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This version is available <http://hdl.handle.net/2318/129450> since

*Published version:*

DOI:10.1016/j.foreco.2012.09.041

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D. Ascoli, M. Lonati, R. Marzano, G. Bovio, A. Cavallero, G. Lombardi (2013). Prescribed burning and browsing to control tree encroachment in southern European heathlands. *Forest Ecology and Management*, Volume 289, Pages 69-77, Novembre 2012,  
<http://dx.doi.org/10.1016/j.foreco.2012.09.041>

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<http://dx.doi.org/10.1016/j.foreco.2012.09.041>

Prescribed burning and browsing to control tree encroachment in southern European heathlands

D. Ascoli, M. Lonati, R. Marzano, G. Bovio, A. Cavallero, G. Lombardi

DOI: 10.1016/j.foreco.2012.09.041

## Abstract

Land abandonment and the cessation of traditional management practices is favouring scrubland and forest expansion throughout Europe, reducing the extent of many semi-natural open habitats of a high ecological value. Tree encroachment is threatening several *Calluna vulgaris* (L.) Hull heathlands. The objective of this study was to analyze vegetation dynamics resulting from an experiment designed to test management options aiming at controlling the encroachment of *Populus tremula* (aspen) and favouring heathland recovery. The research was conducted at Vauda Heath, North-western Italy, from 2005 till 2009. We studied prescribed burning and goat browsing, both alone or in combination, assessing their effects on structure and density of encroaching trees, as well as on heathland main species, *C. vulgaris* and *Molinia arundinacea*. Treatments were applied to 42 experimental units (300–650 m<sup>2</sup> each), with each treatment combination replicated from six to twelve times (including untreated controls).

Prescribed burning and browsing showed complementary effects on post-fire vegetation development. Both back and head fire behaviors were effective in inducing stem mortality of aspen and rejuvenating the heathland, but in the absence of measures to control post-fire suckering, aspen tended to recover the pre-treatment stand structure. A higher fire frequency (annual winter fire) controlled tree encroachment, but hindered *Calluna* recovery, whilst favouring competing grass species. Goat browsing alone was initially able to reduce tree growth and slow down woodland expansion, until aspen individuals reached an escape size of 1.5 m in height. Prescribed burning followed by yearly goat browsing effectively contained tree encroachment while maximizing post-fire heathland regeneration. This integrated approach thus proved its efficacy also at the southern limits of *Calluna* distributional area.

## Highlights

We test prescribed fire and browsing to control aspen in southern European heaths. Treated units (n. 42) were monitored from 2004 to 2009 at Vauda heath, NW Italy. One-off burns within prescription rejuvenate heaths, but do not restrict tree recovery. Browsing after fire limits tree competition effects on heathland regeneration. Planning pastoral fire use and pasturing is necessary to maintain open heathlands.

## Keywords

Prescribed burning; Browsing; Aspen; Heathland; Tree encroachment; Conservation management

## 1. Introduction

Anthropogenic disturbance has been a major factor affecting European landscapes and ecosystems for thousands of years mostly through fire, pastoral and agricultural activities (Antrop, 2005, Plieninger et al., 2006 and Moreira and Russo, 2007). Since the middle of the XIXth century, land abandonment has favored scrubland and forest expansion, resulting in a strong decrease of many semi-natural open habitats (Chauchard et al., 2007 and Garbarino et al., 2011). In Europe, given the tight integration among biodiversity and traditional human activities (Farina et al., 2003 and Foster et al., 2003), the reforestation of formerly open lands can be a main cause of habitat loss (Dullinger et al., 2003 and Faluccci et al., 2007). *Calluna vulgaris* (L.) Hull heathlands are a major cultural landscape in Europe (Gimingham, 1972). Given their conservation importance there is interest in reducing the decline they are experiencing mainly because of the abandonment of traditional management (Pywell et al., 2011). A significant amount of research has been studying practices which maintain open heathlands such as burning, cutting, grazing (e.g., Hobbs and Gimingham, 1987, Sedláková and Chytrý, 1999, Bokdam and Gleichman, 2000, Vandvik et al., 2005, Newton et al., 2009 and Davies et al., 2010). Research has been focused on the response of *Calluna* to management in presence of competitors such as grasses and ferns (e.g., Miles, 1981, Mugion, 1996, Brys et al., 2005 and Mohamed et al., 2006). Fewer studies have addressed heathland restoration in presence of advanced tree encroachment (Marrs, 1987, Hester et al., 1991, Bokdam and Gleichman, 2000 and Manning et al., 2004), particularly at the southern limits of *Calluna* distributional area (Bartolomé et al., 2005). Transition toward woodlands in southern heathlands is favored by several factors: (i) limiting conditions (e.g., drought; poorly drained soils) which reduce *Calluna* competitiveness (Gimingham, 1972); (ii) no thick acidic organic layer (Pavari, 1927) which could inhibit tree establishment (Rode, 1999); (iii) heathland fragments surrounded by forests (Bartolomé et al., 2005). European aspen (*Populus tremula* L.) and birch (*Betula pendula* Roth) are the primary tree species that out-compete lowland heathlands on stream terraces which border southern European Alps (Mugion, 1996, Sindaco et al., 2008 and Borghesio, 2009). In this region heathlands covered large areas since the late Middle Age and there are evidences they were maintained by anthropogenic disturbance in the form of pastoral burning and pasturing (Pavari, 1927 and Sulli, 1985). Nevertheless, very few formal knowledge about traditional management practices (e.g., type of pasturing; fire regime) is available (Ascoli et al., 2009). During the last two centuries several agro-forestry programs converted these lands to forest plantations or intensive agriculture (Sulli, 1985). In addition, urbanization in last decades constrained heathlands to isolated patches, which have been recently included in nature reserves. Despite protection policies, remnant heathlands are rapidly converting to aspen-birch woodlands (Sindaco et al., 2008) and restoration programs need to be implemented (Borghesio, 2009).

Prescribed burning is one of the main management tools to maintain heathlands (Mohamed et al., 2006, Davies et al., 2010, Måren et al., 2010 and Harris et al., 2011), inducing stem mortality of trees and rejuvenating *Calluna* before it degenerates (*sensu* Watt, 1955). Nevertheless, *Calluna* regeneration after fire may be modified by local environment (Vandvik et al., 2005) and interactions with encroaching trees (Manning et al., 2004). Previous studies suggest that fire provides sites for aspen and birch seed germination (Chantal et al., 2005 and Borghesio, 2009),

and promotes seedling establishment by removing the vegetation cover and depleting allelopathic soil compounds (Mugion, 1996). In addition, aspen post-fire stem mortality induces root suckering over sizeable areas, consequently encroaching stands enlarge at each fire event until they merge and out-compete the heathland (Ascoli and Bovio, 2010). Borghesio (2009) underlies that burning alone is insufficient to stop woodland expansion, and that subsequent, prolonged grazing, might be essential. Few studies have addressed *P. tremula* control by domestic ruminants (Gudmundsson, 1986). Moreover, most of the research on the management of *Populus tremuloides* Michx., the vicariant species in North America (Chantal et al., 2005), is carried out through grazers such as cattle and sheep (DeByle, 1985; Bailey et al., 1990). Browsers (e.g., goats) are expected to result in a minor impact on *Calluna* than grazers (Hancock et al., 2010) and in a higher tree selection than other animal species (Celaya et al. 2010; Van Soest, 1994).

The aim of this study is to investigate the effects of prescribed burning and browsing on tree control in heathlands at the southern limits of their distribution area by testing the following hypotheses: (1) prescribed burning followed by browsing maximizes tree control and *Calluna* regeneration; (2) heathland regeneration and tree encroachment are affected by fire frequency and behavior; and (3) heathland regeneration is affected by tree competition despite management.

## 2. Methods

### 2.1. Study site

A heathland conservation experiment started in 2005 at the Nature Reserve of Vauda (Ascoli et al., 2009), northwest Italy (7°41'17"E, 45°13'13"N). The Vauda is located on a stream terrace at 240 and 480 m a.s.l. It is characterized by ancient and leached soils, with a fairly low pH (4.8), rich in clay and with a thin organic layer (Borghesio, 2009). Annual precipitation is 1130 mm, 40% of which fall during the growing season (May–September). The driest period is in winter from late December to March with 130 mm of rain. The mean annual temperature is 11.8 °C, with monthly means ranging from 1.4 °C in January to 22.1 °C in July. The Reserve was instituted in 1993 to maintain a 2646 ha fragment of a larger heathland that covered the area until the early 20th century (Mugion, 1996). A recent study has listed several important habitats within the Reserve which are favored by the maintenance of the heathland (Sindaco et al., 2008) such as wetland-based endangered species *Utricularia australis* L., *Ranunculus flammula* L., *Eleocharis carniolica* Koch and *Isoetes malinverniana* Ces. & De Not., and the extremely rare species *Rynchospora fusca* (L.) W.T. Aiton. The area is rich in fauna with 150 bird species, and several amphibians, reptiles, and insects of conservation importance (Borghesio, 2009). Despite protection policies, the area is experiencing woodland expansion, heathland decline and biodiversity loss (Borghesio, 2004). Wildfires and the absence of pasturing planning are the main responsible for the heathland degradation (Mugion, 1996 and Borghesio, 2009). Uncontrolled fires occur frequently (every 1–5 years), over relatively large areas (up to 250 ha) and when fire danger is high at the end of the dry period in late winter (February–March). This fire regime is mainly due to unplanned fires lit by

shepherds who burn surreptitiously because of fire bans and control policies (Ascoli and Bovio, 2010). Pastoral fires are set when the fire danger is high so as fire can spread without attendance, but this practice results in negative effects on the heathland (Mugion, 1996). In addition, the current pasturing system is not appropriate and different sections of the Reserve are subjected to unequal levels of exploitation. In most places the heathland is no longer used as a pasture, while in a few others there is an excessive density of domestic animals (Borghesio, 2004).

## 2.2. Experiment design

The pre-fire vegetation composition was characterized by *Calluna* dominated stands in the building phase (*sensu* Watt, 1955), together with aspen and birch encroaching the heathland and covering an area of about 4 ha. Five treatments were implemented from 2005 to 2009: (1) annual-fire: fire every year (2005–09) in late winter to mimic current pastoral burning practices; (2) one-off-fire: single early winter prescribed burning in 2005 with a longer fire return interval, to be assessed under an adaptive management approach (see Ascoli et al., 2009); (3) browsing-only: annual spring goat browsing; (4) fire + browsing: single early winter prescribed burning in 2005 with a long fire return interval followed by annual spring goat browsing; and (5) control: unburnt and unbrowsed. As few knowledge is available about traditional management practices in the area, alternative treatments were set on the basis of a review of heathland conservation management and aspen control studies (Ascoli et al., 2009). A completely randomized design was used. Each treatment was replicated 6–12 times for a total of 42 experimental units (Table 1). The number of replicates was unbalanced among the treatments due to practical constraints. The lowest number of experimental units ( $n = 6$ ) was associated with annual-fire and control treatments, for which lower variability was expected. The highest number of experimental units was in treatment fire + browsing ( $n = 12$ ), where the interaction of fire and browsing could have resulted in a higher variability. In early winter 2005, experimental units destined to fire treatments (annual-fires, one-off-fire, fire + browsing) were burned under homogenous weather conditions. During burning operations, mean ( $\pm$ SE) air temperature, moisture and wind speed were measured at fixed interval (30 s.). Average burn conditions were  $8\text{ }^{\circ}\text{C}$  ( $\pm 3$ ), 47% ( $\pm 6$ ) and  $5.8\text{ km h}^{-1}$  ( $\pm 0.4$ ), respectively. The moisture of dead fine fuels (mainly cured grasses) on a dry weight basis ranged between 10% and 30% while the live fuels moisture (*Calluna* leaves) from 60% to 65%. The topsoil was moist ( $>100\%$ ) as recommended for prescribed burning in heathlands (Davies et al., 2010 and Fernandes and Loureiro., 2010). Burns were ignited with the wind but shifts in wind direction determined both backfire (against the wind) and headfire (with the wind) phases. Fire rate of spread and direction, flame length and Byram's (1959) fireline intensity were assessed adopting a 'microplot-scale' approach (Ascoli et al., 2009). The timing of the fire front arrival to marked rods along a regular grid was used to appraise fire spread variation within each burn. Back fire and headfire phases were thus assessed. Marked differences resulted in the two fire behaviors: rate of spread was  $1.7 \pm 0.7$  vs.  $7.1 \pm 0.8\text{ m min}^{-1}$ ; fireline intensity  $307 \pm 51$  vs.  $2052 \pm 257\text{ kW m}^{-1}$ ; and flame length was  $0.6 \pm 0.1$  vs.  $1.9 \pm 0.3\text{ m}$ , respectively. Among experimental units undergoing fire treatments ( $n = 27$ ), 13 resulted burned by back-fire and 14 by head-fire (Table 1). This provided the opportunity to test fire behavior effects on the heathland. After 2005, annual-fire units were burnt every year in late winter to mimic common pastoral fire practices. All treated areas were

fenced. A herd of about 100 goats exploited fire + browsing and browsing-only areas for 3.5 h day<sup>-1</sup> over a period of four weeks each year (between April and May), corresponding to a stocking density of about 20 Livestock Units (LU) ha<sup>-1</sup> day<sup>-1</sup> and to a stocking rate of about 135 LU ha<sup>-1</sup> (Lonati et al., 2009). Stocking densities were lower when compared literature data about sheep grazing (e.g., Pakeman et al., 2003), in order to take into account the different goat behavior towards trees and minimize the impact on the heathland.

### 2.3. Vegetation sampling

Tree vegetation surveys were conducted in five permanent quadrats (4 m<sup>2</sup>) randomly placed in each experimental unit. Within each quadrat tree species, diameter at the root collar and height of each stem were recorded. Average stem density, height and basal area were computed. Pearson's skewness of stem frequency by diameter class (0.5 cm) was used as an index of structural diversity (McCarthy and Weetman, 2007). The presence of *Calluna* and *Molinia arundinacea* Shrank was assessed by the point-intercept method (Daget and Poissonet, 1971 and Jonasson, 1988). *M. arundinacea* is a grass species competing with *Calluna* and its abundance indicates succession towards grasslands or woodlands (Mugion, 1996 and Borghesio, 2009). In each experimental unit one fixed-line transect (10 m long) was placed so as to overlap on permanent quadrats. In each transect, at 20-cm intervals, the species touching a steel needle was recorded. The absolute number of point intercepts of *Calluna* and *Molinia* was used to estimate their cover; species relative abundance was calculated following Gallet and Rozé (2002). Vegetation survey was conducted during summer from 2004 (pre-treatment year) to 2009, each year for the tree layer and every two years for the heathland layer.

### 2.4. Statistical analyses

After initial variable reduction three linear model analyses were carried out to study the effect of: (i) treatments; (ii) fire behavior; and (iii) tree competition.

#### 2.4.1. Variable reduction analysis

An exploratory pair-wise correlation (Kendall) on pre-treatment data evidenced collinearity both within and between heathlands and tree variables. Principal Component Analysis (PCA) was thus used to reduce correlated variables to new derived components which could summarize the original tree and heathland variables (Quinn and Keough, 2002). These independent components were then used in subsequent linear model analyses (Repeated Measure ANOVA and multiple regression) as predictor and response variables. The PCA used a correlation matrix composed by both tree and heathland variables as measured in 168 replicates: 42 experimental units × year 2004, 2005, 2007, 2009. Each row of the matrix was weighted according to a factor inversely proportional to the treatment replicate number (1/n replicates). We selected components with eigenvalues greater than 1 and performed an orthogonal rotation to improve their interpretability (Quinn and Keough, 2002). PCA scores for 2004 (PC-pre) and post-treatment years 2005 (PC-05), 2007 (PC-07) and 2009 (PC-09) were extracted for subsequent linear model analyses.

#### 2.4.2. Comparison among treatments

A Repeated Measure (RM-) ANOVA was used to test treatment differences along the studied period. Since pre-treatment vegetation status (PC-pre) could affect species response to treatments, particularly for aspen (e.g., Brown and De Byle, 1987 and Wang, 2003), PC-pre was factored as a covariate to account for the within treatment variability of PC-pre. ANOVA was used to verify the assumption that there were no significant differences in PC-pre among treatment groups. The RM-ANOVA tested within and between differences of the following subjects: time (2005, 07, 09), treatments (one-off-fire, annual-fire, fire + browsing, browsing-only, control) and the covariate PC-pre. Assumptions of the analysis of variance were tested for unbalanced experimental design according to Quinn and Keough (2002). When the RM-ANOVA evidenced significant effects, planned contrasts were carried out.

#### 2.4.3. Fire behavior effect on heathland and tree recovery

In order to test the hypothesis that heathland regeneration is affected by fire behavior (back vs. head fire), a second RM-ANOVA was carried out. Since the fire behavior was not planned a priori but resulted from fire treatments application, it was considered as a random factor. The RM-ANOVA tested within and between differences of the following subjects: time (2005, 07, 09), fire treatments (one-off-fire, annual-fire, fire + browsing), the random factor fire behavior (back vs. head fire) and the covariate PC-pre.

#### 2.4.4. Tree competition effect on the heathland

In order to test the hypothesis that heathland regeneration is affected by trees, without distinction among treatments and besides pre-treatment heathland status, component multiple regressions (Quinn and Keough, 2002) were carried out separately for each treatment group. The PCA components interpreted as related to tree encroachment were used as predictor variables of components related to the heathland regeneration. Significant standardized regression coefficients were examined to compare tree competition among treatments. Linear models were carried out with SPSS® version 17.0, and PCA was performed using XL-Stat (Addinsoft®).

### 3. Results

#### 3.1. Vegetation response to treatments

Before treatments, average ( $\pm$ SE) tree density and basal area were  $22,722 \pm 1518$  stems  $\text{ha}^{-1}$  and  $3.1 \pm 0.4$   $\text{m}^2$   $\text{ha}^{-1}$ , respectively. Aspen root collar diameter ranged from 0.5 to 7 cm and accounted for 86% of the total density and 69% of basal area (birch accounted for the rest). Mean species abundance of Calluna and Molinia were  $42\% \pm 2$  and  $47\% \pm 3$ , respectively. After fire treatments in winter 2005, the percentage of fire-killed stems was 100% for aspen and 96% for birch, with a consequent strong reduction in basal area ( Fig. 1a) and height ( Fig. 1b). Subsequent resprouting resulted in a dramatic increase in density ( Fig. 1c), which ranged between 55,000 and 138,500 stems  $\text{ha}^{-1}$ . Aspen comprised 88% of density and 97% of the basal area of post-fire shoots. The high number of resprouts in the smallest diameter class (0–0.5 cm) caused skewness

to increase ( Fig. 1d). From 2005 to 2009, in one-off-fire areas all tree variables tended to recover their pre-treatment values, while in annual-fire and fire + browsing areas both basal area and height did not recover. Compared to fire treatments, in browsing-only areas all tree variables were almost stable until 2008 while an increase in basal area and height was observed in 2009. In control plots, density remained constant while height and basal area increased markedly. In 2005, abundance and cover of *Calluna* were reset in all fire treatment areas ( Fig. 1e and f), conversely *Molinia* recovered and exceeded its initial abundance since the first growing season, and maintained it for the entire study period ( Fig. 1g and h). *Calluna* was deeply impacted in annual-fire areas but, after one single prescribed burning (one-off-fire; fire + browsing) it was able to recover mainly by vegetative regeneration, while a little number of seedlings was observed. In browsing-only areas *Calluna* showed few increases in species abundance and cover while a minor decrease occurred to *Molinia*; an inverse trend was observed in the control.

### 3.2. Comparison among treatments

The PCA identified two components with an eigenvalue greater than 1, which explained 66.1% of the total variance. Heathland variables were significantly correlated (Kendall's correlation > 0.7) to the first eigenvector: abundance and cover of *Calluna* were positively correlated, while *Molinia* negatively. Conversely, they contributed to a minor extent to the second component ( Table 2). Basal area and height were positively correlated to the second eigenvector, while skeweness negatively. Tree variables were not significantly correlated to the first component. Density was not strongly correlated with either of the two eigenvectors. The first component was thus interpreted as a gradient mainly related to the heathland regeneration success (PC-heath), while the second component to increasing tree encroachment level (PC-tree). Mean components scores followed different trajectories according to the treatment ( Fig. 2). ANOVA showed no significant differences in PC-pre mean values among overall treatment areas both for the first ( $F[4,41] = 0.221$ ,  $P = 0.925$ ) and the second component ( $F[4,41] = 0.349$ ,  $P = 0.843$ ). The RM-ANOVA relating both PC-heath and PC-tree scores to time (2005-07-09), treatments and the covariate PC-pre, evidenced a significant within subjects effect of time and time vs. treatment ( Table 3). Between subjects differences were significant for both the treatment and the covariate fixed factors. Consequently, the  $H_0$  of equality within treatment groups was rejected. Results of planned contrasts among treatments are displayed in Table 4. In annual-fire areas heathland regeneration (PC-heath) was significantly lower compared to other treatments, as evidenced also by the mean scores trajectory in Fig. 2. Similarly, the tree abundance (PC-tree) was lower with annual-fire in comparison with the other treatments, except for the fire + browsing one ( Table 4). Compared to the one-off-fire, in fire + browsing areas PC-tree was significantly lower while PC-heath recovered to higher scores but it did not reach browsing-only and control means. Finally, in the control PC-tree was significantly higher in comparison with all treatments ( Fig. 2).

### 3.3. Fire behavior effect on heathland and tree regeneration

The RM-ANOVA relating PC-heath and PC-tree to time, fire treatment (annual-fire, one-off-fire, fire + browsing), fire behavior and PC-pre, showed results similar to the previous analysis. Significant differences between subjects were evidenced for both the treatment fixed factor and

the covariate PC-pre (Table 5). Conversely, the fire behavior random factor was not significant indicating that back and head fire produced comparable effects on both the heathland and the tree component.

### 3.4. Tree competition effect on the heathland

Multiple linear regressions were fitted for each treatment using the PC-heath in 2009 as response variable and including its PC-pre and PC-tree in 2009 scores as predictor variables. Results of linear models are reported in Table 6. All models were significant and showed a View the MathML source  $R^2$  close to 0.6, except for the fire + browsing one. Standardized coefficients were all positive for the PC-pre predictor, and resulted significant in one-off-fire and control areas. Conversely, coefficients were negative for the PC-tree predictor and, except for the annual-fire and the fire + browsing groups, were all significant. The highest negative slope was in control areas (stand. coeff. =  $-0.813$ ;  $P = 0.013$ ) followed by slopes in browsing-only (stand. coeff. =  $-0.792$ ;  $P = 0.009$ ) and one-off-fire areas (stand. coeff. =  $-0.547$ ;  $P = 0.032$ ).

## 4. Discussion

Prescribed burning, browsing and their combinations affected differently the tree layer, the heathland and their competition dynamics. Prescribed burning followed by yearly goat browsing effectively contained tree encroachment while maximizing post-fire heathland regeneration. Fire significantly reduced tree competition on a short term by inducing a high tree stem mortality. Similar results have been reported for *P. tremuloides* (Brown and De Byle, 1987, Bailey et al., 1990 and Wang, 2003) whose fire ecology is comparable to the *P. tremula* one (Chantal et al., 2005). Brown and De Byle's (1987) mortality models after prescribed fire predict a probability of stem mortality (for diameters less than 10 cm at breast height) greater than 95% when flame length is beyond 58 cm. Similarly, in our experiment back-fires with a flame length of 60 cm were sufficient to kill the cambium around the entire stem circumference of most individuals.

Stem mortality induced a dramatic re-sprout. The extent of suckering was related to the pre-fire tree abundance as observed in previous studies (Brown and De Byle, 1987, Wang, 2003 and Zakrisson et al., 2007), but no differences were found between areas burnt by back- vs. head-fires, which leads to two conclusions. First, apical mortality was high in both cases, which suggests that stimulation of resprouting was likely the same; second, increasing fire intensity did not result in increasing damage to tree stumps and roots. Burning in drier conditions could have resulted in a minor post-fire suckering (Wang, 2003). Nevertheless, Brown and De Byle (1987) did not find a significant relationship between aspen sucker density and severity (i.e., rate of duff consumption), because suckers originated from deeper roots with increasing duff consumption. Wang (2003) observed decreased sucker density only after high severity wildfires (i.e., soil organic horizon consumed), a severity level that is likely to affect also *Calluna* stumps (Davies et al., 2010 and Harris et al., 2011). Prescribed burning carried out in heathlands in the building phase under soil moist conditions, as recommended for *Calluna* management (Davies et al., 2010 and Fernandes

and Loureiro., 2010), was effective in rejuvenating *Calluna* which regenerated vigorously mainly by resprouting. As observed for tree response to fire, no differences in heathland recovering were found between back and head fire behavior.

In our experiment, beside moisture conditions, also soil properties (i.e., clay substrate; thin organic layer) are probably responsible for the lack of correlation between fire behavior and severity on both tree and heathland vegetation. A heath fire severity analysis conducted by Davies et al. (2010) demonstrated how moisture content and substrate composition largely control temperature residence times and heat transfer to soil, and stresses the fact that fire severity does not necessarily respond linearly to changes in surface fire behavior. Clay soils have in fact low thermal conductivity (Abu-Hamdeh and Reeder, 2000), and a moist and thin organic layer cannot sustain a smouldering combustion (Rein et al., 2008). Consequently, both during back- and head-fires below-ground heat penetration did not prevent profuse *Calluna* and aspen shoot regeneration.

Due to tree resprouting, the sole prescribed burning was not sufficient to limit tree encroachment. In the absence of measures to control post-fire shoots, aspen tended to recover the pre-treatment stand structure. In addition, although *Calluna* showed a successful post-fire agamic regeneration, heathland recovery was halted by aspen shoots. The regression analysis, in fact, showed a significant and negative effect of tree competition on the heathland regeneration after a single prescribed burning. Annual fires reset aspen regeneration each year, maintaining tree encroachment at significant lower levels in comparison with other treatments, but deeply impacted *Calluna* stumps while favouring the opposing *Molinia*, which is well adapted to high frequency fire regimes (Mugion, 1996, Marrs et al., 2004 and Brys et al., 2005).

Repeated browsing from the first growing season after prescribed fire (fire + browsing) limited selectively tree recovery and did not affect the heathland regeneration. The decreased tree competition in these areas could explain the significantly higher heathland regeneration, in comparison with the sole prescribed burning, and the absence of a significant effect of tree competition on the heathland regeneration, as evidenced by the regression model.

While post-fire browsing maintained aspen shoots in a dwarf shape, similarly to grazers and other type of browsers (DeByle, 1985, Bailey et al., 1990 and Ericsson et al., 2002), the sole browsing initially halted tree growth, but increases in tree encroachment were observed at the end of the study. This result was due to the number of trees that attained "escape" size (Romme et al., 1995), a point beyond the effectiveness of goats, which increased the average stand height. Several studies have reported that extensive grazing and browsing appear to suppress aspen growth for a short time until a threshold height is attained, e.g., 1.5 m for small-sized animals (DeByle, 1985). Once reached, aspen growth is no further limited by animals as they are no more able to browse apical buds (Romme et al., 1995 and Ericsson et al., 2002). In addition, goat browsing was not effective in rejuvenating the heathland. *Calluna* layering does not take place in the studied area, probably due to the absence of a humus-rich or peaty soil horizons in the soils (MacDonald et al., 1995), so rejuvenating treatments are crucial before *Calluna* reaches the degenerative phase (Watt, 1955).

Prescribed burning before browsing seems thus needed to both reset aspen height to a level at which goats can be effective, and to rejuvenate the *Calluna* stands.

The present study verified the necessity to integrate prescribed burning and browsing to maintain the southern lowland heathland. Tree encroachment in control areas increased over the study period, showing significant higher values in comparison with other treatments. The increased tree competition resulted in the most pronounced negative effect on the heathland. Furthermore, without rejuvenating the heathland by fire *Calluna* in control areas will age and reach the degenerate phase, thus forming crown gaps (Watt, 1955) that will accelerate the encroachment process (Hester et al., 1991 and Rode, 1999; Kuiters and Slim, 2002). Consequently, in the absence of an active management to rejuvenate the heathland and control trees, southern heathlands will be out-competed.

#### 4.1. Management implications

Results evidenced the need to change the current unplanned pastoral practices. Both frequent fires and fire exclusion enhance heathland losses. Prescribed burning is a suitable tool to induce stem mortality of young trees but its effectiveness when stems are larger remains to be assessed. Burning under moist conditions is successful in rejuvenating the heathland. Increasing fire intensity do not relate to higher severity on *Calluna* stumps, consequently headfires, ignited in parallel strips distanced 10–30 m to assure fire control, are suitable for heathland management while reducing operative times. Prescribed burning alone is not sufficient to control trees on a long term. Goat browsing is effective in halting the growth of young aspen individuals (below ~1.5 m in height); beyond this size, pasture management could be integrated with selective tree cutting. Nevertheless, actions to periodically rejuvenate the heathland should be implemented. Our results demonstrate the efficacy of integrating prescribed fire in winter followed by repeated browsing to control *P. tremula* post-fire shoots and, at the same time, leave heathland regeneration unaffected.

This study clarifies some management questions, but longer monitoring is needed to assess other important issues such as the effect of alternative prescribed burning intervals on heathland recovery, and effects on species others than *Calluna* and *Molinia*, particularly the exotic species *Panicum acuminatum* Swartz. This latter was actually particularly abundant in 2007 in fire + browsing areas (Lonati et al., 2009). Moreover, research should not be limited to study species response to management regimes at the stand level (Driscoll et al., 2010). These results should feed back in a 'landscape experiment' with the objective to maximize species and structural diversity creating a mosaic of heathlands, grasslands and woodlands. Such work requires an adaptive approach (Ascoli et al., 2009) to assess how heathlands and tree competition dynamics are influenced by flexible spatial arrangement and temporal sequences of prescribed burning and pasture. Furthermore, to change current firing and grazing practices, it will be necessary to implement conflict resolution on fire use issues (Aguilar and Montiel, 2011) and to augment local agro-pastoral products (Quetier et al., 2005) promoting participatory processes that commit stakeholders (i.e., land managers, shepherds, fire agencies) to combine multiple goals with prescribed burning (i.e., heathland conservation + pasture improvement + fire-fighter training).

## Acknowledgements

We thank the Vauda managers (Aschieri A, Maccioni A) for technical support, the State Forestry Corp (Noveri D), the Regione Piemonte Fire Fighting Volunteers for logistic support in prescribed burning, Sacco D and Garbarino M for statistical analysis suggestions and Ceccato R, Cugno D, Gorlier A, Mello N, Zerbini M, for fieldwork assistance. We also thank three anonymous reviewers and the open review of Marrs RH. The work was in part financed by the Regione Piemonte and in part carried out within the project PRIN 2009 "in\_FLAMING: Developing innovative models and techniques for integrated fuel management for fire prevention in Mediterranean and temperate forests" (national coordinator: P. Corona) funded by the Italian Ministry for Education, University and Research.

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**Tab. 1** Experimental design with the five treatments, number of disturbance events and season of application, the size and number of experimental units by treatment and fire behavior.

<i>Treatment name</i>	<i>Disturbance</i>	<i>Season</i>	<i>Size (m<sup>2</sup>)</i>	<i>n.</i>	<i>n. (back-head fire)</i>
Annual-fire	5 fires	Winter	650	6	2 – 4
One-off-fire	1 fire	Winter	650	9	4 – 5
Browsing-only	5 grazes	Spring	650	9	7 – 5
Fire + browsing	1 fire + 5 grazes	Winter + spring	650	12	-
Unburnt-unbrowsed control	0	-	300	6	-

**Tab. 2** Results of a Principal Component Analysis of tree and heathland structural variables and the component correlation for each heathland and tree vegetation variable. Combined, these Principal Components (PCs) explain 66.1% of data set variation. Strong relationships (Kendall's correlation > 0.7) are bolded.

<i>Variables</i>	<i>PC1 (PC-heath)</i>	<i>PC2 (PC-tree)</i>
<i>Calluna</i> abundance	<b>0,872</b>	0,525
<i>Calluna</i> cover	<b>0,863</b>	0,509
<i>Molinia</i> abundance	-0,597	-0,534
<i>Molinia</i> cover	<b>-0,795</b>	-0,232
Density	-0,587	-0,466
Basal area	0,399	<b>0,920</b>
Height	0,507	<b>0,907</b>
Skewness	-0,580	<b>-0,894</b>

**Tab. 3** Results of Repeated Measure ANOVA variation modeling in PC-scores with changes in time (2005, 07, 09), treatment fixed factor (TR = annual-fire, one-off-fire, fire+browsing, browsing-only, control) and covariates (PC-pre) for both PC-heath (heathland regeneration) and PC-tree (tree encroachment level). The table shows Type III sum of squares (SS), degrees of freedom (d.f.), and F and P values of both within subject and between subject effects for each variable.

	<i>PC-heath (heathland regeneration)</i>				<i>PC-tree (tree encroachment level)</i>			
<b>Within subject</b>	<i>SS</i>	<i>d.f.</i>	<i>F</i>	<i>Sig.</i>	<i>SS</i>	<i>d.f.</i>	<i>F</i>	<i>Sig.</i>
Time	0.539	2	3.15	<b>0.05</b>	3.123	2	31.141	<b>0.000</b>
Time x TR	2.339	8	3.417	<b>0.002</b>	6.712	8	16.732	<b>0.000</b>
Time x PC-pre	0.25	2	1.461	0.24	.197	2	1.963	0.149
Time x TR x PC-pre	1.621	8	2.369	<b>0.027</b>	.359	8	.895	0.526
Residuals	5.476	64			3.209	64		
<b>Between subjects</b>	<i>SS</i>	<i>d.f.</i>	<i>F</i>	<i>Sig.</i>	<i>SS</i>	<i>d.f.</i>	<i>F</i>	<i>Sig.</i>
Intercept	19.598	1	70.166	<b>0.000</b>	12.024	1	53.640	<b>0.000</b>
TR	18.930	4	16.944	<b>0.000</b>	48.322	4	53.892	<b>0.000</b>
PC-pre	11.006	1	39.406	<b>0.000</b>	12.689	1	56.606	<b>0.000</b>
TR x PC-pre	1.972	4	1.765	0.160	5.431	4	6.057	<b>0.001</b>
Residuals	8.938	32			7.173	32		

**Tab. 4** Planned contrasts of treatment group means for both PC-heath (heathland regeneration) and PC-tree (tree encroachment level): for each contrast mean difference and P value (in brackets) are provided. Significant differences ( $P < 0.05$ ) are evidenced in bold.

	<i>PC-heath (heathland regeneration)</i>				<i>PC-tree (tree encroachment level)</i>			
	<i>Annual-fire</i>	<i>One-off-fire</i>	<i>Fire+browsing</i>	<i>Browsing-only</i>	<i>Annual-fire</i>	<i>One-off-fire</i>	<i>Fire+browsing</i>	<i>Browsing-only</i>
<b>One-off-fire</b>	-0.733 <b>(0.016)</b>				-0.566 <b>(0.000)</b>			
<b>Fire+browsing</b>	-1.042 <b>(0.001)</b>	-0.308 <b>(0.042)</b>			-0.148 <b>(0.110)</b>	0.418 <b>(0.000)</b>		
<b>Browsing-only</b>	-1.579 <b>(0.000)</b>	-0.845 <b>(0.000)</b>	-0.537 <b>(0.001)</b>		-0.883 <b>(0.000)</b>	-0.317 <b>(0.000)</b>	-0.735 <b>(0.000)</b>	
<b>Control</b>	-1.374 <b>(0.000)</b>	-0.640 <b>(0.000)</b>	-0.332 <b>(0.025)</b>	0.205 <b>(0.155)</b>	-1.122 <b>(0.000)</b>	-0.557 <b>(0.007)</b>	-0.974 <b>(0.000)</b>	-0.479 <b>(0.012)</b>

**Tab. 5** Results of Repeated Measure ANOVA variation modeling in PC-scores with changes in time (2005, 07, 09), fire treatment fixed factor (f-TR = annual-fire, one-off-fire, fire+browsing), fire behavior (back, head) random factor and covariates (PC-pre) for both PC-heath (heathland regeneration) and PC-tree (tree encroachment level). The table shows Type III sum of squares (SS), degrees of freedom (d.f.), and F and P values of both within subject and between subject effects for each variable.

	<i>PC-heath (heathland regeneration)</i>				<i>PC-tree (tree encroachment level)</i>			
<b>Within subject</b>	<i>SS</i>	<i>d.f.</i>	<i>F</i>	<i>Sig.</i>	<i>SS</i>	<i>d.f.</i>	<i>F</i>	<i>Sig.</i>
Time	0.435	2	2.026	0.147	2.548	2	28.216	<b>0.000</b>
Time x f-TR	0.616	4	1.779	0.295	3.530	4	19.542	<b>0.000</b>
Time x Fire behavior	0.004	2	0.019	0.981	0.047	2	0.525	0.597
Time x PC-pre	0.219	2	29.044	<b>0.004</b>	0.113	2	1.256	0.298
Time x f-TR x PC-pre	0.347	4	0.505	0.732	0.157	4	0.869	0.492
Time x f-TR x Fire behavior	0.168	4	0.392	0.813	0.163	4	0.903	0.473
Time x Fire behavior x PC-pre	0.008	2	0.035	0.965	0.022	2	0.249	0.781
Residuals	3.646	34			1.535	34		
<b>Between subjects</b>	<i>SS</i>	<i>d.f.</i>	<i>F</i>	<i>Sig.</i>	<i>SS</i>	<i>d.f.</i>	<i>F</i>	<i>Sig.</i>
Intercept	20.533	1	119.032	<b>0.000</b>	41.533	1	314.396	<b>0.000</b>
f-TR	3.088	2	23.877	<b>0.040</b>	8.814	2	20.242	<b>0.047</b>
Fire behavior	0.038	1	0.223	0.643	.077	1	0.586	0.455
PC-pre	5.072	1	61.570	<b>0.016</b>	1.623	1	70.267	<b>0.014</b>
f-TR x Fire behavior	0.129	2	0.505	0.612	0.435	2	0.505	0.612
f-TR x PC-pre	0.689	2	1.996	0.167	0.422	2	1.597	0.231
Fire behavior x PC-pre	0.082	1	0.478	0.499	0.023	1	0.175	0.681
Residuals	2.932	17			2.246	17		

**Tab. 6** Results of the multiple linear regression models for the abundance of PC-heath in treatment areas in 2009.

<i>Model</i>	<i>Predictors</i>	<i>Regression coefficient</i>	<i>Standard error</i>	<i>Standardized coefficient</i>	<i>t -Value</i>	<i>P</i>	<i>Sign. levels</i>	<i>R<sup>2</sup><sub>adj</sub></i>
<b>One-off-fire</b>	Intercept	-.750	.326		-2.302	.061	n.s.	0.702
	PC-heath	.787	.258	.600	3.058	.022	*	
	PC-tree	-.894	.321	-.547	-2.790	.032	*	
<b>Annual-fire</b>	Intercept	-3.081	1.357		-2.271	.108	n.s.	0.696
	PC-heath	2.877	1.016	.984	2.833	.066	n.s.	
	PC-tree-09	.353	1.037	.118	.341	.756	n.s.	
<b>Fire+browsing</b>	Intercept	-.267	.184		-1.456	.179	n.s.	0.422
	PC-heath	.270	.169	.374	1.600	.144	n.s.	
	PC-tree-09	-.319	.176	-.456	-2.380	.041	*	
<b>Browsing-only</b>	Intercept	.876	.297		2.949	.026	*	0.651
	PC-heath	.250	.207	.254	1.209	.272	n.s.	
	PC-tree-09	-.653	.173	-.792	-3.762	.009	**	
<b>Control</b>	Intercept	.818	.131		6.234	.008	**	0.951
	PC-heath	.159	.044	.467	3.651	.035	*	
	PC-tree-09	-.492	.077	-.813	-6.364	.008	**	

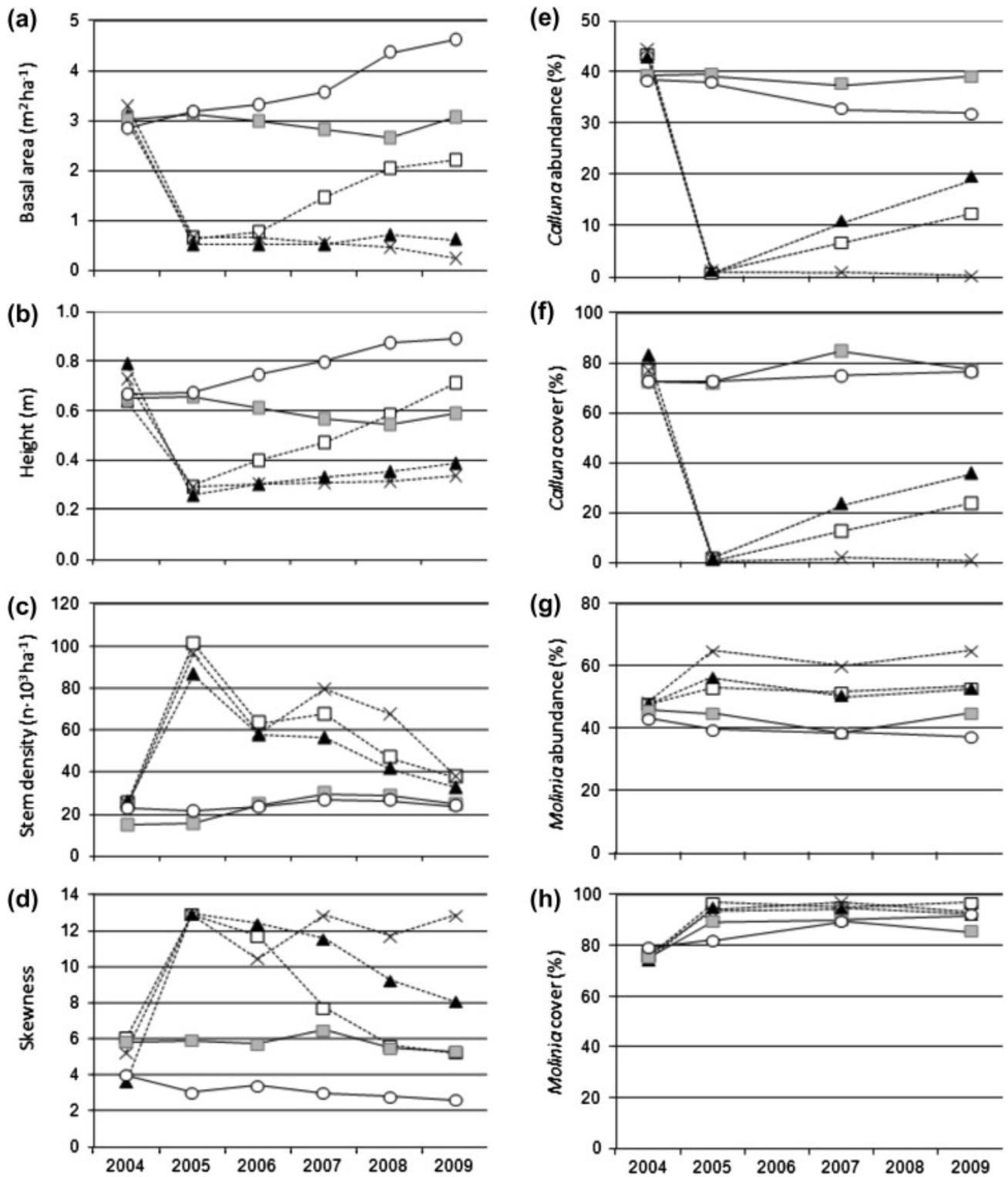


Fig. 1. Mean values of tree: (a) basal area, (b) height, (c) stem density, (d) skewness, every year from 2004 (pre-treatment) to 2009, (e) relative abundance of *Calluna*, (f) cover of *Calluna*, (g) relative abundance of *Molinia*, (h) cover of *Molinia*, every 2 years from pre-treatment to 2009. Treatments: - - x - - annual-fire; - -▲- - fire + browsing; - -□- - one-off-fire; —■— browsing-only; —○— control.

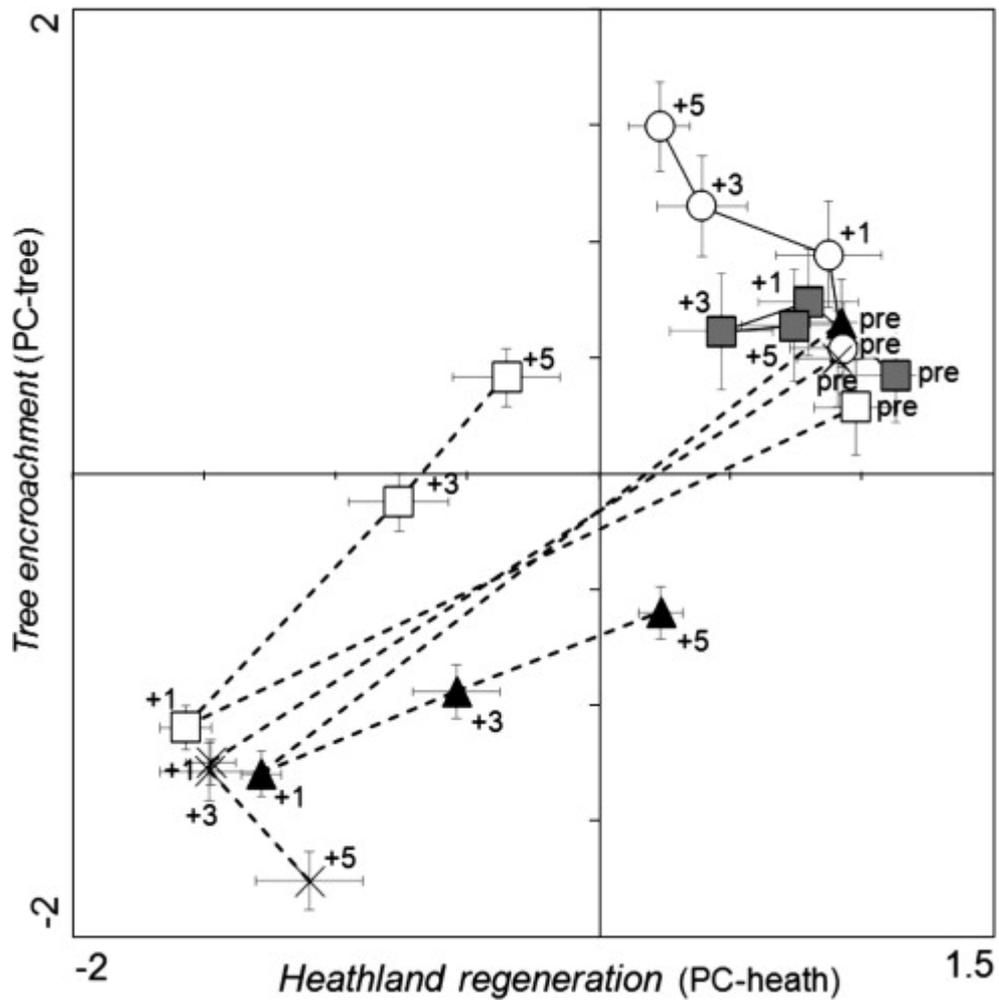


Fig. 2 Mean ( $\pm$ SE) scores for both PC-heath and PC-tree by treatment and year. Treatments: --x-- annual-fire; --▲-- fire+browsing; --□-- one-off-fire; —■— browsing-only; —○— control. The changes in census from pre-treatment (upper right, marked year - pre) to 2005 (+1), 2007 (+3) and 2009 (+5) are drawn as trajectories.