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Fuel loads and fuel structure in Austrian coniferous forests

Mathias Neumann[A,*], Lena Vilà-Vilardell[B], Mortimer M. Müller[A] and Harald Vacik[A]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
Mathias Neumann
Institute of Silviculture, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences, Vienna, 1190 Austria
Email: mathias.neumann@boku.ac.at

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ABSTRACT

Understanding fires in temperate European coniferous forests is hindered by a lack of reliable field observations on fuel load and structure. Fuel load influences the spread, intensity and spotting distance of a surface fire, torching likelihood and potential carbon emissions. We quantified fuel load and structure for Austrian coniferous forests using 93 sample plots across Austria. We compared Austrian fuel types with fuels collected in other regions and biomes. We found significant differences among regions and forest types. Fuel load was more dependent on region and forest type than on age class. Highest fuel load was found in *Picea abies* stands, lowest in *Pinus nigra* forests. Dead fuel loads were positively correlated with basal area, while live fuels were negatively correlated, suggesting that basal area drives accumulation of dead fuels and suppresses growth of understorey vegetation. Fuel loads in Austria are similar to published data for other temperate forests. The large variation in observed fuel loads and lack of previous studies highlight the need to further develop fuel models for mixed conifer–broadleaf forests. This pilot study underpins that consistent terminology and fuel classification are important to interpret differences between regions and forest types.

Keywords: carbon emissions, destructive sampling, fire hazard, fire severity, fuel sampling, fuel types, line-intercept method, stand structure, wildfire.

Introduction

Wildfires (i.e. uncontrolled high-intensity vegetation fires) are a global threat to wildlife, property value, cultural assets, human health and lives (Keane 2015; Doerr and Santin 2017; Vilà-Vilardell *et al.* 2020). Fuel load (that is, combustible organic material) determines the carbon emissions of a forest fire (Possell *et al.* 2015), its spread and intensity (McCaw *et al.* 2012; Wotton *et al.* 2012; Oliveira *et al.* 2021), its spotting potential and the likelihood of a transition from surface to crown fire (Stephens 1998; Cruz and Alexander 2010; Werth *et al.* 2011). Fire intensity is commonly calculated from the energy content of the fuel, rate of spread of the fire front and consumed fuel, assuming direct proportionality between fuel load and fire intensity (Byram 1959; Alexander 1982). For these reasons, fuel load is a central parameter of the fire behaviour fuel models used in the United States (Anderson 1982; Scott and Burgan 2005), the European Forest Fire Information System (EFFIS) and the European fuel classes (San-Miguel-Ayanz *et al.* 2012; de Rigo *et al.* 2017), as well as the fuel accumulation curves used in Australia (Tolhurst *et al.* 2008; Thomas *et al.* 2014). In central Europe, potentially owing to low and only local relevance of forest fires, there has been little work done on collecting *in situ* fuel load observations using destructive sampling – the most accurate fuel sampling method (Volkova *et al.* 2016; McColl-Gausden and Penman 2017). Although canopy fuel load can be now modelled by remote sensing with promising accuracy (González-Ferreiro *et al.* 2014, 2017; Skowronski *et al.* 2016), the estimation of surface fuels requires ground observations. For southern Europe and the boreal region, more data are available than for Central Europe (see, for instance, Dimitrakopoulos 2002; Curt *et al.* 2013; Elia *et al.* 2015; Piqué and Domènech 2018; Ascoli *et al.* 2020; Ivanova *et al.* 2020). Fuel loads are recognised as the foundation for reliable fire modelling

(Pugnet *et al.* 2013) and can be linked with fuel type mapping (Ascoli *et al.* 2020; Aragoneses and Chuvieco 2021).

Fuels are commonly classified by condition or status (live and dead) and fuel layer (e.g. ground, surface and canopy fuels) (Gould *et al.* 2011; Pugnet *et al.* 2013; Keane 2015). Dead fuels according to the classification used in the United States are divided into four timelag categories (1, 10, 100, 1000-h) as a function of their diameter (0–6, 6–25, 25–75, >75 mm). The timelag refers to the time the fuel particle needs to reach 2/3 of the difference between its initial moisture content and the moisture of the current environment, which is related to its diameter and its ability to lose or gain moisture content. We follow the North American approach for classifying fuel, as it is the one used in European forests (Schimmel and Granstrom 1997; Elia *et al.* 2015). In temperate and boreal regions, duff, humus or moss layers are often considered separately (Tanskanen *et al.* 2007; Stevens-Rumann *et al.* 2020). Besides fuel load, horizontal and vertical fuel continuity (that is, spatial continuity across the landscape and the gap size between surface and canopy fuel layers) is a key determinant for fire hazard, with more horizontal continuity increasing fire spread and vertical continuity increasing the likelihood of transition into crown fire (Stephens 1998; Hollis *et al.* 2015; Smith *et al.* 2016). In central Europe, the importance of forest fires is expected to increase owing to climate change (Seidl *et al.* 2014), including in Austria, where forest fires mostly occur as small-sized (<1 ha) surface fires in spring and summer (Vacik *et al.* 2011; Müller *et al.* 2015). Although mostly small in size, under favourable conditions such fires can spread fast and affect considerable areas. A recent forest fire south of Vienna in the Rax mountain range in October 2021 was reported to be one of the largest forest fires in Austria (~100 ha) and attracted international attention and support from neighbouring countries (https://fireblog.boku.ac.at/2021/11/08/waldbrand-hirschwang-nachbetrachtung/). Low fuel moisture due to heat waves in summer or high pressure conditions with föhn winds in winter are a key trigger of forest fires in central Europe (Müller *et al.* 2013; Eastaugh and Hasenauer 2014; Zhou and Vacik 2017). Although fire hazard assessments for estimating the ignition danger are well developed (Müller *et al.* 2013, 2020; Müller and Vacik 2017), to date there are no fuel models available for predicting fire behaviour and fire intensity in Austria. In consequence, current fire modelling studies have to rely mainly on fuel models from North America (Arpaci *et al.* 2011).

The objectives of the present study are: (1) to quantify fuel structure (fuel load, vertical and horizontal fuel continuity) for coniferous forests in Austria, and (2) to analyse variation in fuel structure as determined by region, forest type, age class and basal area. We compare Austrian surface fuel types with results of international studies focusing on similar forest types and using destructive sampling and discuss the results.

Material and methods

Study sites

We selected sample plots in three regions of Austria: Bad Bleiberg (south), Neunkirchen (east) and Tirol (west). Bad Bleiberg is mostly dominated by *Pinus sylvestris* L. with an average elevation of 1024 m above sea level (asl) (min.–max. 955–1090 m across plots). The plots in Bad Bleiberg were within 5 km of each other. The average annual mean precipitation total is 1455 mm (min.–max. 1423–1566 mm) and the average annual mean temperature 5.8°C (min.–max. 4.5–6.2°C for 1970–2000, Fick and Hijmans 2017). Plots in Neunkirchen are entirely composed of *Pinus nigra* Arnold ssp. *nigra* with an average elevation ~323 m asl (min.–max. 320–328 m) and were located on flat terrain less than 500 m from each other, with an average annual precipitation total of 648 mm (min.–max. 645–648 mm) and an average mean temperature of 9.5°C (min.–max. 9.5–9.5°C). Tirol plots are mostly dominated by *Picea abies* Karst., at an average elevation of 1206 m asl (min.–max. 543–1912 m), with an average annual precipitation total of 1011 mm (min.–max. 763–1286 mm) and an average annual mean temperature of 6.2°C (min.–max. 2.3–9.3°C). The plots in Tirol Bleiberg were located along the Inn valley up to 140 km from each other.

We assigned biological meaningful vegetation zones (bioregions) using the standard Austrian classification system after Kilian *et al.* (1994) to all plots. The western sites in the Tirol province are located in three vegetation zones, aggregated here as 'Northern and Central Alps'. The southern sites in Bad Bleiberg (Carinthia province) are labelled 'Southern Alps' and the eastern sites in Neunkirchen (Lower Austria province) are labelled 'Eastern plains' (Fig. 1).

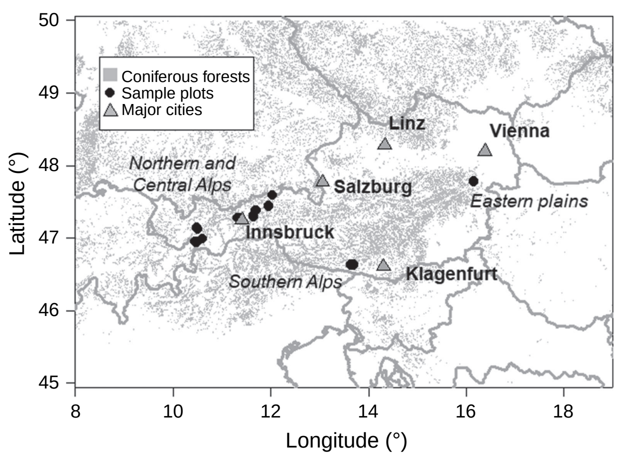

Fig. 1. Location of fuel field sample plots in Austria. Bioregions are highlighted in italics. Green areas show coniferous-dominated forests using CORINE landcover. Coniferous forests in this region of the European Alps are dominated by *Picea* spp. and *Pinus* spp. (Büttner and Maucha 2006; Brus *et al.* 2011).

Field measurements

We inventoried live and dead vegetation on sample plots chosen to ensure a good distribution among forest types and age classes. We sampled 93 plots in total, 24 in the Southern alps, 12 in the Eastern plains, and 57 in the Northern and Central alps. Measurement campaigns took place from July to August 2009 in the Southern Alps, from July to September 2011 in the Northern and Central Alps and from September to October 2013 in the Eastern plains. We placed all plots next to a recent forest fire event, ensuring similar site and structural characteristics between our plots and the burnt forest. This plot selection ensured efficient field work, focusing on fire-prone forests dominated by *Picea abies*, *Pinus sylvestris* and *Pinus nigra*. These three species are among the most common coniferous tree species (88% of all coniferous species) covering ~54% of Austrian forests (BFW 2019). *Picea abies* forests cover ~1 646 000 ha, *Pinus sylvestris* 138 000 ha and *Pinus nigra* 18 000 ha. Stand age was determined as the average tree ring count from two to four cored representative overstorey trees. To sample fuels, we used a combination of fixed-area plots, transects and destructive sampling (Fig. 2).

All trees higher than 2 m and with a DBH (diameter at breast height) larger than 10 cm within a single 25 × 25 m square plot (625 m^2) were inventoried. In four nested circular subplots (randomly chosen from eight possible locations, Fig. 2) with 2 m diameter each (each 3.14 m^2), we measured root collar diameter and height of all shrubs and trees smaller than 2 m height and 10 cm DBH. We then estimated the mass of live woody fuels for shrubs and tree branches smaller than 6 mm by applying allometric functions; see further details in the next section (Annighöfer *et al.* 2016). We collected live herbaceous and grass fuels, litter (mostly needles, L-layer), 1-h fuel (0–0.6 cm diameter), 10-h fuel (0.6–2.5 cm) and 100-h fuel (2.5–7.5 cm) within two 0.5 × 0.5 m nested square subplots (each 0.25 m^2). Surface fuels were separated into litter, herbs and living woods (shrubs and regeneration). Litter and woody dead material smaller than 6 mm constitute the 1-h fuels. However, we kept litter separated from dead woody material, owing to the different origin and turnover rates of these two fuel components (Bradford *et al.* 2016; Neumann *et al.* 2021). The 1000-h fuels (>7.5 cm diameter, coarse woody debris, CWD) were sampled along two 50-m transects, following the line intersect method (Van Wagner 1968). The transects were placed through the centre of the large square plot and the four centres of the outer circular subplots. We did not sample duff or F + H layers. Destructive sampling is laborious and most accurate but unpractical for large fuel components (Keane 2015; Neumann *et al.* 2021). CWD volume can be efficiently determined with transects, where the larger area compensates for the commonly heterogenous distribution of CWD in forests (Harmon *et al.* 1986; Woldendorp *et al.* 2004).

Analysis of fuel loads and fuel structure

To assess structure and characteristics of surface and canopy fuels (Keane 2015) of each study site, we computed the following parameters from our field data: basal area, stem volume, stem density, average tree height, fuel bed depth, live fuel load (herbaceous and woody plants) and dead fuel load (litter and downed woody material). If present, non-leaf litter like cones or bark fragments were included in the litter.

We computed the fuel load by component and fuel bed depth (related to vertical fuel structure) as well as the distribution of surface cover (horizontal fuel structure, fuel continuity). Fuel bed depth was calculated based on cover and height of herbs, shrubs, regeneration and litter depth, measured on the eight subplots. Fuel bed depth is defined here as the cover-weighted height of herbs, shrubs and regeneration plus the litter depth, similarly to the definition used in the BEHAVE model (Burgan and Rothermel 1984). Surface cover (shrubs, grass, trees and bare ground) was estimated visually also on the eight subplots (Fig. 2).

Samples of live herbaceous, litter and dead woody fuels (<7.5 cm diameter) were oven-dried at 105°C, until weight was constant (usually for 48 h), and samples were weighed

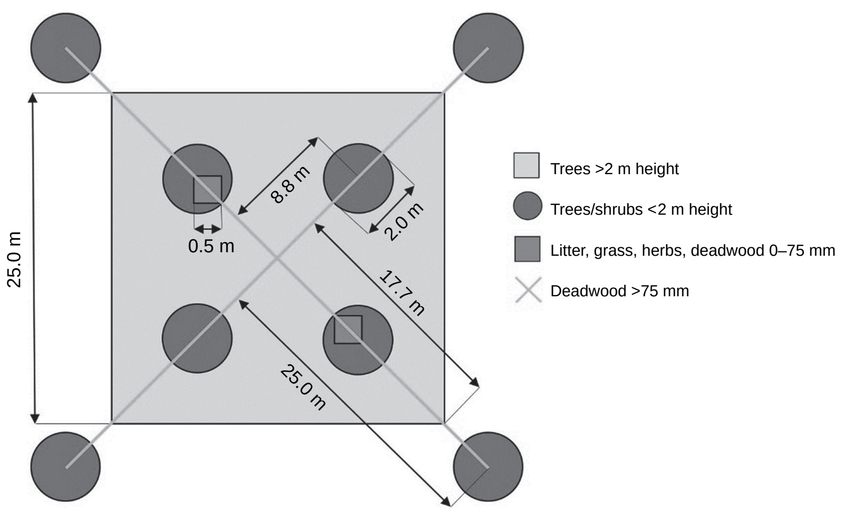

Fig. 2. Schematic illustration of the sample plot design (not to scale) used for the field measurements.

to an accuracy of less than 0.1 g. Amount of wood >7.5 cm (1000-h fuel load) was quantified using the Van Wagner (1968) transect method (Eqn 1).

$$1000\,\mathrm{h} - \mathrm{FL} = \mathrm{WD} \times \sum(d^2) \times \pi/8 \times L \qquad (1)$$

WD is wood density, assumed to be 380 kg m^{-3} for *Picea abies*, 410 kg m^{-3} for *Pinus sylvestris* and *Pinus nigra*, and 620 kg m^{-3} for broadleaved species. These are common basic wood density values for these tree species in Europe (Neumann *et al.* 2016); d is the diameter of fuel pieces (cm) intersecting the transect with a length of L (m). L was slope-corrected.

We calculated live woody fuel load (live woody-FL) for trees and shrubs with root collar diameter <6 mm using allometric aboveground biomass functions developed for central European tree saplings and seedlings (Annighöfer *et al.* 2016). The power function used estimates aboveground dry biomass in grams (Eqn 2), as developed with destructive sampling in central European temperate mixed and coniferous forests.

$$\text{Live woody} - \mathrm{FL} = a \times \mathrm{RCD}^b \qquad (2)$$

RCD is root collar diameter (mm), a and b are coefficients, with $a = 0.202$ and $b = 2.329$ for *Picea abies*, $a = 0.015$ and $b = 2.881$ for *Pinus nigra, Pinus sylvestris* and *Larix decidua*, and $a = 0.027$ and $b = 2.729$ for all broadleaf species (using the coefficients for *Quercus robur* reported by Annighöfer *et al.* 2016).

Statistical analysis

We classified all stands according to the dominant overstorey (*Picea abies*, *Pinus sylvestris*, *Pinus nigra*) and age class (young, <40 years; middle-aged, 41–80 years; old, >80 years) for further analysis.

We used the Shapiro–Wilk test to check for normality. Irrespective whether grouping by forest type, age class or region, the data were non-normally distributed and occasionally heavily skewed. We applied the non-parametric Kruskal–Wallis test to check for significance among forest types, regions and age classes in the R language and environment (R Development Core Team 2021).

We conducted a quantitative analysis of the potential drivers to explore the variability in fuel load and vertical and horizontal fuel structure using *P*-values. For that, we calculated Pearson's correlation coefficient between fuel characteristics and basal area (proxy for biomass abundance and stocking).

Results

Fuel structure of Austrian coniferous forests

Some stand structure metrics assessed on the 93 sample plots had a clear age-related pattern (Table 1). Basal area,

Table 1. Stand structure metrics grouped by dominant tree species and age class.

		Picea abies			*Pinus sylvestris*			*Pinus nigra*		
		Young	Middle-aged	Old	Young	Middle-aged	Old	Young	Middle-aged	Old
n plots	( )	16	10	31	3	11	10	1	3	8
Age	(years)	27 ± 9	60 ± 16	128 ± 21	31 ± 5	60 ± 15	129 ± 30	20	47 ± 12	90 ± 0
Basal area	(m^2 ha^{-1})	25.6 ± 11.7	37.7 ± 14.6	51.3 ± 15.9	10.4 ± 3.7	37 ± 17.6	44.4 ± 11.0	0.3	3.7 ± 2.9	7.1 ± 2.3
No. of stems (>10 cm DBH)	(ha^{-1})	860 ± 488	692 ± 183	651 ± 262	517 ± 185	1120 ± 600	560 ± 158	32	213 ± 103	188 ± 103
Tree height	(m)	15.4 ± 2.8	16.8 ± 4.9	19.6 ± 4.2	9.4 ± 0.2	13.1 ± 3.6	14.9 ± 3.2	7.1	12.2 ± 2.3	17.0 ± 2.7
Diameter	(cm)	18.9 ± 3.4	26.2 ± 5.2	32.6 ± 4.5	16.0 ± 0.7	21.1 ± 5.3	32.2 ± 5.3	11.3	14.3 ± 2.8	23.6 ± 5.7
No. of stems (0–10 cm DBH)	(ha^{-1})	50 ± 199	955 ± 1637	51 ± 286	928 ± 608	1483 ± 1379	279 ± 532	2723	1231 ± 646	2392 ± 5803

Arithmetic means plus/minus standard deviation are shown average tree height and average tree diameter increased with age, independently of dominant tree species. Stem number of large trees (>10 cm DBH) and small trees (<10 cm DBH) was not related to age. *Pinus nigra* stands (the least productive forest type in Austria, located in the warmest and driest region; Fig. 1) were mostly young (<10 cm DBH) and rather dense (Table 1). *Picea abies*-dominated forests reached the highest tree height and basal area, and in consequence the highest stem volume, indicating that this forest type was most productive in terms of wood.

We show the main fuel components grouped by bioregion in Fig. 3 and grouped by dominant tree species in Fig. 4. The largest fuels loads were observed in the Northern and Central Alps, yet live woody fuel was on average low in this region. In the Southern Alps, live and dead woody fuel were the most abundant fuel components, whereas in the Eastern plains, herbs contributed most to the total fuel load. We found more litter in the Northern and Central Alps as well as in the Eastern plains compared with the Southern Alps. We noted a large variation and skewness for most fuel components, in particular for live and dead woody fuels. Coarse dead fuels (1000-h fuels) were not found in the Eastern plains (dominated by *Pinus nigra*; see previous section).

Fuel loads were lower in young stands (Fig. 5). The largest variation in live woody fuels was found in middle-aged stands (41–80 years). In old stands, the accumulation of large-sized woody debris (1000-h, >7.5 cm diameter) was greatest.

Vegetation cover (trees, shrubs and grass) was used to describe the horizontal continuity of fuel within the stand (Fig. 6). Tree cover was on average 70%, ranging from 40 to 90%. Shrubs generally covered a low fraction of the ground in Austrian coniferous forests. Only in *Pinus nigra* forests did

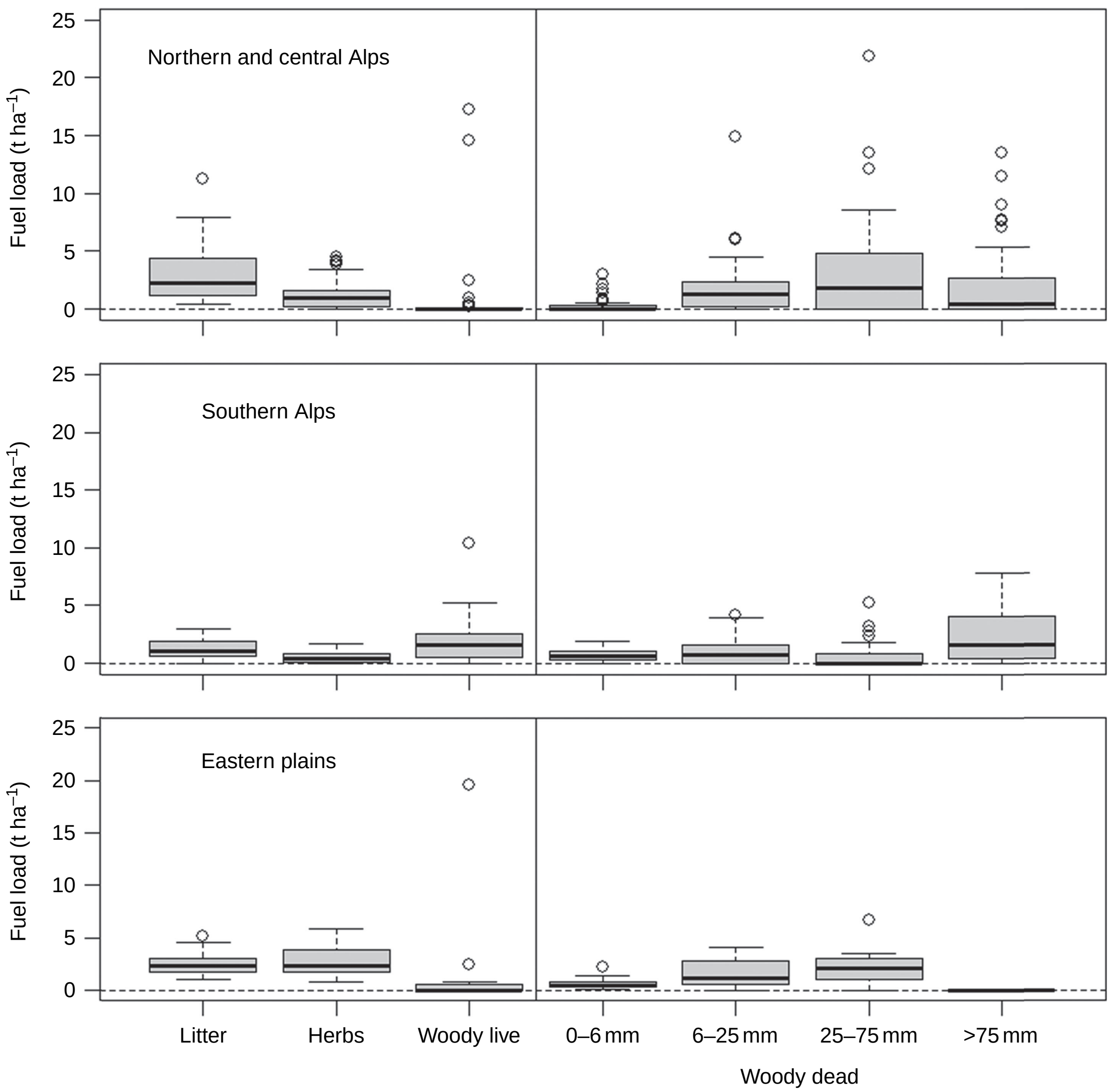

Fig. 3. Fuel loads by component and region. Boxes represent the median and the 25th and 75th percentiles. Whiskers extend to 1.5 of the interquartile range; values outside this range are indicated by circles. The plots in the Eastern plains had no 1000-h fuel load present (0 t ha^{-1}).

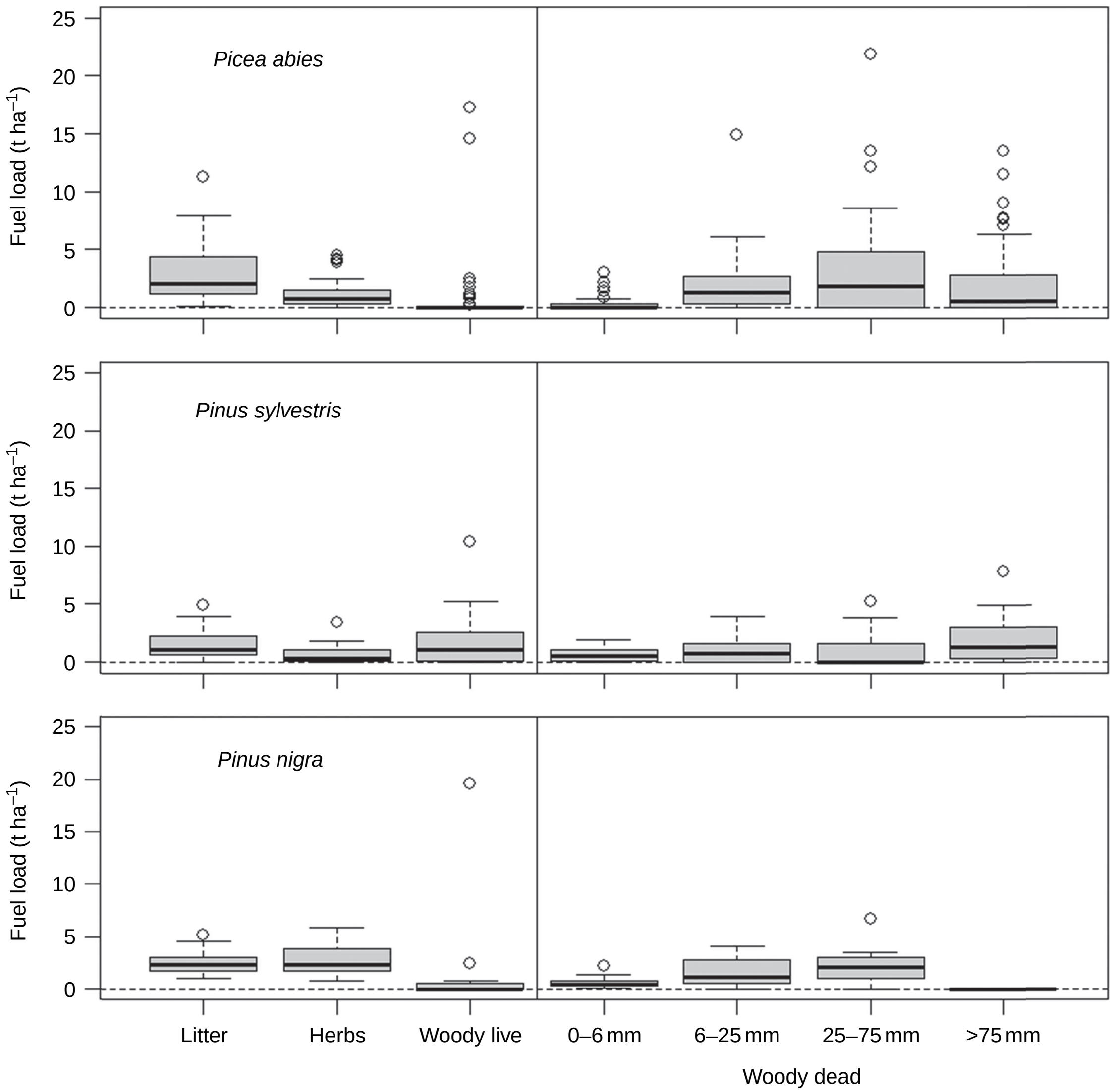

Fig. 4. Fuel loads by component and dominant tree species. For details on the boxplots, please see description in Fig. 3.

shrubs cover more than one-third of the ground surface. Grasses were the main (yet highly variable) surface cover in *Pinus* communities. *Pinus sylvestris* stands had a high portion of bare soil (not flammable), reaching up to 100% in some plots.

The fuel bed depth, the average vertical depth of organic components that can be burnt by a surface fire (i.e. litter, shrubs, grass and herbs), ranged between 8 and 30 cm. The highest fuel depth was observed in *Pinus nigra* stands (Fig. 7).

We provide a summary using mean and standard deviation for the studied coniferous forests and all assessed fuel characteristics in Table 2.

Drivers of fuel structure

We found significant ($P < 0.05$) differences in fuel load (litter, woody live, herbs, woody dead 0–6 mm) among regions and forest types (Table 3). Woody dead material 6–25 mm did not differ among any of the three groupings tested. Woody dead material 25–75 mm differed moderately by region ($P = 0.001$), whereas the correlation was weaker for forest types ($P = 0.016$) and age class ($P = 0.061$). Woody dead material larger than 75 mm was significantly different among regions and forest types, but this fuel particle was not present in any of the Eastern plain sites (dominated by *Pinus nigra*). Age classes did not explain the variability in fuel load. In other words, fuel load was more dependent on region (i.e. soil and climate) and forest type than on age classes.

Basal area was in general positively correlated (Pearson correlation coefficient + 0.178) with litter load; therefore, higher litter load was found in stands with high basal area (Table 3). Understorey live fuel load (herbs, woody live) was negatively correlated with basal area. The correlation of herbaceous fuels with basal area was stronger (Pearson

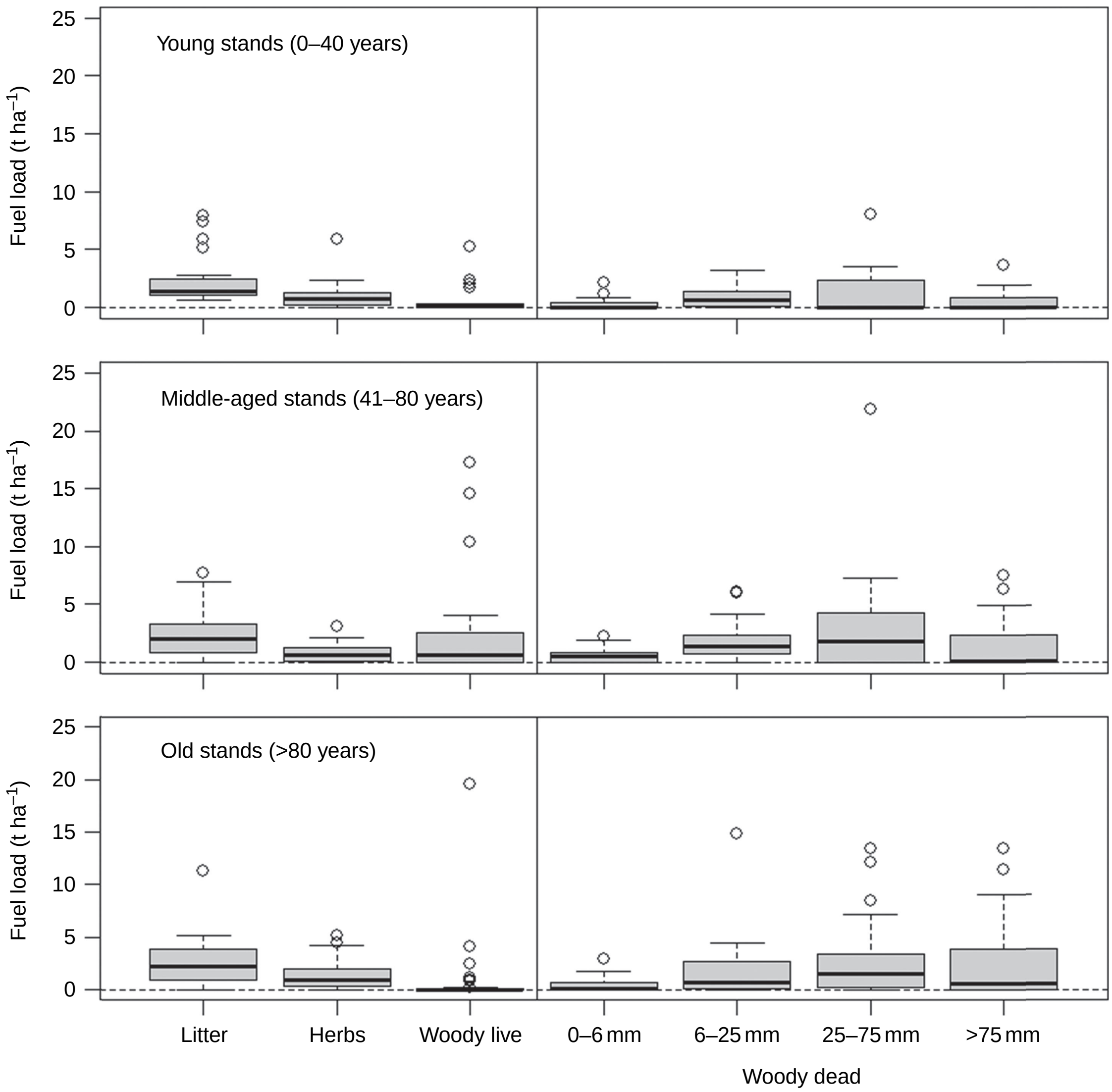

Fig. 5. Fuel loads by component and age class. For details on the boxplots, please see description in Fig. 3.

correlation coefficient − 0.193) than that of live woody fuels (−0.061), except for the live woody fuels in the Eastern plains and the herbaceous fuels in the Southern Alps. Dead woody material was highly variable across Austrian fuel types (see also Figs 3–5). Loading of dead woody material >75 mm (1000-h fuel) was positively correlated with basal area (Pearson correlation coefficient + 0.304), while the correlation for woody debris with smaller size was less pronounced, yet still positive. Live fuel load (herbaceous and woody) was positively correlated with basal area in young stands and in the Southern Alps, in contrast to the general pattern across all coniferous forests. Dead woody fuel smaller than 25 mm in the Eastern plains, which is negatively correlated to basal area, also does not follow the overall pattern (Table 3).

Partly, horizontal fuel structure differs by regions, forest types and age classes (Table 4). Cover with trees, shrubs and bare soil are significantly different at $P < 0.05$ by age class. Grass cover and fuel bed depth, however, do not vary significantly between any of the three groupings. The correlation analysis using basal area yields similar results to fuel loading (Table 3) and is not highly conclusive. Strong negative correlations can be observed for tree cover in Eastern plains and for grass cover in young stands. We found strong positive correlations for tree cover in young stands and grass cover in *Pinus sylvestris* forests.

Discussion

Assessments of fuel structure and fuel loads based on destructive sampling are the foundation of fire modelling and mapping, decision-making in fire management (e.g. to plan prescribed burnings or mechanical treatments) and the quantification of carbon emissions following wildfires

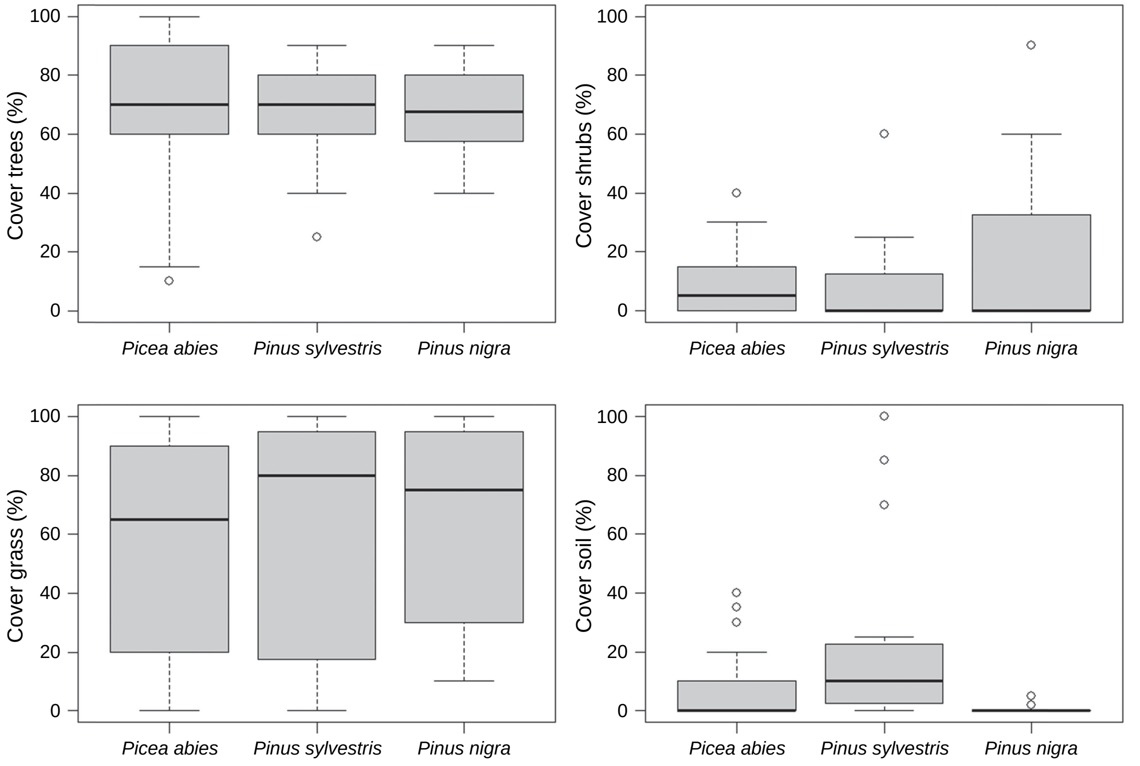

Fig. 6. Cover as percentage with trees, shrubs, grass and bare soil classified for the dominant tree species. For details on the boxplots, please see description in Fig. 3.

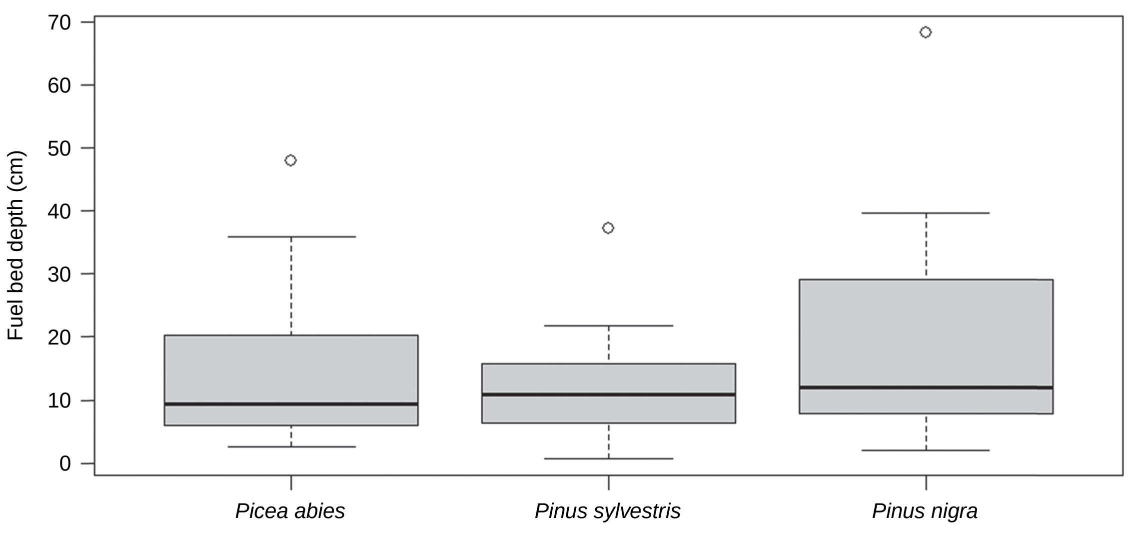

Fig. 7. Fuel bed depth in cm for *Picea abies*, *Pinus sylvestris* and *Pinus nigra*-dominated plots. For details on the boxplots, please see description in Fig. 3.

(Keane 2013; Andela *et al.* 2019). The present study is the first assessment of fuel loads, cover and fuel bed depth in Austrian coniferous forests related to fire research. In the discussion, we aim to compare our results with international literature on forest fuel characteristics and to discuss drivers of fuel structure in Austria and implications on forest fuel management.

International context

A non-exhaustive literature survey based on 30 references (see Supplementary Table S1) revealed that definitions are important in understanding fuel loads. Many studies did not specify the definitions used in field sampling or provide only scant details. Examples of some studies that used destructive

Table 2. Summary of fuel observations for Austrian coniferous forests.

Vegetation type	Litter	Dead woody 0–6 mm (1-h)	Dead woody 6–25 mm (10-h)	Dead woody 25–75 mm (100-h)	Dead woody >75 mm (1000-h)	Live herb	Live woody
Picea abies	2.837 ± 2.341	0.295 ± 0.573	1.795 ± 2.357	3.027 ± 4.079	1.982 ± 3.112	1.062 ± 1.095	0.753 ± 2.965
Pinus sylvestris	1.522 ± 1.256	0.695 ± 0.627	1.020 ± 1.123	0.889 ± 1.451	1.898 ± 2.024	0.671 ± 0.826	1.825 ± 2.378
Pinus nigra	2.569 ± 1.280	0.671 ± 0.607	1.624 ± 1.411	2.316 ± 1.790	0.000	2.871 ± 1.551	1.946 ± 5.610

	Tree cover (%)	Shrub cover (%)	Grass cover (%)	Soil cover (%)	Fuel bed depth (cm)
Picea abies	68.4 ± 23.4	7.8 ± 9.5	56.8 ± 34.8	7.3 ± 11.2	13.2 ± 9.3
Pinus sylvestris	68.1 ± 15.0	7.5 ± 14.0	60.6 ± 39.1	19.0 ± 27.2	11.4 ± 8.1
Pinus nigra	66.7 ± 14.5	18.3 ± 29.9	64.6 ± 35.8	0.6 ± 1.6	19.7 ± 19.2

Arithmetic mean plus/minus standard deviation are shown. Top row are fuel loads ($t\,ha^{-1}$).

Table 3. Test for significance between fuel load components and regions, forest types and age classes (top), and correlation between fuel load components and basal area (bottom).

Grouping	*P*-values Kruskal–Wallis tests			Woody dead			
	Litter	Woody live	Herbs	0–6 mm	6–25 mm	25–75 mm	>75 mm
Regions	<0.001	<0.001	<0.001	<0.001	0.366	0.001	<0.001
Forest types	0.015	0.005	<0.001	<0.001	0.224	0.016	<0.001
Age classes	0.719	0.004	0.167	0.030	0.106	0.061	0.102
	Pearson's correlation coefficient versus basal area						
	Litter	Woody live	Herbs	0–6 mm	6–25 mm	25–75 mm	>75 mm
All	0.178	−0.061	−0.193	0.026	0.261	0.232	0.304
Northern and Central Alps	0.109	0.086	0.059	0.198	0.304	0.203	0.274
Southern Alps	0.436	−0.084	0.359	0.522	0.434	0.398	0.118
Eastern plains = *Pinus nigra*	0.294	0.099	−0.277	−0.298	−0.365	0.178	–
Picea abies	0.214	0.077	0.141	0.198	0.331	0.262	0.231
Pinus sylvestris	0.175	−0.221	0.174	0.196	0.362	0.304	0.135
Young	0.623	−0.421	−0.548	0.312	0.494	0.532	−0.105
Middle-aged	0.299	0.379	−0.195	−0.080	0.233	0.275	0.217
Old	0.025	−0.314	−0.256	−0.001	0.212	0.115	0.241

Hyphen indicates that no observations were available.

sampling to estimate fuel load are found in Supplementary Table S1. According to the literature, litter and ground fuels (duff and humus) comprise the largest portion of fuel loads (for instance, Ascoli *et al.* 2020), which is in line with the results of this study (excluding humus and duff layers). Thanks to country-wide inventories of the Austrian forest floor (Englisch *et al.* 1991; Mutsch *et al.* 2013), we could infer that the entire organic layer above the mineral soil (L, F and H-layers; Zanella *et al.* 2011) has a much higher load than litter alone (Table 2, Supplementary Table S1). This fact has also been reported in Spain, Finland and Russia. Thus, a fragmented and humified organic layer has to be considered in fuel assessments, including the ecosystems studied here even though humus generally has a high moisture content and may not burn during a low-intensity fire (Brown *et al.* 1985; Hille and Den Ouden 2005). The recent fire in October 2021 in the Rax mountains, for instance, only partly consumed surface litter and duff layers. Climate change (e.g. lower summer–autumn rainfall and/or an extended fire season) can lead to duff layers dry enough to catch fire and burn and smoulder for extended time periods (Flannigan *et al.* 2016; Han *et al.* 2021). Until duff observations are available for Austrian coniferous forests, we can estimate that duff (fermentation and humus layer) contributes from 15 $t\,ha^{-1}$ (Hille and Den Ouden 2005) up to 30–70 $t\,ha^{-1}$ (Mutsch *et al.* 2013) of additional fuel load that can burn under dry conditions.

In this study, we considered dead woody material smaller than 6 mm as 1-h fuel (6–25 mm as 10-h fuel, 25–75 mm as

Table 4. Test for significance between horizontal (cover with trees, shrubs, grass and soil) and vertical (fuel depth) fuel structure and regions, forest types and age classes (top) and correlation with basal area (bottom).

Grouping	*P*-values Kruskal–Wallis tests				
	Tree cover	Shrub cover	Grass cover	Soil cover	Fuel bed depth
Regions	0.365	0.025	0.826	0.002	0.500
Forest types	0.774	0.406	0.741	0.002	0.496
Age classes	0.003	0.002	0.892	0.004	0.293
	Pearson's correlation coefficient versus basal area				
	Tree cover	Shrub cover	Grass cover	Soil cover	Fuel bed depth
All	0.065	−0.079	−0.104	0.056	−0.172
Northern and central Alps	−0.119	0.197	−0.196	0.330	−0.050
Southern Alps	0.319	−0.193	0.196	−0.339	−0.142
Eastern plains = *Pinus nigra*	−0.716	0.154	−0.320	0.332	0.127
Picea abies	0.040	0.271	−0.257	0.310	−0.122
Pinus sylvestris	0.145	−0.184	0.338	−0.386	0.017
Young	0.413	−0.065	−0.631	−0.175	−0.443
Middle-aged	0.157	0.064	−0.149	−0.154	−0.067
Old	0.257	−0.275	−0.019	0.326	−0.348

100-h fuel and >75 mm as 1000-h fuel). Some references did not report fuel particle diameters, but only the timelag category (e.g. Curt *et al.* 2013). Comparing data reported for timelag categories with fuel data based on size (e.g. present study, Elia *et al.* 2015) requires information on the inferred link between timelag category and size. We assumed here that the authors used the same fuel definition as in our study. The discrepancy in dead woody fuel classes between Australia and North America (Brown *et al.* 1982; Hollis *et al.* 2011) can be partly explained by the higher flammability of Australian fuels due to presence of waxes and oils and/or lower fuel moisture (Gill *et al.* 1978; Keane 2013; Prior *et al.* 2017). Reporting both size class and inferred combustion time may preclude misinterpretations.

Our literature review (Supplementary Table S1) suggests that Austrian coniferous forests have similar or lower fuel loads than comparable temperate forest ecosystems. Fuel models used in the United States and Switzerland (Harvey *et al.* 1997; Scott and Burgan 2005) aggregate litter and twigs smaller than 6 mm into the 1-h fuel load class. This is also the case for many fuel studies (e.g. Curt *et al.* 2013; Elia *et al.* 2015; Piqué and Domènech 2018). In the present study, we assessed and reported litter and twigs separately, as these components represent distinct parts of the fuel bed in Austria and elsewhere (Gould *et al.* 2011; Gould and Cruz 2012). A compact litter layer composed of needles will dry more slowly than exposed fine twigs and thus have different ignition and combustion properties. Austrian 1-h fuel loads are comparable with the models from North America, but have lower values than the Swiss models. However, Swiss models were developed in national parks (Harvey *et al.* 1997), whereas our fuel observations represent managed forests.

Forest type drives fuel load in Austria

Table 2 shows a high variability of fuel load across regions and forest types in Austria. Understanding the underlying reasons (drivers) for this variation will help to quantify the spatial distribution of fuel loads and identify appropriate fuel management strategies to reduce fire hazard. Forest type (based on dominant tree species) was the most important driver of fuel structure in all coniferous forests we studied. Stand age was poorly correlated with fuel load (Table 3), but appears to be linked to vertical fuel structure (Fig. 3). *Pinus nigra* forests (growing in the Eastern plains, covering ~18 000 ha in Austria) had more open canopies and higher shrub and grass cover as well as a greater fuel bed depth. This forest type burns most often in Austria (Vacik *et al.* 2011; Müller and Vacik 2017), which suggests that fuel structure may be an important reason for fire frequency in Austria. The more flammable nature of *Pinus nigra* forests may be also associated with generally drier climates in the Eastern plains with frequent rainfall deficits (see *Field measurements* section).

Picea abies forests (most common in the Northern and Central Alps, covering ~1.7 million ha in Austria) have the most variable tree cover and have higher loads of litter and dead woody material as compared with *Pinus sylvestris* forests (most common in Southern Alps, covering 0.14 million ha). Shade-tolerant *Picea abies* usually has a higher leaf area index and more foliage mass than early-successional *Pinus sylvestris* (Hille and Den Ouden 2005; Neumann *et al.* 2016). In addition, the larger stocking of *Picea abies* (see basal area and stand volume, Table 3) may increase branch shedding and litterfall through inter-tree competition (Lehtonen *et al.* 2004; Neumann *et al.* 2018). Higher stocking is positively correlated with surface fuels (litter, dead woody material). Surface live fuel load, however, is higher if the stocking level is lower (more open stands, lower basal area). This inverse relationship between tree cover and live fuel load is in line with literature from Russia (Ivanova *et al.* 2020), Spain (Castedo-Dorado *et al.* 2012) and North America (Hall *et al.* 2006).

We estimated canopy fuel loads for *Picea abies* forests to be on average 10.0 t ha^{-1}, for *Pinus sylvestris* 5.5 t ha^{-1} and for *Pinus nigra* 0.8 t ha^{-1}. We used for this assessment of stem diameters and density of trees larger than 10 cm DBH and allometric biomass functions from the Austrian National Forest Inventory (Neumann *et al.* 2016). Based on these data, canopy fuels are the largest fuel components in *Picea abies*- and *Pinus sylvestris*-dominated forests, although this rough estimation excludes small branches and twigs <6 mm. Canopy fuels are, however, only consumed in crown fires (Schimmel and Granstrom 1997; González-Ferreiro *et al.* 2017), which are currently rare in central Europe, including in Austria (Vacik *et al.* 2011; Fernandez-Anez *et al.* 2021).

We measured more sample plots for this study in *Picea abies* (n = 67) and in *Pinus sylvestris* forests (n = 24) than in *Pinus nigra* forests (n = 12, Table 1). Comparing the number of sample plots with the covered forest area in Austria, however, indicates that our sampling density (plots per hectare of forest) for *Pinus nigra* is 4–16 times larger than *Pinus sylvestris* or *Picea abies* forests. However, further studies will have to focus on currently still under-represented forest communities (e.g. broadleaf-dominated forests, *Pinus mugo* forests) to obtain fuel information with similar accuracy across Austria.

Fuel management strategies to reduce fire hazard

One of the widely used management strategies to modify fuel loads and reduce fire hazard is prescribed burning, as time since last fire is the most important factor explaining fuel loads (e.g. Schimmel and Granstrom 1997; Stephens 1998; Curt *et al.* 2013; Neumann *et al.* 2021). We were not able to determine exactly when our chosen sites were burnt last; thus, we considered them to be unburnt for >30 years. Other fuel management interventions may include species change (decrease the share of pyrophilic species), thinning (reducing basal area and dead wood, removing ladder fuels, increasing height-to-crown), grazing (reducing herbaceous and grassy fuel loads) or promoting fuel breaks (easier access and firefighting) (Xanthopoulos *et al.* 2006; Kirkpatrick *et al.* 2011; Afonso *et al.* 2020). Grazing has been found to have large effects on fuel loads (Zumbrunnen *et al.* 2012). Although grazing livestock focus on living plants (therefore directly reducing surface fuel loads), we can also expect a lower litter load through reduced deposition of dead leaves on the ground. Thinning – as adaptive forest management to increase resilience (Buma and Wessman 2013; Lindner *et al.* 2014) – has the potential to change species composition and reduce basal area, thus affecting two important drivers of fuel load and fuel structure. *Pinus nigra* forests studied here commonly exhibit small-scale ownership structures and are intensively managed. Thinning operations remove logs with diameters larger than 7 cm, the merchantability limit in Austria for industrial wood. The missing fuel with diameter larger than 7.5 cm (1000-h fuels) on Eastern plains sites underpins the impact of forest management in modifying this fuel component.

Until now, Austrian foresters and scientists could only make inferences on the potential impacts of fuel load and fuel structure on fire hazard (including rate of spread, fire severity, tree mortality). Historically, fire has appeared to be a common feature of central European forests, based on available evidence (Valese *et al.* 2014). This presumably included agricultural and pastoral fires to reduce tree cover and improve forage. Prescribed burning is currently not considered as a management option and lighting a bonfire in forests is prohibited by law in the Austrian Forestry Act (Hesser 2011). However, prescribed burns would be needed to better understand fire effects across varying fuel structure under controlled conditions (Cruz *et al.* 2018; Hollis *et al.* 2018). Wildfires can be seen as 'field experiments started by nature' and have been useful for fire research as well as training for firefighters (Chafer *et al.* 2004; Santín *et al.* 2012; Adams *et al.* 2013). Landscape and fuel load often determine local fire severity, but these two factors are highly variable (i.e. owing to wind erosion of fuel particles or more productive stands near gullies). This makes robust fire hazard modelling challenging. As fires have been reported to promote growth of target species in temperate forests (e.g. *Quercus* sp.) (Petersson *et al.* 2020) and are useful for ecosystem restoration (Lindberg *et al.* 2020), prescribed fires may become a useful tool in Austria for research and training as well as improved land management. Yet they require careful planning and support from decision makers, fire brigades and forest owners.

Conclusions and outlook

For the first time, we report fuel loading values of Austrian coniferous forests, and found that forest type is probably the main driver of fuel loads in Austria. Fuel load can be reasonably quantified using a combination of destructive sampling, transect measurements and desktop analysis. Considering changes in environmental conditions and management practices (a reduction or intensification, depending on region), accurate data on fuel loads will become even more important in the future. In the last three decades, Europe has been affected by large and intense forest fires, including some regions that rarely experienced such fires in the past (Seidl et al. 2014; Fernandez-Anez et al. 2021). Species and stocking are determinants of fuel load, composition and forest structure and both can be modified by management. Forest inventory data can provide information on fuel load, by linking more advanced statistical models with the empirical observations in coniferous forests collected for this study and new additional observations for other important forest types, including mixed and broadleaf forests. Canopy fuel loads (canopy leaves, needles and branches, which are consumed by fire, commonly smaller than 6 mm) were studied here in detail, but our analysis suggest that average canopy fuel loads may be as large as 10 t ha^{-1} for *Picea abies* forests. A shift from surface fires to more frequent crown fires, due to vegetation densification, higher vertical structure or more severe fire weather conditions, would increase fuel loads up to two-fold.

Supplementary material

Supplementary material is available online.

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Data availability. The used data are available as an electronic supplement (data_a2.csv).

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Author affiliations

[A]Institute of Silviculture, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences, Vienna, 1190 Austria.

[B]Joint Research Unit CTFC – AGROTECNIO, Ctra de Street Llorenç de Morunys, km 2, 25280 Solsona, Spain.