger than 5 ha) per ecological region, for the period 1990–94

n = number of fires. Minimum, maximum, mean and median sizes are given in hectares. The number of outliers excluded from analysis (see text) is also shown. Regions are ordered by decreasing mean fire size

Region	*n*	Minimum	Maximum	Mean	Median	Standard deviation	Outliers
Beira Serra	540	5.0	12 163.2	190.2	25.8	729.58	6
Beira Litoral	110	5.7	5777.6	137.7	20.5	581.80	11
Algarve	120	5.0	4268.2	124.7	24.7	469.95	4
Beira Alta	569	5.1	6541.4	106.7	24.1	366.58	8
Estremadura	345	5.0	6097.0	102.5	17.9	466.51	9
Beira Douro	591	5.0	2819.7	93.0	27.4	211.29	6
Nordeste	771	5.1	1856.0	64.5	22.3	136.37	2
Beira Baixa	156	5.0	1009.1	60.0	19.8	128.43	10
Sado e Ribatejo	221	5.1	2301.7	48.9	18.9	169.65	17
Alto Portugal	960	5.0	1351.4	45.0	18.6	96.02	5
Noroeste	926	5.0	2338.2	39.0	17.0	103.29	6
Alentejo	282	5.1	459.4	29.6	17.3	42.18	14

for shrublands. The last group included five regions in central and north-eastern Portugal, mostly with fire selection patterns intermediate between the other two groups, but also the highest selection for conifers and the lowest for eucalyptus.

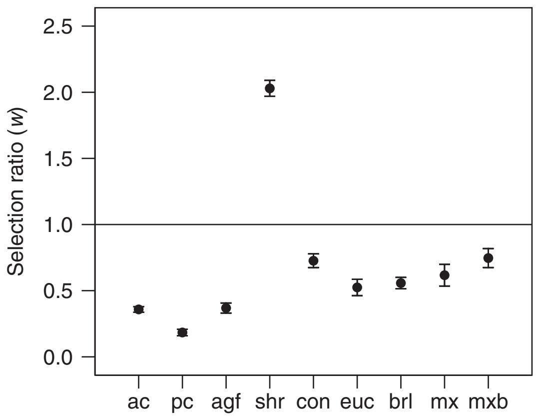

Fig. 1. Mean selection ratios (w) (with 95% confidence intervals) for land-cover types burned in Portugal between 1990 and 1994. Land cover includes annual crops (ac), permanent crops (pc), agro-forestry (agf), shrublands (shr), conifer forests (con), eucalyptus forests (euc), broadleaved forests (brl), mixed conifer and eucalyptus forests (mx) and mixed forests of broadleaved and conifer, or broadleaved and eucalyptus (mxb).

Regional variations in fire selection patterns

The results for each land cover can be seen in Figs 3 and 4. There was avoidance of fire for annual crops in all regions except Sado e Ribatejo and Alentejo, where they burned proportionally to availability (i.e. confidence intervals for selection ratios included the value 1). They were particularly avoided in the north-western regions. Permanent crops were also avoided by fire in all regions, although they were comparatively more susceptible in the south (Estremadura, Sado e Ribatejo, Alentejo and Algarve). Agro-forestry systems burned proportionally to availability in Sado e Ribatejo and Alentejo. In the other regions, they were avoided by fire, particularly in the north-western regions.

Selection ratios showed a clear preference of fire for shrublands except in Alentejo and Sado e Ribatejo, where confidence intervals suggest shrublands burned proportionally to availability. Susceptibility to fire was particularly high in Noroeste, Beira Alta and Beira Litoral, where the mean selection ratio was over 2.

For conifer forests, selection ratios suggest slight avoidance in all regions except central Portugal, where conifer forests burned proportionally to their abundance in Beira Litoral, Beira Alta, Beira Serra, Beira Baixa and Estremadura. Lowest preference occurred in two different groups of regions, one including Noroeste and Beira Douro, and the other corresponding to Alentejo and Algarve.

Eucalyptus forests burned in proportion to availability in Algarve, Beira Litoral and Estremadura. In the other regions, they burned less than expected. Higher preference for this land

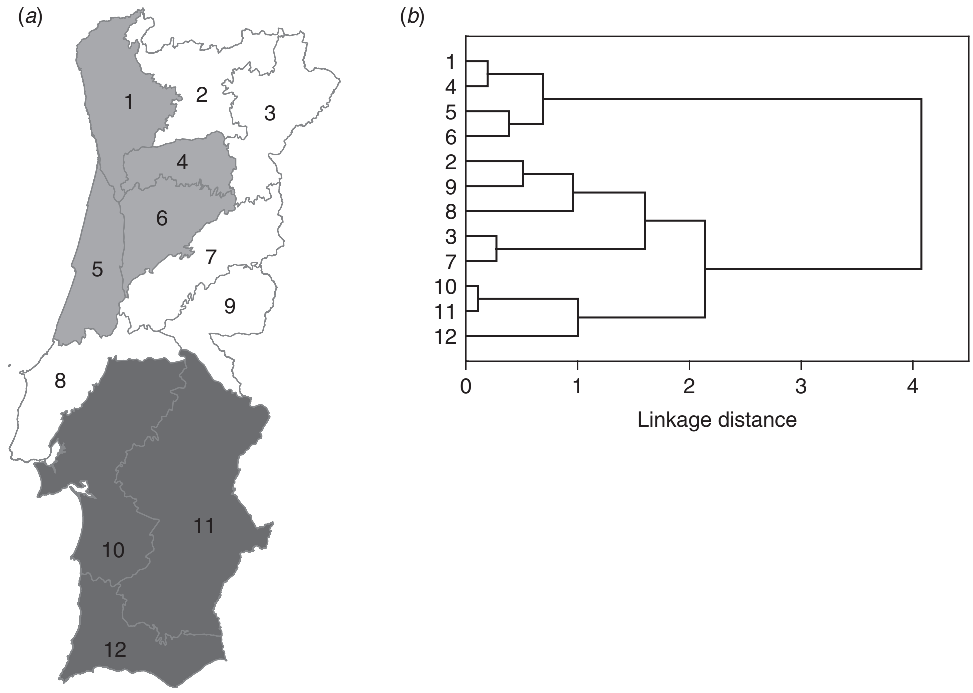

Fig. 2. (*a*) Ecological regions, defined by Albuquerque (1985), used in the present study, and region clustering based on fire selection patterns. Each of the three clusters is represented by a different shade. Codes for regions: 1 – Noroeste; 2 – Alto Portugal; 3 – Nordeste; 4 – Beira Douro; 5 – Beira Litoral; 6 – Beira Alta; 7 – Beira Serra; 8 – Estremadura; 9 – Beira Baixa; 10 – Sado e Ribatejo; 11 – Alentejo; 12 – Algarve. (*b*) Dendrogram resulting from a cluster analysis of regions based on similarity of fire selection patterns across land-cover types. Each number represents a region code.

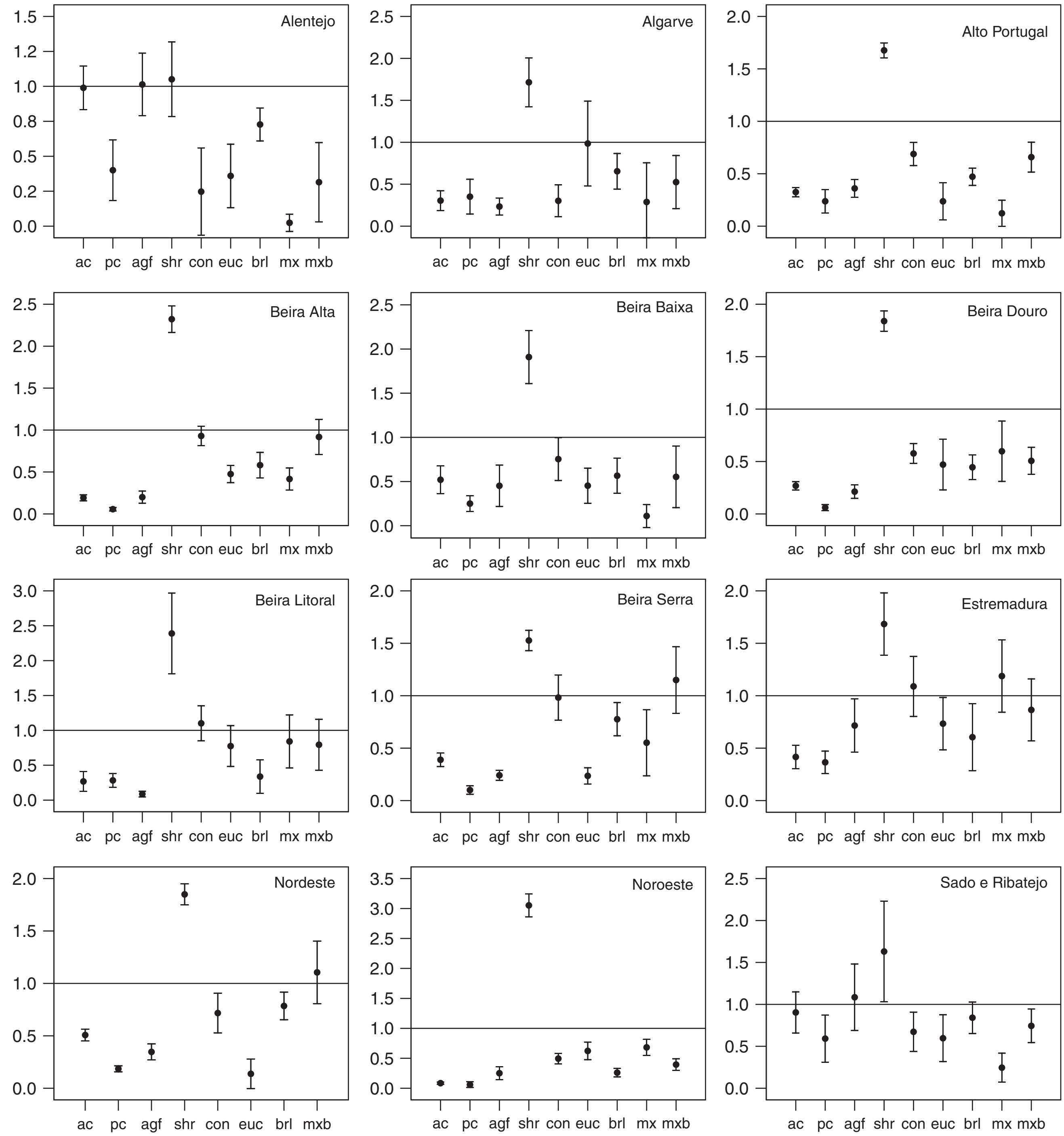

Fig. 3. Mean selection ratios (*w*) (with 95% confidence intervals) for land-cover types burned in 12 regions of Portugal. Land cover includes annual crops (ac), permanent crops (pc), agro-forestry (agf), shrublands (shr), conifer forests (con), eucalyptus forests (euc), broadleaved forests (brl), mixed conifer and eucalyptus forests (mx) and mixed forests of broadleaved and conifer, or broadleaved and eucalyptus (mxb).

cover occurred in coastal regions, with a decrease towards the interior. In comparison with conifers, they were less susceptible to fire in Alto Portugal, Nordeste, Beira Serra and Beira Alta, but more susceptible in the Algarve. In the remaining regions, conifers and eucalyptus had a similar selection pattern.

Broadleaved forests burned less than expected except in Sado e Ribatejo, where they burned proportionally to availability. Preference for this land-cover type was higher in Alentejo, Sado e Ribatejo, Beira Serra and Nordeste, and lower in the coastal north-west. Broadleaves were less fire-prone than conifers and

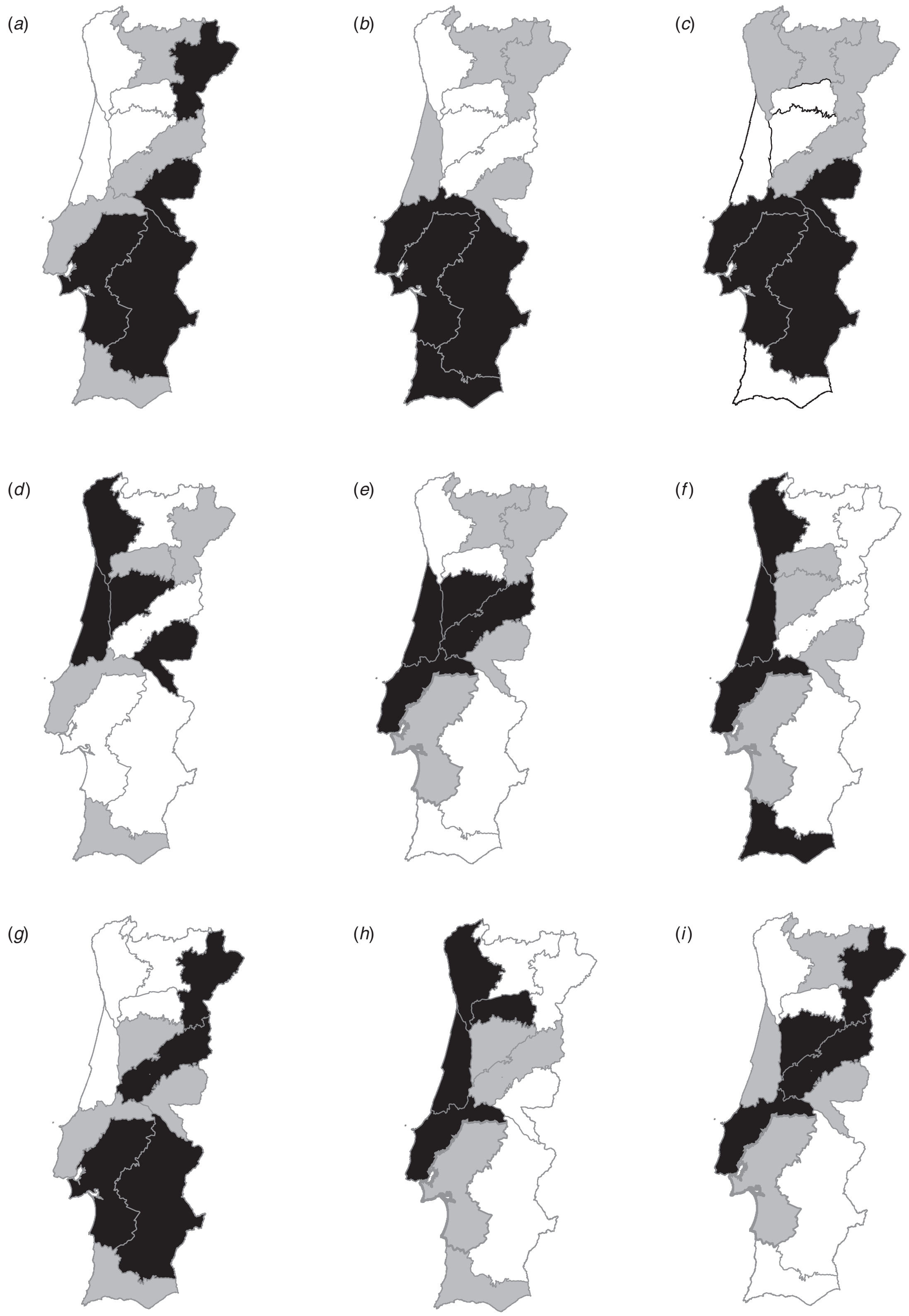

Fig. 4. Regional variations in selection ratios by fire for: (*a*) annual crops; (*b*) permanent crops; (*c*) agro-forestry; (*d*) shrublands; (*e*) conifer forests; (*f*) eucalyptus forests; (*g*) broadleaves; (*h*) mixed conifer and eucalyptus forests; (*i*) mixed forests of broadleaved and conifer, or broadleaved and eucalyptus. Shades indicate quantiles, with black, grey and white corresponding respectively to the higher, medium and lower values. Values for different regions can be seen in Fig. 3.

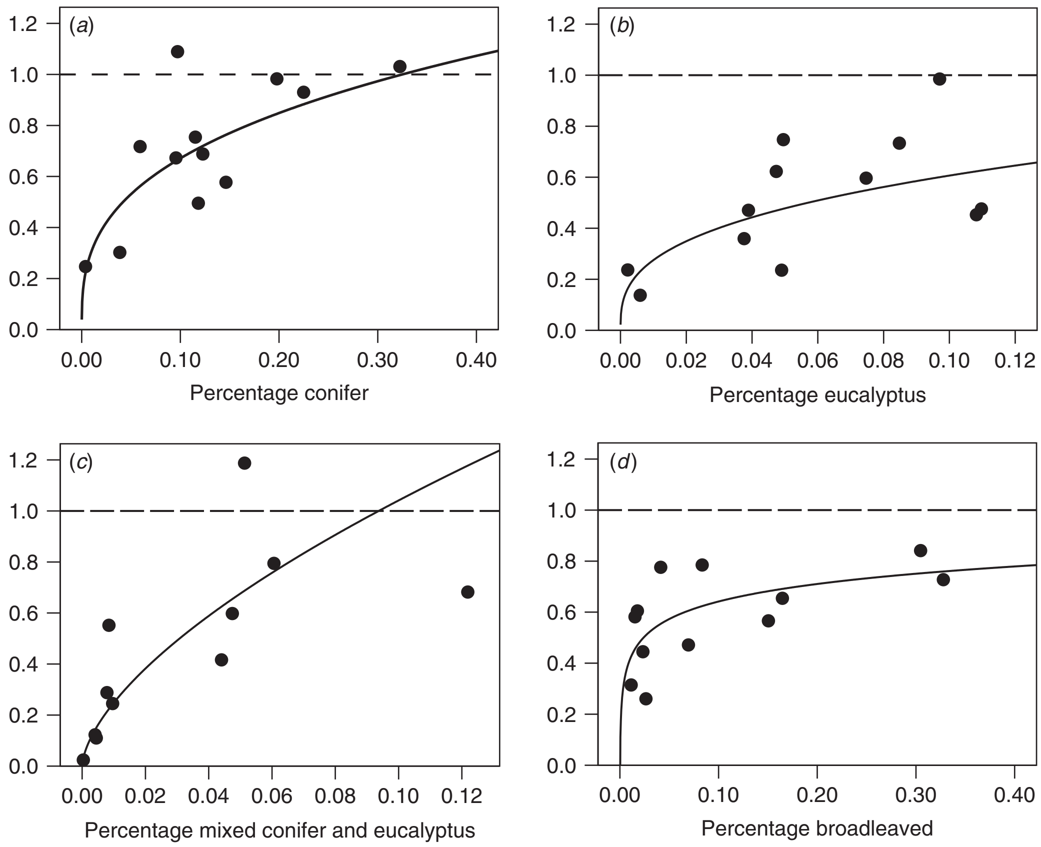

Fig. 5. Relationship between mean selection ratio (w) for a given land cover and proportion of the area available for all the fires in the region, for the 12 regions considered in the present study. The lines show the best fit to the data: (*a*) conifer forests; power equation: $y = 1.49x^{0.344}$, $r^2 = 0.68$, $P < 0.001$; (*b*) eucalyptus forests; power equation: $y = 1.34x^{0.344}$, $r^2 = 0.52$, $P = 0.008$; (*c*) mixed conifer and eucalyptus forests; power equation: $y = 4.44x^{0.626}$, $r^2 = 0.85$, $P < 0.001$; and (*d*) broadleaved forests; logarithmic equation: $y = 0.097\ln(x) + 0.865$, $r^2 = 0.39$, $P = 0.030$.

eucalyptus in Noroeste and Beira Litoral, and this effect was visible when these species were used in mixed stands (susceptibility decreased when in comparison with pure conifer and eucalyptus stands). This trend was also visible in Estremadura and Beira Douro, but with no significant differences. In Beira Alta and Alto Portugal, they were less fire-prone than conifers but similar to eucalyptus, and in mixed stands they burned as much as conifers. In Nordeste and Beira Serra, they were preferred to eucalyptus but similar to conifers (and in mixed stands, they burned as much as conifers). In Alentejo, they were more susceptible to fire than conifers and eucalyptus. In the remaining regions, there were no differences in fire preference for broadleaves, conifers and eucalyptus.

Mixed conifer and eucalyptus forests burned proportionally to availability in Beira Litoral and Estremadura. In the remainder regions, they burned less than expected. They were more fire-prone in the coastal regions of northern Portugal. In regions where pure stands of eucalyptus were less selected than conifers (Alto Portugal, Beira Alta, Beira Serra), these mixed stands showed a fire preference similar to pure eucalyptus, or intermediate between conifers and eucalyptus. In Alentejo, Beira Baixa and Sado e Ribatejo, there was a trend for a lower fire preference, when compared with pure stands. In the other regions, they had a selection ratio similar to pure stands.

Mixed forests of broadleaves and conifers or eucalyptus burned proportionally to availability in Beira Serra, Beira Alta, Beira Litoral, Nordeste and Estremadura, and were avoided in the other regions. In comparison with conifers and eucalyptus, these mixed stands had lower preference by fire in Noroeste and Beira Litoral. In contrast, they burned similarly, or more, than conifer or eucalyptus in the other regions.

Fire selection v. *land cover availability*

There was a significant positive correlation between selection ratios and the regional availability ($n = 12$) for mixed conifer and eucalyptus forests (Spearman rank correlation, $r_s = 0.91$, $P < 0.001$), broadleaved forests ($r_s = 0.60$, $P = 0.039$), conifer ($r_s = 0.63$, $P = 0.028$), and nearly significant for eucalyptus ($r_s = 0.57$, $P = 0.055$). For the other land-cover types, no significant correlations were found. The best fit for the four land-cover types was the power function, with the exception of broadleaves, where the best fit was logarithmic (Fig. 5). Using the fitted equations to extrapolate the value of proportional cover for which selection ratios attained the value 1 (burning in proportion to availability), estimates of 10% for mixed conifer and eucalyptus forests, 30–35% for conifers and 40–45% for eucalyptus were obtained. For broadleaves, the maximum estimate of selection ratio was below 1 (0.87 for a theoretical 100% cover).

Discussion

Overall fire selection patterns

Even considering that the obtained selection ratios for shrublands may have been underestimated owing to the methodology used, this was still the most fire-prone land-cover type, with a confidence interval clearly above 1. A similar result was obtained by Nunes *et al*. (2005). In contrast, agricultural areas (annual crops, permanent crops and agro-forestry systems) were globally the least fire-prone. Forests were at intermediate level, with conifer stands, pure or mixed, more susceptible to fire than eucalyptus and broadleaved forests. This general pattern highlights the relationships between agricultural abandonment and fire hazard in the Mediterranean, as the land-cover types more avoided by fire (agricultural crops) are progressively replaced, in many cases, by the fire-preferred land-cover type (shrublands). Previous studies at local or regional levels have found similar patterns of abandonment of agricultural land, shrub encroachment and increased fire frequency for different areas of the Mediterranean (e.g. Ales *et al*. 1992; Moreira *et al*. 2001; Lloret *et al*. 2002; Romero-Calcerrada and Perry 2002; Mouillot *et al*. 2005).

The main reason for the high avoidance of agricultural areas by fire is their low combustibility, due to the usually low fuel load and high moisture content (mainly in irrigated crops) (e.g. Anderson 1982; Duguy *et al*. 2007). In addition, croplands are usually closer to urban areas, or to scattered populations; thus fire detection is quicker and firefighting easier. In contrast, lower priority is given for firefighting in shrublands (they are the less valuable land cover), which probably also have a large number of ignitions (e.g. burning for rangeland management purposes, such as creating pastures) and higher rate of fire spread (Anderson 1982; Fernandes *et al*. 2006; Duguy *et al*. 2007). Also, shrublands are probably the most common land-cover type in steeper slopes where the rate of fire spread is even higher (Rothermel 1983). All these factors probably contribute to the high fire susceptibility of this land cover. In terms of susceptibility to fire of the different forest types, results are discussed in the following sections.

Three different clusters of regions could be defined in terms of fire selection patterns, differing mainly in fire preference for agricultural areas, shrublands and broadleaved forests. The north-western cluster includes regions where abandonment of agricultural practices has greater implications in terms of fire hazard. On one side, it represents the loss of crops (annual and permanent) and agro-forestry systems in the region where they are more avoided by fire. At the same time, this is the area where the higher susceptibility of shrublands occurs. In contrast, in the southern cluster of regions, crops and agro-forestry systems are comparatively more susceptible to fire, particularly in Sado e Ribatejo and Alentejo, whereas shrublands are much less fire-prone. The higher susceptibility of annual crops and agro-forestry systems may be explained by increased combustibility (dry crops in the South *v.* irrigated crops in the North; see below). Alternatively, agro-forestry systems in these regions may have been suffering agricultural abandonment and a consequent shrub encroachment in the understorey (Pinto-Correia 1993), leading to increased fire hazard. The central cluster of regions is characterised by intermediate susceptibility to fire for most land-cover types.

What explains regional variations in land-cover susceptibility to fire?

Regional variations in susceptibility to fire for a given land cover are expected to result from several factors, listed below.

First, ignition patterns, which will determine subsequent fire spread, may vary depending on the region. For example, in northern Portugal, shrubland burning for the renewal of livestock pastures is usual, whereas in the South, burning of agricultural residues (e.g. stubble) is a common practice.

Second, climatic variations may also influence regional susceptibility to fire. As an example, in the Noroeste region, the mean temperature is ~12.5–15.0°C, whereas in the Algarve region it is higher than 17.5°C (IA 2003). Furthermore, in the former region, annual rainfall can reach over 1500 mm, whereas in the latter, it usually ranges from 500 to 600 mm (IA 2003). Obviously, a given land-cover type may be more prone to fire in drier regions.

Third, differences in management type and species composition may also contribute to the observed regional variations. Regional differences observed in fire susceptibility of annual crops, permanent crops and agro-forestry systems can be explained by agricultural management, also linked with climatic conditions. Thus, annual crops in north-western Portugal are mostly irrigated (mainly corn, potato and fodder) (INE 1993), which significantly decreases combustibility. In southern Portugal and the interior Nordeste, the climate is much drier (Ribeiro *et al*. 1987) and the proportion of irrigated crops much lower (INE 1993). As a consequence, the proportion of dry pastures and fallow land increases significantly, contributing to increased fire risk of this land cover. For permanent crops, the pattern is similar; the proportion of irrigated permanent crops (mainly vineyards and orchards) is higher in the North as a whole, whereas non-irrigated crops (mainly olive and nut tree groves) are more common in the south of the country and also in Nordeste (INE 1993). The pattern for agro-forestry systems is very similar to the one of annual and permanent crops, probably reflecting the regional variations in fire preferences of the crops (i.e. agro-forestry systems typically merge the annual and permanent crops available in the region; thus their fire susceptibility should be similar). Forest stands may also be composed of different species in different regions, in particular for broadleaves; deciduous species are more common in the North (e.g. *Castanea sativa*, *Quercus robur* and *Q. pyrenaica*) and evergreen species (*Q. rotundifolia* and *Q. suber*) more common in the South and Nordeste (DGF 2001). The latter are probably more fire-prone, given the lower moisture content of evergreen when compared with deciduous broadleaved species. Mixed stands with broadleaves are mostly composed of conifers, rather than eucalyptus. This is probably why the regional pattern in fire susceptibility is rather similar to the one of pure conifer stands. The main difference occurs in the Nordeste, where deciduous oaks are replaced by cork oak in these mixed stands, thus explaining increasing fire susceptibility. In Alentejo and Algarve, they are mostly composed of stone pine with cork or holm oak.

Fourth, differences in fire-fighting strategies and effectiveness, which can be related to land-cover composition, population density and accessibility (e.g. road density), may also contribute to the observed variations.

Fifth, in regions where it is scarce, a given land-cover may be avoided by fire, even if it is highly combustible, just because the probability of being burned is low. For conifers, eucalyptus, broadleaves and mixed stands of conifers and eucalyptus, 40 to 85% of the variation in regional susceptibility to fire could be explained by regional availability. Thus, susceptibility to fire increases proportionally to the area covered by these land-cover types.

The regional variations in shrubland susceptibility to fire are more difficult to understand. Possible differences in species composition, with implications on combustibility, may explain the observed patterns, but there are no detailed data on species composition across regions. The pattern of ignitions may also explain these results, as traditional shrubland burning for rangeland management is more common in the north-western regions. Also, given the higher rainfall, the higher productivity of these regions potentially leads to higher fuel loads in shrublands.

Finally, regional variations in fire selection patterns may also be due to different landscape configurations. For example, small patches of shrublands surrounded by an agricultural matrix, which may be burned to create pastures, will result in high selection ratios. In contrast, vast expanses of shrublands affected by large wildfires will result in selection ratios near 1 (random use). Future studies should clarify the role of spatial configuration in determining fire selection patterns in the landscape.

Fire susceptibility of different forest types

When analysing fire susceptibility in relation to regional availability in the different forest types, the threshold where they start becoming more fire-prone seems to be lowest for mixed conifer and eucalyptus forests ($\sim$10% of the total area), intermediate for conifers ($\sim$30–35%), higher for eucalyptus ($\sim$40–45%) and very high for broadleaves (theoretical value of selection ratio is $<$1 even for a region vastly dominated by broadleaves). This confirms the generally low fire susceptibility of broadleaves compared with other forest types, probably explained by differences in fuel load composition, moisture content and flammability (e.g. Rothermel 1983; Bond and van Wilgen 1996).

In relation to the other forest types, several explanations can be put forward to interpret these differences. First, differences in stand structure, mainly in terms of fuel vertical continuity, may have caused differential combustibility and fire hazard. Large areas of eucalyptus stands are intensively managed, including a significant proportion ($\sim$20% of the total area) by private companies, with several treatments such as thinning, pruning and shrub clearing, thus making them less fire-prone. In contrast, a larger proportion of conifer stands is extensively managed, with a lower frequency of management actions. Differences between pine and eucalyptus forest structure were recently confirmed by Godinho-Ferreira *et al*. (2005), who showed that more than 90% of the area of pine stands had an understorey shrub cover higher than 30%, whereas in eucalyptus stands, only 38% of the stands attained such a developed understorey cover, suggesting a more frequent management. The situation with mixed stands could be even worse, as they often correspond to small-sized properties whose owners make no effort in terms of stand management. According to Godinho-Ferreira *et al*. (2005), stands with a mixture of conifers and eucalyptus always had a large understorey cover. A second explanation for the reduced fire susceptibility in eucalyptus stands is that private companies have their own fire prevention and suppression mechanisms that add to public ones, probably resulting in more effective firefighting. Last, eucalyptus stands commonly have much shorter rotations than conifers, which results in a higher relative proportion of recent plantations and clearcut areas that may be less fire-prone. All these factors could contribute to the slower rise in fire susceptibility as the area of eucalyptus increases, in comparison with mixed or pure conifer stands. In short, we hypothesise that the observed trend of decreasing susceptibility to fire along the gradient mixed conifer and eucalyptus > conifers > eucalyptus is due to different silvicultural treatments and firefighting effectiveness. Further studies should clarify this hypothesis.

Conclusions

Intensive silviculture: conifers or eucalyptus, which is the best option?

The present study showed that regional variations in fire selection pattern for these two forest types depend on their relative availability. Both types showed increased fire hazard when their area of occupancy increased at the regional level, although fire proneness increased more rapidly in conifers, suggesting that it could be the worst option anywhere. Note that in the region with a similar availability of both conifers and eucalyptus (Beira Alta), the former is much more fire-prone, and the same pattern is visible at a national scale. The main question is whether the current difference in fire hazard between conifers and eucalyptus is mostly explained by the different management intensity, resulting in different fuel load, and consequently fire hazard in these forests, rather than some characteristics inherent to the selection of the species. If this holds true, then the selection of species is much less important than the type of management in the stand. Recent evidence of this was found by Fernandes *et al*. (2006).

Effectiveness of broadleaves in reducing fire hazard

In terms of forest management, broadleaves can be effective in reducing fire hazard, but not in all regions. In the coastal regions of Noroeste, Beira Litoral, Estremadura, and also Beira Douro, they are less fire-prone, preferably in pure stands, but also mixed with either conifers or eucalyptus. The previous study by Moreira *et al*. (2001), where a higher avoidance of oak stands by fire was found, was carried out in Noroeste. In Beira Alta and Alto Portugal, they are effective but only when used in pure stands. In the other regions, they are not particularly effective in comparison with other types of forest stands, and they can be, when used in mixed stands, even more susceptible than conifers and eucalyptus. These regional variations in effectiveness can be partly explained by variations in tree species composition and regional availability.

Best options for landscape management to reduce wildfire hazard

The present study provides valuable information for the design of fuel breaks at the landscape scale. It showed that annual crops (including pastures), permanent crops and agro-forestry systems, particularly if they are irrigated, are the most effective for reducing fire hazard. Thus, whenever possible, existing areas with this cover type should be included in the fuel break delimitation, or, if needed, promoted in specific locations. In terms of forest management, native deciduous broadleaves seem to be preferable to other tree species. The fire hazard of conifers and eucalyptus is higher, and for these, the application of correct silvicultural practices is probably more important that the selection of the species.

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