Harmonized dataset of surface fuels under Alpine, temperate and Mediterranean conditions in Italy. A synthesis supporting fire management

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Surface biomass characterization plays a key role in wildfire management. It allows classifying vegetation fuels flammability for fire risk analysis, to define silvicultural prescriptions for fire hazard reduction, to plan prescribed burning, or to model fire behavior and its effects, such as greenhouse gas and pollutant emissions. To facilitate fuel classification and analysis of potential fire behavior and effects in Italy, we harmonized 634 measurements of surface wildland fuels from Alpine, temperate and Mediterranean environments. The dataset provides quantitative data for duff, fine dead fuels and downed woody material, live grasses and shrubs fuel components. Surface fuel data were harmonized by subdividing loads (Mg ha^{-1}) to standard size classes for dead (0-6, 6-25 and 25-75 mm) and live (0-6, 6-25 mm) fuels, collecting percent cover and depth/height (cm) of the various fuel components, and classifying observations into 19 fuelbed categories. To ensure comparability with existing vegetation classification systems, we classified each observation according to the European Fuel Map, the Corine Land Cover classes (level IV), the European Forest Types, and the forest categories of the Italian National Forest Inventory. The dataset and a photo description of each fuelbed category are available as Supplementary material. This dataset is the first step to develop several products at the national scale such as: (i) fuel type classification and mapping; (ii) carbon stock and wildfire emission estimates; (iii) calibration of fuel models for the simulation of fire behavior and effects.

Keywords: Wildfire, Fire Behavior, Simulation, Fuel Types, Emissions

Introduction

Fire is a widespread disturbance in most vegetation types in Italy under Alpine, temperate and Mediterranean conditions (Elia et al. 2020). Regional fire management agencies and National Parks are in an increasing need of fire risk assessment, estimates of fire emissions at different spatial scales, fuel management and prescribed burning planning (Ascoli & Bovio 2013, Corona et al. 2015, Bacciu et al. 2018). The use of decision support systems (DSS) for fire effects modeling, fire behavior simulation and risk analysis is spreading in both the research and operational sectors in Italy

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(Salis et al. 2013, Vacchiano et al. 2014, Elia et al. 2015). A quantitative characterization of fuels in Italian forests, shrublands and grasslands is the first step towards developing harmonized fuel datasets to support fire management decisions and calibrating fuel inputs for fire software applications and DSS used by professionals and researchers (Bacciu et al. 2009, Ascoli et al. 2015).

Several approaches have been proposed to quantify and classify fuel complexes, each compatible with a specific modeling system for fire behavior and effects prediction (Sandberg et al. 2001, Dimitrakopoulos 2002, Alvarez et al. 2012, Keane 2013, Cruz et al. 2018). Fire effect models, *e.g.*, FOFEM (Reinhardt et al. 1997), requires several information about fuel components (*e.g.*, litter, downed woody fuel), often based on vegetation types or fuelbed characteristics (Reinhardt et al. 1997, Ottmar et al. 2007). Widespread DSS for fire behavior prediction – such as BehavePlus (Andrews et al. 2005), Farsite (Finney 1998), FlamMap

(Finney 2006), the Fire and Fuel Extension to the Forest Vegetation Simulator (Andrews 2018), or the Rothermel R package (Vacchiano & Ascoli 2015) – require a number of parameters represented by "fire behavior fuel models" as input (hereafter "fuel model"), related to surface fuels according to the fuel modeling system developed by Rothermel (1972). However, a source of uncertainty in available fuel description derives from the use of different terminologies to indicate similar fuel classes or categories (Keane 2013). This paper employs the terminology provided by Keane (2015), who defined the fuelbed as the array of biomass types for a given area, further composed by fuel types (*e.g.*, litter, shrubs, grasses, downed woody material and tree crown foliage) and components (*e.g.*, diameter size range; live or dead status) with specific properties. Furthermore, a fuel complex identifies the dominant fuel of a fuelbed (Bebi et al. 2003).

Due to the increased use of Rothermel's based fire software and DSS in Italy by fire

managers and researchers (Arca et al. 2007, 2019, Bacciu et al. 2009, Vacchiano & Ascoli 2015, Ascoli et al. 2015, Elia et al. 2016, Salis et al. 2016), a standardized field protocol for inventorying surface fuels according to Rothermel's fuel models inputs has been proposed in Italy (Bovio & Ascoli 2013, Bovio et al. 2014). This protocol represented the basis for several unpublished surveys carried out nationwide in the last decade. However, a complete and harmonized inventory of Italian wildland fuels is still lacking.

The aims of the present paper are to: (i) harmonize and make freely available unpublished surface fuel data across major vegetation types in Italy; (ii) categorize data into fuelbeds and establish associations with land cover classes and forest classifications used in Europe and Italy; (iii) summarize fuel data for each fuelbed, providing descriptive statistics of average characteristics and their variability; (iv) release a fuel characteristics dataset useful to calibrate Rothermel's based models and DSS.

Material and methods

Sampling design

Provided the spatial distribution of the available data, an *a priori* sampling design was not applicable to this study, which is instead based on an *a posteriori* collection of unpublished inventories carried out over the last 10 years. Among existing surveys, only those with data harmonizable in terms of the protocol adopted to characterize the surface fuel complex were included in the study. Most fuel observations in the dataset (65%) followed the field protocol described by Bovio & Ascoli (2013) and Bovio et al. (2014). This uses a mixed approach with both destructive (*i.e.*, vegetation removed and analyzed in the laboratory) and non-destructive techniques (see next paragraph), such as indirect estimates of fuel loads based on allometry equations (Corona et al. 2012, Castagneri et al. 2013, Sirca et al. 2016, Conti et al. 2019). The remaining 35% of survey data adopted protocols that are similar to the ones mentioned, but applied a fully destructive sampling to the shrub component, as they were mostly carried out in shrubland fuelbeds (Bacciu et al. 2009, Duce et al. 2012, Castagneri et al. 2013, Vacchiano et al. 2014).

The study sites encompass grasslands, shrublands and forest ecosystems growing in Alpine, temperate, and Mediterranean environments throughout a large part of insular and peninsular Italy (Fig. 1). Site selection excluded forests disturbed in the previous 10 years (*e.g.*, affected by wildfire or windthrow, intensively grazed areas, or silvicultural interventions); thus the data set includes 377 sites with a number of randomly located sample plots ranging from 1 to 15 per site (average of 2.28 ± 2.11). According to the aforementioned protocols (Bovio & Ascoli 2013, Bovio et al. 2014), the
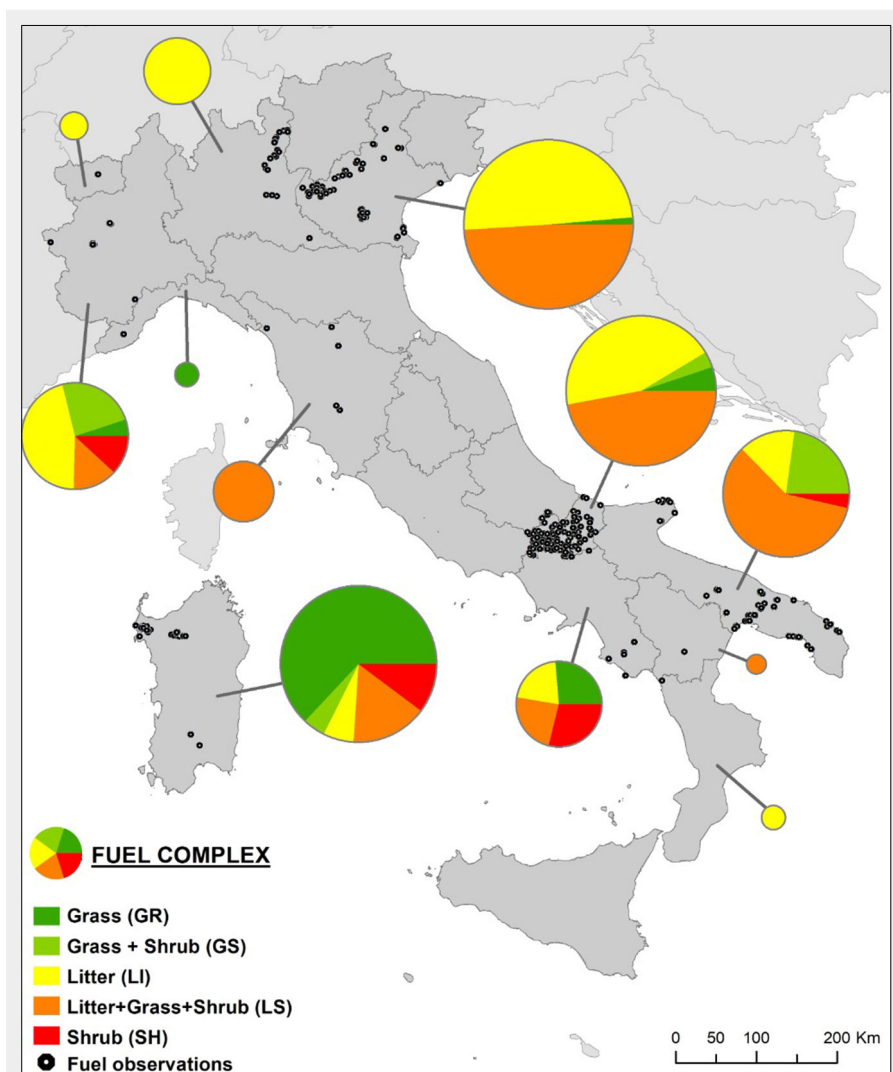
Fig. 1 - Distribution of study sites (black dots) where fuel data were inventoried in Italy. Pie charts represent the relative amount of samples in different fuel complexes (grass only, grass + shrub, litter only, litter + grass + shrub, shrub only). Pie dimension is relative to sample abundance.

FUEL COMPLEX

- Grass (GR)
- Grass + Shrub (GS)
- Litter (LI)
- Litter+Grass+Shrub (LS)
- Shrub (SH)
- Fuel observations

0 50 100 200 Km

structure of the fuel complex was assessed along three 10-m long transects, positioned to form an equilateral triangle (*i.e.*, each transect had a different direction to avoid directional bias). Along each transect, surface litter depth, grasses height, and shrub crown height were measured at 1 m intervals. Surface litter and duff were collected through destructive sampling in three 0.0625 m² squares (1 square along each transect); downed wood < 75 mm, grasses and shrub fuels were collected on three 1 m² squares. Harvested fuels were oven-dried in the laboratory at 90 °C for 12 to 48 hours depending on the fuel component (*i.e.*, 12 hours only for fully cured, very fine grasses) to determine the dry weight (Pellizzaro et al. 2007, Dimitrakopoulos et al. 2010, Ubysz & Valette 2010). For each sampling point, we calculated the dry weight load of dead (duff, litter, downed woody material, dead fraction of grasses and shrubs) and live (grasses, shrubs) fuel components and structural variables as described in the next paragraph and synthetized in the Fig. S1 (Supplementary material).

Dataset description

The dataset includes 634 surface fuel samples, each described by 41 variables (Tab. S1), and is available in Excel® (.xlsx) format as Supplementary material (Tab. S3). The first dataset field is an identification code (*ID*) combining the broad fuel type (2nd field), the study site code (3rd field), and the number of the fuel sample collected at each site (4th field), useful for filtering data. According to the protocol (Bovio & Ascoli 2013, Bovio et al. 2014), surveys were carried out during the typical environment-specific fire season, to describe fuel characteristics dynamics (*e.g.*, level of grass curing) in the nature of their flammable status. The field *SamplingSeason* (Tab. S1) reports winter or summer classes, corresponding to Alpine and Mediterranean fire regime seasons in Italy (Elia et al. 2020), respectively. *FuelComplex* is a broad fuel classification system to identify the dominant fuel of a fuelbed driving fire spread (*i.e.*, litter, grass, shrubs, grass + shrubs, litter + grass + shrubs). Fields from the 5th position to the 20th are variables that quantitatively characterize each fuel sample (Fig. S1). All fields with a *W* as the first letter (i.e., *Wduff, W1h, W10h, W100h, WGr, WSh1h, WSh10h*) report fuel load in Mg ha⁻¹ on a dry weight basis. Loads of dead fuels (*W1h, W10h, W100h*) are partitioned by particle diameter classes (<6 mm, 6-25 mm, 25-75 mm, >75 mm), corresponding to timelag classes 1h, 10h, 100h, *i.e.*, the amount of time necessary for dead fuels to lose-gain 63% of the difference between their initial moisture content and their equilibrium moisture (Brown et al. 1982). Live grasses (*WGr*) included <6 mm fuels only and cured grasses were added to the 1h dead fuels. Live shrub fuel load was partitioned in <6 mm (*WSh1h*) and 6-25 mm

(*WSh10h*) size classes. Fuel cover (%) and fuelbed depth (cm) of dead fuels (*Cdead, Ddead*), live grasses (*CGr, DGr*) and shrubs (*CSh, DSh*) fuels were measured in 81% and 79% of sampling points, respectively. In addition, 45% of observations included data on duff fuel load (*Wduff*) – a key component to estimate fire emissions, especially in forest ecosystems – while 96% of observations reported an estimate of the tree canopy cover (*CanCov*). Each observation contains information about elevation, slope and aspect, and climate information according to the Köppen-Geiger climate classification (Beck et al. 2018) and the "Worldwide Bioclimatic Classification System" (Rivas-Martínez et al. 2011) available in raster format for Italy at 900 m grain (Pesaresi et al. 2017). Most sampling sites belong to Köppen-Geiger temperate and mesothermal climates (41% Csa Mediterranean hot summer, 32% Cfb Oceanic, 21% Cfa Humid subtropical), with a small fraction (6%) of boreal and tundra climates at the topmost elevations up to 2100 m a.s.l. From Rivas-Martinez classification, we extracted values for bioclimate, continentality type based on the difference between annual maximum and minimum temperature (63% subcontinental and semicontinental, 37% euoceanic or semihyperoceanic), ombrotype (Tab. S1) based on the annual ombrothermic index (24% dry and semiarid, 21% subhumid, 55% humid and hyperhumid), and thermotype (Tab. S1 in Supplementary material) based on thermicity index and yearly positive temperatures (38% Thermo-, Meso- and Supramediterranean , 23% Mesotemperate, 39% Supra- and Orotemperate).

Fuel observations were then grouped into 19 surface fuelbeds (fields: *FuelBed, FuelBedCode* – Tab. 1), based on expert opinion considering the vegetation type, dominant fuel, its spatial arrangement and species-specific flammability properties that determine potential surface fire behavior (Ottmar et al. 2007, Keane 2013). For example, fuel observations in Mediterranean conifer forests with a long-needle and porous litter (*i.e.*, *Pinus halepensis, P. pinaster* and *P. pinea* forests) were grouped into two fuelbeds according to the absence (fuelbed 16) or presence (fuelbed 17) of flammable understory grasses and shrubs. Fuelbeds with codes from 1 to 3 represent grass-dominated fuel complexes, 4 to 6 shrublands, 7 to 12 broadleaved forests, 13 to 17 coniferous forests, while 18 and 19 relate to riparian vegetation and marshes, respectively. A photo description of each fuelbed is provided in Fig. S2 (Supplementary material).

The vegetation physiognomy at each sample point was used to associate (*sensu* Keane 2013) fuelbed classes to relevant fuel, land cover and forest classification systems. Cross-links were established with existing vegetation classification systems in Europe and in Italy (Tab. 1): (i) European fuel map classification (EFFIS 2017); (ii)

Corine Land Cover, level IV (ISPRA 2010); (iii) European Forest Types (Barbati et al. 2014); and (iv) forest categories of the Italian National Forest Inventory (INFC 2005), for forest fuelbeds only. In some cases, a fuelbed was uniquely associated with a vegetation class. For example, fuelbed 7 "Mountain beech litter", which has a distinctive combustibility due to the compactness of the beech litter and the lack of grasses and shrubs in the understory typical in mountain beech forests (Maringer et al. 2020), was uniquely associated with the "*Faggete*" class in the INFC (Tab. 1). However, different fuelbeds may be associated to the same vegetation class, and conversely, more vegetation classes may be associated to the same fuelbed description (*e.g.*, fuelbeds 8 and 9 are both associated to the European Forest Type 8.2 and the INFC category "*Boschi a rovere, roverella e farnia*"), which is a typical issue in fuelbed classification systems (Keane 2013).

In addition to surface fuel data, a bibliographic research on crown foliage and branch fuel loads is presented in Tab. S2 (Supplementary material) with the aim to complement forest fuelbeds (from 7 to 19) with canopy information, necessary for several fire effect models, *e.g.*, FOFEM (Reinhardt et al. 1997).

Results

Dataset descriptive statistics are presented by the sampled variability across the fuel complexes (*i.e.*, dominant fuel of the fuelbed), and then by the variability within the fuelbeds. A comparison with international established fuel inventories is also presented to verify that the range in loads by fuel components falls within the range of variability in reference inventories (see also the Discussion). Finally, a multivariate analysis was carried out to describe geographical and climatic gradients in the dataset.

Dataset descriptive statistics

Fuel complexes show distinct characteristics (Fig. 2). Loads of dead fine fuels (size <6 mm) and downed fuels (size 6-75 mm) were generally higher in fuel complexes with litter only (LI), or litter mixed with grasses and shrubs (LS), and shrubs only (SH). Although in grasses the mean load of dead fine fuels was very low, several outliers were recorded (Fig. 2a), mainly due to fuelbed 3 "Continuous tall Mediterranean grasslands", which is dominated by the tall grass *Ampelodesmos mauritanicus* (Poir.) T. Durand & Schinz and characterized by relatively high loads of fine dead leaves within the tussock. This represents a species-specific surface fire environment characterizing fire-prone grasslands of the southern Tyrrhenian cost (Incerti et al. 2013) and was therefore identified as a specific fuelbed (fuelbed 3 in Fig. S1). Live fuel load with particle size 6-25 mm was particularly abundant in the shrub fuel complex (Fig. 2d).

Tab. 2 and Tab. 3 provides descriptive sta-

Tab. 1 - Fuelbed association with the European Forest Fire Information System (EFFIS) fuel map classes, Corine Land Cover classes (level IV), the European Forest Types and the forest categories of the Italian National Forest Inventory (INFC). For fuelbeds 1 to 6, 12 and 19, there was no meaningful correspondence ("na") with either the European Forest Types or the forest categories of the Italian National Forest Inventory.

Fuelbed	EFFIS fuel map class	Corine LC IV level	EU Forest Types	INFC Categories
1. Sparse and very short grasslands	4. Sparse grasslands	3212. Discontinuous grassland	na	na
2. Continuous short grasslands	5. Mediterranean grasslands and steppes; 6. Temperate, Alpine and Northern grasslands	3211. Continuous grassland	na	na
3. Continuous tall Mediterranean grasslands	5. Mediterranean grasslands and steppes	3211. Continuous grassland	na	na
4. Temperate and Alpine heathlands	8. Temperate, Alpine and Northern moors and heathlands	322. Moors and heathlands	na	na
5. Short Mediterranean shrublands and garrigues	9. Mediterranean open shrublands (sclerophylous)	3232. Low maquis and garrigues	na	na
6. Tall Mediterranean shrublands and heathlands	10. Mediterranean shrublands (sclerophylous)	3231. High maquis	na	na
7. Montane beech litter	33. Montane beech forest; 38. Mixed beech with conifers forest	3115. Beech forests	7.1 South western European mountainous beech forest; 7.3 Apennine-Corsican mountainous beech forest	Faggete
8. Compact mesophytic broadleaved litter	31. Mesophytic broadleaved forest	2241. Young tree plantations for wood production; 3112. Deciduous oak forests; 3113. Mesophilous broad-leaved forests; 3117. Non-native broadleaved forests	5.1 Pedunculate oak-hornbeam forest; 5.9 Other mesophytic deciduous forests; 8.2 Turkey oak, Hungarian oak and Sessile oak forest; 14 Introduced tree species forest	Boschi a rovere, roverella e farnia; Cerrete, boschi di farnetto, fragno, vallonea; Ostrieti, carpineti
9. Porous thermophilous broadleaved litter	30. Thermophilous broadleaved forest	3112. Deciduous oak forests 3113. Mesophilous broad-leaved forests	8.1 Downy oak forest; 8.2 Turkey oak, Hungarian oak and Sessile oak forest; 8.8 Other thermophilous deciduous forests	Boschi a rovere, roverella e farnia; Cerrete, boschi di farnetto, fragno, vallonea; Ostrieti, carpineti
10. Mediterranean evergreen broadleaved litter	29. Mediterranean evergreen broadleaved forest	3111. Mediterranean evergreen oak forests	9.1 Mediterranean evergreen oak forest	Leccete; Sugherete; Altre latifoglie sempreverdi
11. Long broadleaved litter	30. Thermophilous broadleaved forest	3114. Chestnut forests	8.7 Chestnut forest	Castagneti
12. Eucaliptus litter	na	3117. Non-native broad-leaved forests	14.2 Plantations of not-site-native species and self-sown exotic forest	na
13. Alpine and Mediterranean short needled conifer litter	23. Mediterranean montane short needled conifer forest (fir); 26. Alpine short needled conifer forest (fir, alpine spruce)	3123. Silver fir and/or Norway spruce forests	3.2 Subalpine and mountainous spruce and mountainous mixed spruce-silver fir forest; 7.9 Mountainous Silver fir forest	Boschi di abete rosso; Boschi di abete bianco
14. Montane long needled conifer litter	22. Mediterranean montane long needled conifer forest (Black and scots pines); 25. Alpine long needled conifer forest (pine)	3122. Mountain and oro-Mediterranean pine forests; 3124. Larch and/or Arolla pine forests; 3125. Non-native coniferous forests	10.2 Mediterranean and Anatolian Black pine forest; 14.2 Plantations of not-site-native species and self-sown exotic forest; 3.1 Subalpine larch-arolla pine and dwarf pine forest; 3.3 Alpine Scots pine and Black pine	Pinete di pino silvestre e montano; Pinete di pino nero, laricio e loricato; Piantagioni di conifere
15. Montane long needled conifer understory with shrubs	22. Mediterranean montane long needled conifer forest (Black and scots pines); 25. Alpine long needled conifer forest (pine)	3122. Mountain and oro-Mediterranean pine forests 3124. Larch and/or Arolla pine forests	10.2 Mediterranean and Anatolian Black pine forest; 14.2 Plantations of not-site-native species and self-sown exotic forest; 3.1 Subalpine larch-arolla pine and dwarf pine forest; 3.3 Alpine Scots pine and Black pine	Pinete di pino silvestre e montano; Pinete di pino nero, laricio e loricato; Piantagioni di conifere
16. Mediterranean long needled conifer litter	20. Mediterranean long needled conifer forest (Med. pines)	3121. Mediterranean pine forests	10.1 Mediterranean pine forest	Pinete di pini mediterrane
17. Mediterranean long needled conifer understory with shrubs	20. Mediterranean long needled conifer forest (Med. pines)	3121. Mediterranean pine forests	10.1 Mediterranean pine forest	Pinete di pini mediterrane
18. Riparian vegetation	39. Riparian vegetation	3116. Hygrophilous forests	12.1 Riparian forest	Boschi igrofili
19. Aquatic marshes	41. Aquatic marshes	na	na	na

Fig. 2 - Boxplot of fuel load (Mg ha⁻¹) by fuel complex (GR = grass; GS = grass + shrub; LI = litter only; LS = litter + grass + shrub; SH = shrub only) and fuel components: (a) Dead fuel with particle size < 6 mm; (b) larger dead downed fuels (size 6-75 mm); (c) live grass fuels (< 6 mm); (d) live shrub fuels (<25 mm). Data excluded: duff fuel component; fuelbed 19 "Aquatic marshes".
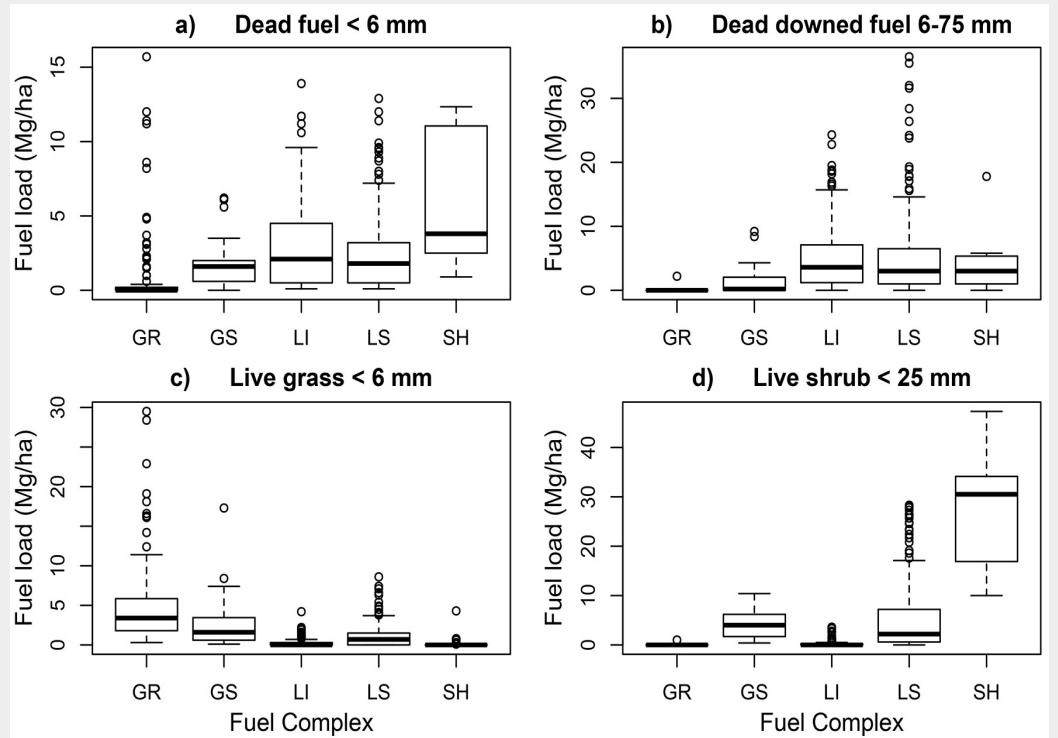
tistics of mean characteristics and variability of fuel loads and cover for grasslands and shrublands fuelbeds (Tab. 2) and for broadleaved and coniferous forests, and aquatic fuelbeds (Tab. 3). The fuelbed with the lowest value in total surface fuel load (excluding duff) is fuelbed 1 "Sparse and very short grasslands" with an average of 2.47 Mg ha⁻¹. Fuelbed 19 "Aquatic marshes" shows the highest total surface fuel load with an average of 80 Mg ha⁻¹. Although sharing the same vegetation classes (Tab.

Tab. 2 - Number of observations (Count), mean fuel load (Mg ha⁻¹), standard deviation (STD), range (min-max) and interquartile range (IQR) by vegetation type (grassland, shrubland), fuelbed and fuel component. Variable names: Duff: fuel duff load; Dead 1h: dead fuels with particle size < 6 mm; Dead (10h, 100h): dead fuels with particle size 6-25 mm, 25-75 mm; Live fuels (grass, shrub): live grasses < 6 mm and live shrubs < 25 mm; Total load: total fuel load (dead + live fuels, but duff excluded).

Type	Fuelbed	Fuel component	Count	Mean	STD	Range	IQR
Grasslands	1. Sparse and very short grasslands	Duff	na	na	na	na	na
		Dead 1h	41	0.08	0.31	0-1.7	0
		Dead (10h, 100h)	41	0.08	0.37	0-2.2	0
		Live fuels (grass, shrub)	41	2.32	1.48	0.3-7.2	1.4
		Total load	41	2.47	1.66	0.3-8.9	1.5
	2. Continuous short grasslands	Duff	4	23.7	24.78	4.6-60.1	15.6
		Dead 1h	43	0.28	0.9	0-4.8	0
		Dead (10h, 100h)	43	0.03	0.18	0-1.1	0
		Live fuels (grass, shrub)	43	3.77	2.03	0.5-10.3	2.6
		Total load	43	4.08	2.27	0.5-10.8	3
	3. Continuous tall Mediterranean grasslands	Duff	25	na	na	na	na
		Dead 1h	25	3.96	4.54	0-15.7	4.3
		Dead (10h, 100h)	25	0	0	0-0	0
		Live fuels (grass, shrub)	25	12.26	7.25	3.5-29.5	7.8
		Total load	25	16.17	10.44	3.5-40.7	10.2
Shrublands	4. Temperate and Alpine heathlands	Duff	11	3.18	2.36	0.1-6.9	3.8
		Dead 1h	11	2.35	2.38	0.03-6.2	3
		Dead (10h, 100h)	11	0	0	0-0	0
		Live fuels (grass, shrub)	11	6.15	2.37	3.3-10.6	3.4
		Total load	11	8.5	4.33	3.6-16.2	5.6
	5. Short Mediterranean shrublands and garrigues	Duff	25	6.89	4.36	0.2-16.7	5.5
		Dead 1h	51	2.26	2.19	0-12.9	1.9
		Dead (10h, 100h)	51	2.92	5.5	0-32	2.7
		Live fuels (grass, shrub)	51	10.35	7.69	1.8-37.5	6.6
		Total load	51	15.52	11.03	2.5-54.5	10.5
	6. Tall Mediterranean shrublands and heathlands	Duff	11	11.65	4.24	6.5-20.1	5.4
		Dead 1h	39	5.33	4.34	0.7-12.3	8.4
		Dead (10h, 100h)	39	3.55	3.2	0-17.8	3.8
		Live fuels (grass, shrub)	39	25.53	8.67	10.4-47.3	15.7
		Total load	39	34.42	12.59	16.8-53.3	25.3

Tab. 3 - Number of observations (Count) and fuel load (Mg ha⁻¹) by vegetation type (broadleaved forests, conifer forests, aquatic vegetation), fuelbed and fuel component. Mean, standard deviation (STD), range (min-max) and interquartile range (IQR) are reported. Variable names: Duff: duff fuel load; Dead 1h: dead fuels with particle size < 6 mm; Dead (10h, 100h): dead fuels with particle size 6-25 mm and 25-75 mm, respectively; Live fuels (grass, shrub): live grasses < 6 mm and live shrubs < 25 mm; Total load: total fuel load (dead + live fuels, excluding duff).

Type	Fuelbeds	Fuel component	Count	Mean	STD	Range	IQR
Broadleaved forests	7. Montane beech litter	Duff	7	35.06	26.75	9.3-90.1	16.5
		Dead 1h	17	1.88	2.37	0.1-6.74	3.1
		Dead (10h, 100h)	17	4.09	3.91	0.3-14.8	3.3
		Live fuels (grass, shrub)	17	0.24	0.55	0-2.2	0.2
		Total load	17	6.2	4.26	0.5-14.9	7.1
	8. Compact mesophitic broadleaved litter	Duff	68	33.07	25.84	2.3-92.4	40.1
		Dead 1h	95	2.18	1.87	0.1-8	3.1
		Dead (10h, 100h)	95	6.83	6.1	0-28.4	7.5
		Live fuels (grass, shrub)	95	1.61	2.54	0-16.5	1.9
		Total load	95	10.63	7.14	0.6-37.6	9.4
	9. Porous thermophilous broadleaved litter	Duff	9	39.87	31.65	3-97	36.6
		Dead 1h	66	1.73	2.35	0.1-10.6	3
		Dead (10h, 100h)	66	3.01	3.33	0-13.3	4.2
		Live fuels (grass, shrub)	66	1.58	1.83	0-9.8	2.1
		Total load	66	6.32	3.84	1-21	4.4
	10. Mediterranean evergreen broadleaved litter	Duff	na	na	na	na	na
		Dead 1h	19	2.25	1.15	0.1-3.8	1.5
		Dead (10h, 100h)	19	4.69	4.82	0.2-15.9	7.1
		Live fuels (grass, shrub)	19	3.76	6.52	0-27.3	2.7
		Total load	19	10.71	7.74	2.3-31.7	9.5
	11. Long broadleaved litter	Duff	33	35.69	27.5	5.8-104	41.5
		Dead 1h	46	2.52	2.65	0.1-11.4	1.9
		Dead (10h, 100h)	46	6.47	4.84	0.7-17.1	7.3
		Live fuels (grass, shrub)	46	2.08	2.83	0-13.7	2
		Total load	46	11.06	6.05	2-22.5	10.6
	12. Eucaliptus litter	Duff	na	na	na	na	na
		Dead 1h	9	9.08	4	0.1-13.9	4.2
		Dead (10h, 100h)	9	4.41	1.39	2.5-6.4	1.8
		Live fuels (grass, shrub)	9	0.26	0.31	0-0.9	0.4
		Total load	9	13.74	4.63	4.6-20.7	4
Conifer forests	13. Alpine and Mediterranean short needled conifer litter	Duff	10	39.36	16.73	19.8-63.8	25.6
		Dead 1h	15	2.36	2.02	0.1-5.9	3.8
		Dead (10h, 100h)	15	4.11	2.44	1-9.1	3.3
		Live fuels (grass, shrub)	15	0.44	0.54	0-1.6	0.8
		Total load	15	6.91	2.29	3-11.7	2.9
	14. Montane long needled conifer litter	Duff	13	39.58	30.17	1.1-93.1	49.9
		Dead 1h	36	3.32	2.63	0.1-8.7	4.2
		Dead (10h, 100h)	36	3.96	3.75	0-14.4	4.9
		Live fuels (grass, shrub)	36	0.79	1.02	0-4.7	0.8
		Total load	36	8.07	5.29	0.7-22.9	7.5
	15. Montane long needled conifer understory with shrubs	Duff	24	23.92	20.1	2.7-74.1	11.7
		Dead 1h	24	1.11	0.94	0.1-3.2	0.8
		Dead (10h, 100h)	24	11.61	11.88	0-36.5	17.2
		Live fuels (grass, shrub)	24	4.5	3.26	0.5-12.9	3.8
		Total load	24	17.23	12.96	2.7-45.3	19.9
	16. Mediterranean long needled conifer litter	Duff	12	31.81	25.73	3.4-96.6	25.6
		Dead 1h	29	2.43	1.52	0.1-5.6	2.2
		Dead (10h, 100h)	29	3.3	3.78	0.2-16.9	2.6
		Live fuels (grass, shrub)	29	0.89	0.99	0-4.3	1.1
		Total load	29	6.61	4.23	0.8-19.7	2.9
	17. Mediterranean long needled conifer understory with shrubs	Duff	18	32.83	25.06	22.7-91.4	18.9
		Dead 1h	44	4.31	2.77	0.5-12	3.1
		Dead (10h, 100h)	44	3.42	3.28	0-14.2	3.7
		Live fuels (grass, shrub)	44	11.3	8.78	1.1-29.3	11.9
		Total load	44	20.13	11.11	4.7-42	16.4
Aquatic vegetation	18. Riparian vegetation	Duff	na	na	na	na	na
		Dead 1h	-	0.49	0.54	0.1-1.2	0.9
		Dead (10h, 100h)	8	3.6	4.2	0.7-10.7	3.7
		Live fuels (grass, shrub)	8	3.11	4.04	0.9-13	0.8
		Total load	8	7.2	4.94	2.6-14.6	8.5
	19. Aquatic marshes	Duff	na	na	na	na	na
		Dead 1h	10	15.22	5.43	9-26.5	7.2
		Dead (10h, 100h)	10	17.73	5.54	8.1-25.1	7.9
		Live fuels (grass, shrub)	10	47.1	20.58	24.7-76	36.8
		Total load	10	80.05	20.69	53.4-112.7	32.4

), long-needle conifer forests of both montane and Mediterranean areas showed marked differences between fuelbed with litter fuels only (fuelbeds 14 and 16) and litter mixed with grasses and shrubs (fuelbeds 15 and 17). For example, shrub live loads (particle size <25 mm), cover and depth in fuelbeds 16 and 17 was 0.87 *vs.* 11.30 Mg ha^{-1}, 12% *vs.* 45%, and 47 cm *vs.* 157 cm, respectively, highlighting the marked difference among these fuelbeds, though associations to vegetation classifications are the same (Tab. 3).

Comparison with international dataset

To verify the congruence of fuel load values devised from the present study with those of similar fuelbeds, the fuel dataset was compared to the Fuel Characteristics Classification System (FCCS – Ottmar et al. 2007). The FCCS stores and classifies fuels data as fuelbeds across the United States, and provides a description of fuel characteristics and properties for 6 horizontal strata including the duff, litter, downed woody material, grasses, and tree canopy, obtained from literature and field data sets. It represents a helpful way for cataloging fuelbeds consumed during the fire (Ottmar et al. 2007, Ottmar 2014). Although the FCCS has been created for the United States, it can be used as reference for different ecosystems, thanks to its accurate description of the horizontal strata of each fuel. When comparing the Italian fuel dataset and FCCS for both total fine fuels (size < 6 mm), larger fuels (size 6-75 mm) and duff fuels (Fig. 3), fuel loads in each size class did not differ markedly between the two (except for a higher load of fine fuels in FCCS), which suggests that the Italian inventory explores the fuel data space in a fairly complete way.

Multivariate relationship in the dataset

To test for relationships between fuel loads and topographical and climatic drivers, we carried out a Redundancy Analysis (RDA). Response variables were 1h, 10h and 100h dead fuel loads, live grasses and live shrubs fuel loads; predictors were elevation, slope, southness (calculated as negative cosine of aspect), canopy cover, ombrotype, thermotype and continentality type according to Pesaresi et al. (2017). Observations were scaled to unit variance; the model was chosen by forward model selection based on adjusted R^2 using the "ordiR2step" function in the "vegan" package for R (R Core Team 2019). The final model was checked for collinearity by making sure that variance Inflation factors for each predictors were <10. The significance of the model, predictors, and RDA axes was checked by an ANOVA-like permutation test with 999 iterations (α =0.05).

The final model had an adjusted R^2 of 0.16. The first four RDA axes were significant, and explained 62.3%, 25.8%, 5.3% and 3.5% of the model variance, respectively. Axis 1 was strongly correlated to canopy cover (standardized loading = 0.83) and climate indices (thermotype loading = 0.77, ombrotype = -0.68), while axis 2 was explained by a combination of all predictors (Fig. 4). Fine dead fuel loadings responded to increasing slope, southness and temperature, while live grass and shrub loadings increased in wetter ombrotypes and de-
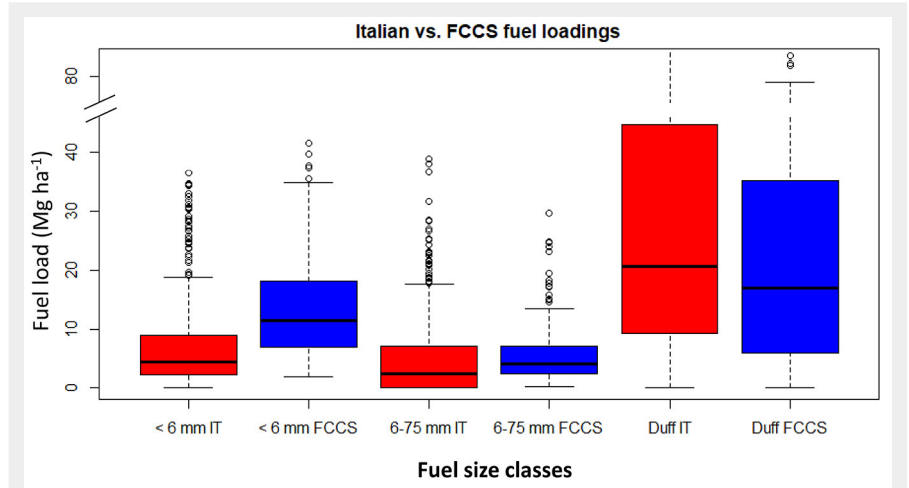
Fig. 3 - Comparison between total load (Mg ha^{-1}) of fine fuels (size < 6 mm), larger fuels (size 6-75 mm) and duff loads in both the Italian fuel survey (red) and in the Fine Fuel Classification System database (blue).
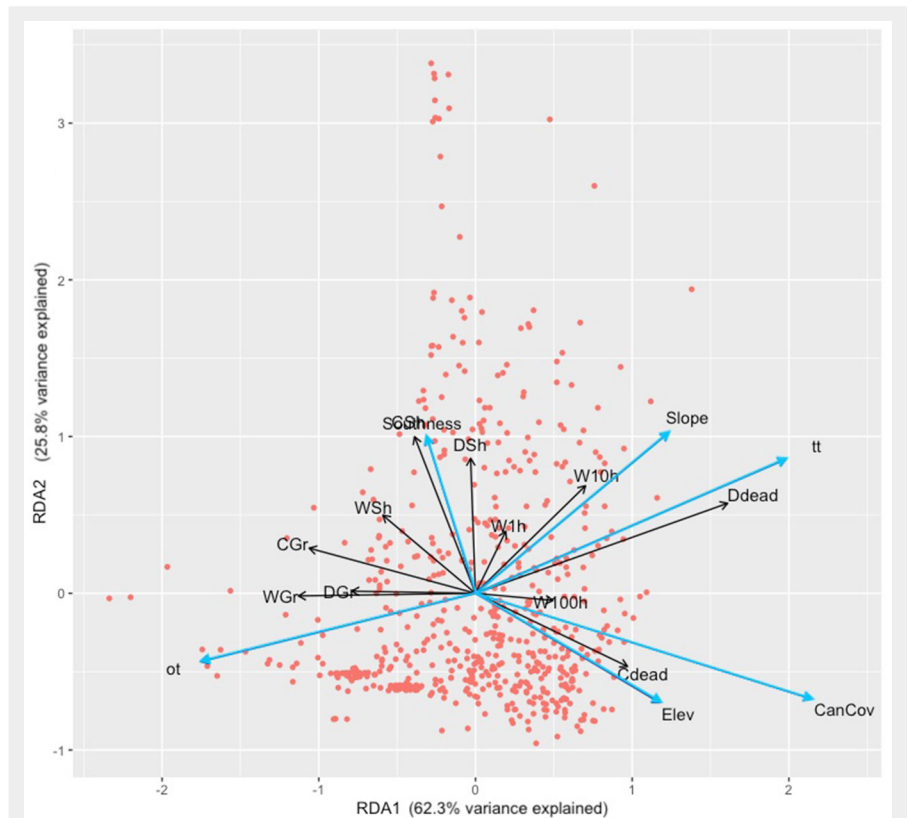
Fig. 4 - Biplot relationships between fuel load and site predictors. Red dots: individual sites; black arrow: response variables (*W1h*: fine dead fuel with particle size < 6 mm; *W10h*: fine dead fuel with particle size 6-25 mm; *W100h*: fine dead fuel with particle size 25-75 mm; *WGr*: grass and grass live fuel < 6mm; *WSh*: shrub live fuel <25 mm); blue arrows: predictors (*CanCov*: canopy cover; *Elev*: elevation; *Southness*: -cos [aspect]; *tt*: thermotype in the bioclimate map of Italy according to Pesaresi et al. 2017, where increasing values correspond to decreasing temperatures; *ot*: ombrotype in the bioclimate map of Italy according to Pesaresi et al. 2017, where increasing values correspond to increasing aridity). Predictors were scaled to improve graphical representation.

creasing elevation and canopy cover. The latter was true also for live grass depth and cover; dead fuel depth and cover were more strongly associated to thermotype/slope and canopy cover/elevation, respectively, while live shrub depth and cover responded mostly to increasing southness (Fig. 4).

Discussion

The fuel dataset deriving from this study provides quantitative characteristics of fuel beds in grasslands, shrublands, broad-leaved and coniferous forests of the Alpine, temperate and Mediterranean regions of Italy. It includes information useful for estimates on fuel biomass, surface fire behavior and effects. Although the sample size was limited and unevenly spatially distributed across the Italian peninsula, the survey covered a broad range of bioclimatic regions and vegetation types. This is apparent from the associations established between the 19 fuelbeds and the European Forest Types (Barbati et al. 2014), and the forest categories of the Italian National Forest Inventory (INFC 2005). Although resulting from an *a posteriori* compilation of fuel observations from different surveys, the fuel dataset covers all the classes of forest, grassland and shrubland mapped in Italy by Corine Land Cover IV level (ISPRA 2010).

In this Italian fuel dataset, the fuelbed with the lowest total surface fuel load was "Sparse and very short grasslands" with an average of 2.47 Mg ha^{-1}. This was due to the dominance of very short grasses with a relatively low cover, which is typical of nutrient-poor and climatically limited sites such as those at high elevation or on very dry sites (fuelbed 1, Fig. S1 in Supplementary material). On the contrary, the fuelbed with the highest total surface fuel load (duff excluded) is "Aquatic marshes". These are very flammable fuel complexes with high spatial continuity, a deep fuelbed (326 ± 19 cm on average), and dead fuels <25 mm representing 40% of total surface fuel load (fuelbed 19, Fig. S1 in Supplementary material).

Fuel characteristics of Italian vegetation fuels are within the range of values in the Fuel Characteristics Classification System (FCCS), one of the most extensive databases on fuel load and structure (Ottmar et al. 2007). Only fine fuel loads (<6 mm) were markedly lower than FCCS loads. This could be related to the higher variability of vegetation types included in FCCS (from tropical to boreal ecosystems), specific fuelbeds with very high biomass levels such as "White fir-giant sequoia-sugar pine forest", and an older stage of development of North American forests (Cheyette et al. 2008), leading to higher productivity when compared to Italian forests. Fuel inventories carried out in similar fuelbeds displayed comparable fuel loads for both Alpine and Mediterranean shrublands. For example, Fréjaville et al. (2018) reported a

total fuel load (excluding duff) of 7.7-12.3 Mg ha^{-1} in Alpine mountainous forest categories, which falls within the range of 6.2 to 17.2 Mg ha^{-1} for fuelbeds 7 to 15 (Tab. 3), *i.e.*, mountain forests under Alpine and temperate conditions. For Mediterranean shrublands, Dimitrakopoulos (2002) reported a total fuel load in Kermes oak and tall evergreen sclerophylous shrubland (excluding duff and diameters > 7.5 cm) of 34.7 and 46.9 Mg ha^{-1}, respectively, which falls within the range of fuelbed 6 "Tall Mediterranean shrublands and heathlands" of 16.8-53.3 Mg ha^{-1} (Tab. 2). Similarly, fuel load in Mediterranean grasslands according to Dimitrakopoulos (2002) was 4.85 Mg ha^{-1}, which approximates the mean total fuel load of 4.08 Mg ha^{-1} of fuelbed 2 "Continuous short grasslands". Total fuel load in long-needled Mediterranean pine forests with sparse understory in Fernandes (2009) ranged from 5.25 to 14.09 Mg ha^{-1}, which is within the range of fuelbed 16 "Mediterranean long needled conifer litter" of 0.8-19.7 Mg ha^{-1}. Furthermore, fuel loads in forest fuelbeds were similar to understory dry weight biomass values published by the Italian National Forest Inventory (INFC 2005). Indeed, mean litter biomass in the INFC (*i.e.*, leaves and twigs up to 25 mm) is 6.4 Mg ha^{-1} while in this fuel dataset the sum of W1h and W10h loads of forest fuelbeds (mean of fuelbeds 7 to 18) is 5.6 ± 0.21 Mg ha^{-1}. Similarly, load of W100h downed woody material (25-75 mm) was 2.1 ± 0.19 Mg ha^{-1}, which is close to INFC mean values for fine deadwood (25-94 mm), *i.e.*, 1.8 Mg ha^{-1}.

Conclusions

This study developed the first Italian vegetation fuel dataset based on 634 surface fuel complex observations collected within 337 study sites and covering the major types of ecosystems found in Italy. Overall, 19 fuelbeds were established, characterized by a set of fuel variables (41 fields), ranging from fuel component loads to the fuel type cover and depth. Although lacking the *a priori* sampling design needed for robust statistical inference, the fuelbed dataset presented in this study includes a broad set of fuel features that can be used for several modeling applications and decision support systems. For example, the range of fuel loadings can be used to calibrate Rothermel's fire behavior fuel models by genetic algorithms (Ascoli et al. 2015) against observed rate of spread in a given fire environment to achieve realistic fire simulations by Rothermel's based software and DSS (Vacchiano & Ascoli 2015). The available fuelbed data can be also used to estimate fuel consumption and emissions of greenhouse gases and particulate through the application of tools such as FOFEM (Reinhardt et al. 1997) or CONSUME (Prichard 2007). Moreover, the fuel dataset provides ranges of carbon pools not yet available in the Italian National Forest Inventory such as grass and shrub

biomass, despite their relevance for carbon inventories (Didion 2020). Further analysis of this data could allow to calibrate allometry relationships between above ground and dead biomass pools (Federici et al. 2008) to broad the carbon stock estimates in forest inventories. Additional field surveys and national sampling efforts, along with a standardization of the sampling scheme/approach, are certainly needed to enhance reliability and accuracy of estimates in fuelbeds/fuel complexes currently less represented (*i.e.*, fuelbed 12 – Eucaliptus litter; fuelbed 18 – Riparian vegetation) or affected by high variability due to the intrinsic heterogeneity of the vegetation and site conditions. Future research will also foresee the association of the fuelbed characteristics to specific non spatial (*e.g.*, forest typologies) and spatial (*e.g.*, forest types maps) products commonly used in natural resource management at the regional scale in Italy. This approach will provide cost-effective fuel related information and maps providing many advantages for land and resource management analysis, *e.g.*, fuel hazard assessment, preventive fire management measures, strategic fire management planning, through the prioritization of areas and resource allocation for fuel treatment to mitigate potential fire danger, risk, and fire emission and model carbon-cycle and air quality. Finally, spatially-explicit information coupled with future climate (Caddeo et al. 2019) and land use change scenarios (Martellozzo et al. 2018) would offer a valuable support towards more comprehensive landscape planning able to minimize risk related disturbances such as wildfires (Marchetti et al. 2014), as well as maximize ecosystem services provisioning and their trade-offs at the landscape level (Vizzarri et al. 2017).

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Supplementary Material

Tab. S1 - Fields of the Italian fuel characteristics dataset.

Tab. S2 - Foliage and branches fuel load and source of data by fuel complex.

Fig. S1 - Scheme showing the structure of the dataset as regards quantitative variables characterizing each fuel observation.

Fig. S2 - Photos describing the 19 fuelbeds included in the dataset.

Link: Ascoli_3587@suppl001.pdf

Tab. S3 - Harmonized fuel characteristics dataset including 634 fuel samples and 41 variables (see Tab. S1) at 377 sites under Alpine, Temperate and Mediterranean conditions in Italy.

Link: Ascoli_3587@suppl002.xlsx