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Comment on "Classification and mapping of European fuels using a hierarchical, multipurpose fuel classification system" by Aragoneses et al. (2023)

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Abstract. Classifying and mapping vegetation as fuel is essential for various fire research and management applications. Aragoneses et al. (2023) proposed a hierarchical fuel classification system for Europe and allocated standard fuel models to the resulting fuel types, producing a continental fuel map. We examine the methods involved and their outcomes. The reasoning behind their system is misguided, as the proposed set of fuel types does not reflect fuel-complex characteristics and the inherent fire behaviour. In their categorization of shrublands and grasslands, fuel depth is a key variable; however, the bioclimatic modelling approach used to map it is unreliable, as it is based on local empirical relationships. The adopted 1-km mapping resolution is one to two orders of magnitude lower than the needs of spatially-explicit fire behaviour simulation, and implied up-scaling procedures adding uncertainty due to loss of thematic detail. Finally, a simplistic aridity-based rule was applied to assign fuel models to fuel types, limiting the options available. This, in combination with fuel-depth overestimation and untenable fuel model choices, contributed to a substantial fire-hazard overestimation across the large portion of Europe occupied by low-flammability cover types.

1 Introduction

Describing the ability of vegetation to burn, i.e. as fuel, allows characterizing and estimating fire behaviour characteristics and the corresponding environmental and socioeconomic impacts for different research and management purposes and at different spatiotemporal scales (Rego et al., 2021). Classifying and mapping fuels is a way to address natural complexity and easily synthesize and communicate fuel characteristics for practical applications (Keane, 2015).

Fuel classification and mapping through fuel models for use with the fire spread model of Rothermel (1972) is a widespread practice. The US Forest Service concept of a surface fuel model considers fuel layers (grass, shrubs, litter, slash) and their combinations (Scott and Burgan, 2005). However, fuel characteristics vary within vegetation types, a variability that may well be higher than that observed between different vegetation types, particularly where ecological disturbances are frequent and land use intensity varies (Brown and Bevins, 1986; Fernandes et al., 2019). Thus, individual fuel models usually apply to several vegetation types and patches of a given vegetation type can be allotted to different fuel models (Scott and Burgan 2005). This challenges the accurate spatial assignment of fuel models, which is further complicated by (i) decreased thematic resolution of the land cover or vegetation data at coarser spatial scales; and (ii) the user generalization and perception of what the expected fire behaviour might be in a certain vegetation type.

Aragoneses et al. (2023) developed a fuel classification system for Europe (hereafter EFCS) based on a combination of land cover categories and vegetation physiognomy and structure and then produced a European map of fuel types and their fuel-model equivalence. Given that the EFCS can be used in both fire research and fire management and is likely to inform further fuel-mapping efforts, an inspection of its assumptions, methodologies and claims is warranted. We structure this comment around the three objectives of Aragoneses et al. (2023): (i) generate a multipurpose hierarchical fuel classification system; (ii) develop a European fuel map resulting from the EFCS, easy to replicate and update; and (iii) assign standard surface fuel models to the fuel types.

2 A classification hierarchy that does not lead to fuel types

A fuel type is defined by a set of qualitative and quantitative fuel characteristics that originate a specific fire behaviour irrespective of vegetation type (Merrill and Alexander, 1987). Canadian fuel types (Forestry Canada Fire Danger Group, 1992), the Australian Bushfire Fuel Classification (Hollis et al., 2015), and the US fuel models (Rothermel, 1972; Scott and Burgan, 2005) all follow this principle. Notwithstanding spatial variability, the expert-based allocation of fuel types and fuel models to vegetation or land cover classes is a common and acceptable practice (e.g., Alcasena et al., 2015; Sá et al., 2023) when fuel structure is coherent within each of those classes.

The EFCS comprises 85 fuel types organized into six primary land cover categories: forest, shrubland, grassland, cropland, wet/peat and semi-peat lands, and urban areas. Croplands and wet/peat lands are divided based on vegetation composition. Forests are categorized based on 'leaf type' (broadleaf, needleleaf, mixed), 'leaf deciduousness' (evergreen, deciduous), canopy cover (open, closed), and surface fuel layer (litter, grass, shrub). Both the forest understorey and shrublands and grasslands are categorized by height (low, medium, tall).

The EFCS structure has several notable shortcomings. First, not all the sub-categories are realistic and fuel types are created as artifacts of the hierarchical combinations, e.g. open forests with litter as the surface fuel layer are unlikely. Second, the EFCS does not account for combinations of fuel layers. Third, key fuel descriptors are omitted. For example, the presence of coarse woody debris and variations in litter structure differ greatly both within 'leaf type' and 'leaf deciduousness' but are ignored. Additionally, distinct grass and shrub fuel types are inappropriately merged within the same classification level. It follows that the EFCS does not adhere to the fuel type concept because the classification is not based on fuel complex characteristics nor on the associated fire behaviour.

3 The European fuel map

The EFCS mapping approach is primarily based on the Copernicus Global Land Cover map at 100-meter resolution, supplemented by other data sources with resolutions of 100 or 300 meters. Aragoneses et al. (2023) resampled this data to a 1-kilometer resolution to match the scale of the climate data (see below). Each 1-km² cell was assigned the dominant fuel type. The mixed forest type was assigned to co-dominant forest types. When two first-level categories were co-dominant, the more ‘dangerous’ fuel type was assigned to the pixel: shrubland if co-dominant with forest, and grassland if co-dominant with either shrubland or forest. Here the criterium seems to have been the spread rate of a surface fire, rather than its fireline intensity or flame length, which are the fire behaviour metric usually adopted to describe fire hazard, e.g. Miller and Ager (2012).

We begin by informally observing that the fuel map derived from the EFCS contains significant incoherences with land cover in Portugal. For instance, evergreen forests are not mapped and are frequently misclassified as deciduous forests (part of the cork oak estate) or as shrubland (including both oak and eucalypt plantations). The presence of pine forests is severely underestimated, often being misclassified as shrubland. Conversely, peat and semi-peat lands, which are extremely localized in Portugal, are grossly overestimated. We will not delve into this issue; however, it is reasonable to question the overall approach, as inaccuracies in mapping vegetation types across Europe can, by themselves, compromise the reliability of fuel type mapping.

3.1 On the estimation of fuel characteristics

Aragoneses et al. (2023) assigned the fuel bed depth categories based on environmental conditions, simplifying bioclimatic variation by grouping Europe’s biogeographic regions into two broad classes: arid/semi-arid and sub-humid/humid. This method has significant implications for fuel classification and mapping outcomes, as will be shown in section 4.

The classification of open vegetation types by depth adopted published relationships between precipitation (mapped at 1-km resolution) and aboveground biomass (‘productivity’), estimating fuel depth from biomass. Shrubland biomass was estimated from mean annual precipitation using an equation developed with data from 36 field plots in California, for which predictive ability is low (R^2=0.23) (Bohlman et al., 2018). Aragoneses et al. (2023) then used the estimated biomass as input to determine shrubland fuel depth according to Saglam et al. (2008). While Saglam's data showed considerable variation in vegetation structure (height 30-230 cm, ground cover 40-98%), it was based on just two locations in Turkey and two variants of Mediterranean shrubland dominated by Kermes oak (*Quercus coccifera*). These shrublands are common in limestone soils of the Mediterranean basin but represent only one of many shrubland types in southern Europe, let alone across the continent. Additionally, the wide variation in biomass bulk density among shrub species — up to an order of magnitude, e.g., 0.39 kg m^{-3} for *Cytisus triflorus* and 4.88 kg m^{-3} for *Ulex parviflorus* in Armand et al. (1993) — shows that fuel depth-load relationships are highly variable (Nunes et al., 2022). Also, negative estimates of fuel depth were treated as outliers. However, these negative values result from not forcing the model to have a zero intercept. Consequently, the depth equation model produces estimates that lack biological significance but are not necessarily anomalous.

We applied the Saglam et al. (2008) relationship to a shrubland-dominated landscape in the Natural Reserve of Malcata, central-eastern Portugal. A previously available dataset (Fernandes et al., 2000), used in Rosa et al. (2011), provided aboveground biomass estimates and corresponding shrub depths for 164 locations within approximately 100 km². These data captured the diversity of existing shrubland communities, defined by dominant species, and highlighted variations in climate, elevation, aspect, soil type, and time since disturbance. When compared with field measurements, shrubland depths estimated as per Saglam et al. (2008) exhibited a mean absolute error of 0.38 m, a mean absolute prediction error of 79.9%, and a mean bias error of -0.34 m, indicating a tendency for underestimation (Fig. 1).

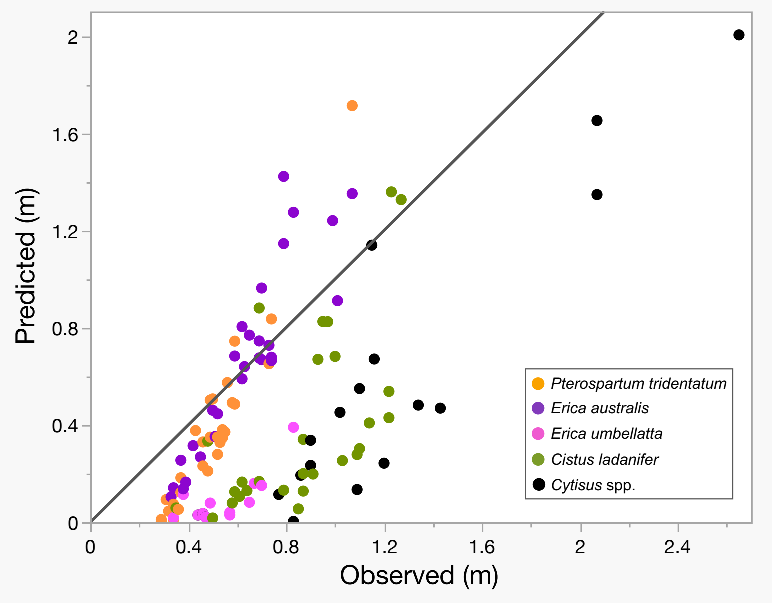

Figure 1: Shrubland fuel depth predicted by the equation adopted by Aragoneses et al. (2023) compared with the depth measured in the field at locations (*n*=164) within the Malcata Natural Reserve, central-eastern Portugal.

Classifying the observed and estimated fuel depth into the three categories adopted by Aragoneses et al. (2023) and performing a contingency analysis yielded a global agreement of 65.8%. However, for shrubland ≥0.5 m tall, which comprises 97.7% of all European shrublands in Aragoneses et al. (2023), the agreement dropped to 39.6%. The more robust Cohen's Kappa coefficient was 0.37, indicating less than moderate agreement between the fuel depth estimates and actual observations, thus a lower agreement than that stated for a random classification. This same concern extends to the

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estimation of grassland depths. The actual agreement between predicted and observed fuel depths would of course have been even lower if biomass had been estimated based on precipitation rather than from plot-level data.

While precipitation and temperature determine broad patterns of plant productivity and biomass (e.g., Peñuelas et al., 2007), and therefore of fuel loading, these patterns are complicated by substantial interannual variability in climatic conditions. In addition, spatial variation in soil fertility and topography, along with disturbances like fire, grazing, silviculture, and fuel reduction treatments, further make fuel estimates even more difficult. Fuel depth estimates could be improved by leveraging satellite surface reflectance data, such as that from Copernicus Sentinel-2 (Lang et al., 2019), which is available for monitoring vegetation removal due to natural or management-related disturbances. These disturbances, along with land use and land cover changes, have significant impacts on fuel load and structure and, consequently, on fire hazard assessments. Additionally, combining GEDI and ICESAT-2 data would allow for the development of models to estimate aboveground biomass across different biophysical contexts. These datasets could also have been used to extract vegetation height and cover metrics (e.g., Duncanson et al., 2022; Leite et al., 2022; Moudrý et al., 2022; Hoffrén et al., 2023) to estimate standard values for fuel types. These could then be applied to stand-level biomass equations built from field data collected throughout European shrublands, e.g. Vega et al. (2022).

3.2 On the justification and utility of a 1-km fuel-type mapping resolution

Aragoneses et al. (2023) state that "The main driver of the classification system was fire behaviour modelling, but its use for fire risk assessment and fire emission estimations was also considered." Fuel mapping for fire behaviour simulation is defensible at a resolution of 100 meters, though higher resolutions, such as the 30-meter scale adopted across the U.S. (https://landfire.gov/fuel.php), are preferable. European fire behaviour simulations based on fuel models generally operate at resolutions between 20 and 120 meters for local-scale applications. While resolution decreases for larger scale applications, it rarely exceeds 250 m (Alcasena et al. 2016, 2019; Oliveira et al. 2016; Salis et al. 2012). Mapping fuel types or fuel models at the coarse-scale resolution of 1-km² proposed by Aragoneses et al. (2023) is unsuitable for fire behaviour modelling and simulation for three main reasons:

1. Variability in vegetation and fuels within mapping units: European landscapes are highly heterogeneous and anthropogenically influenced, leading to significant variability in fuel types and models within a single 1-km² cell size. A recent example by Beetz et al. (2024) highlights this issue.
2. Terrain variability within mapping units: The variability of slope and aspect, especially in mountainous terrain, directly affects fire spread rates and influences input variables like windspeed and dead fuel moisture content, both of which are crucial for accurate fire behaviour simulation.
3. Inadequate for fire management: A 1-km² fuel map is insufficient for operational purposes, including planning fuel treatments and responding to wildfires. Such coarse mapping fails to meet the needs of fire growth simulations used to support firefighting operations and civil protection measures.

While 1-km² fuel mapping might meet the less demanding needs of fire danger and risk assessments, its usefulness and accuracy are questionable, as variability can be expected to be greater within individual 1-km² cells than between them. For instance, Fig. 2 illustrates the diversity of fuel models in Portugal (Sá et al., 2023) that can be identified in the 1-km^2 map used by Aragoneses et al. (2023), calculated using the Shannon Evenness Index, which reveals substantial within-pixel variation. Actual fuel model variability will be even larger, because fuel model allocation in Sá et. al. (2022) was based essentially on land-cover equivalences.

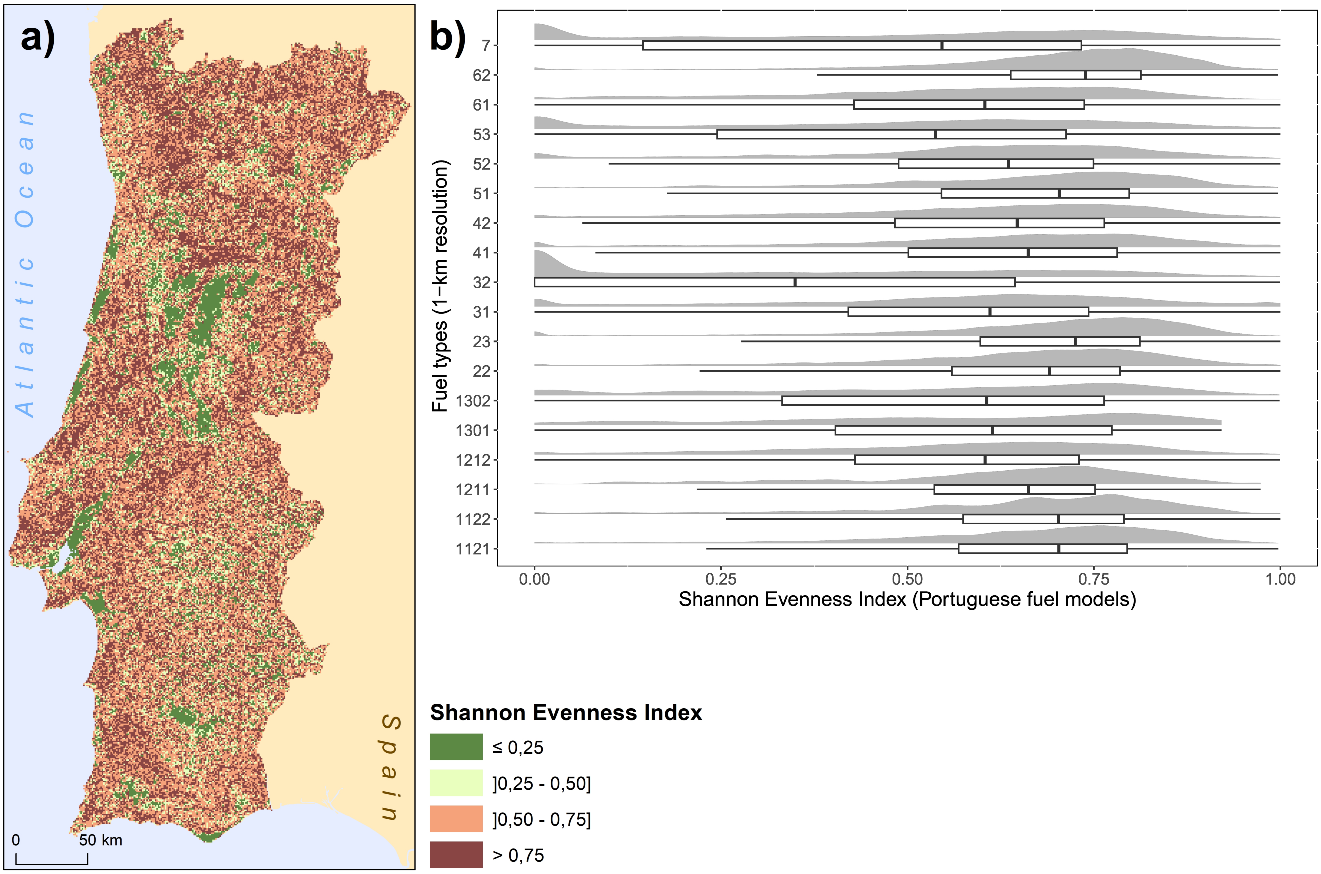

Figure 2: Spatial distribution of a) the Shannon Evenness Index computed using the Portuguese fuel models on the 1-km^2 map of Aragoneses et al. (2023); and b) half-violin plots and boxplots of the same index by fuel types determined by the authors.

The 1-km² resampling of Aragoneses et al. (2023) resulted in thematic detail loss, which is particularly significant in highly heterogeneous landscapes. Upscaling categorical data in such environments is challenging, as the likelihood of no clear dominance by any fuel type within the selected neighbourhood window is high. This limits the reliability of majority-rule techniques during upscaling and calls for alternative resampling methods, such as the Area Preservation method (Johnson and Clarke, 2021).

Preserving spatial heterogeneity is critical when modelling fire hazard and estimating fire behaviour characteristics. For this reason, bioclimatic factors could have been downscaled using more precise and accurate methods, such as bias-corrected spatial downscaling or multivariate adapted constructed analogues, as tested by Abatzoglou and Brown (2011). However, since the bioclimatic data were primarily used to estimate productivity of shrublands and grasslands, the results obtained at a 1-km² resolution could have been assigned to 100-meter pixels without the need for additional resampling, thus avoiding the propagation of uncertainty through data.

4 Assignment of fuel models to fuel types

Aragoneses et al. (2023) propose a cross-walk between fuel types and the set of 40 standard fire behaviour fuel models (FBFM) developed for the US by Scott and Burgan (2005) for use with fire modelling tools based on Rothermel (1972) fire spread model. Scott and Burgan (2005) established two sets of fuel models, categorized as ‘dry’ or ‘wet’. Moisture of extinction, to which Rothermel’s model is highly sensitive (Burgan, 1987) is set at low values (12-20%) for the dry group and high values (30-40%) for the wet group, assuming that fuel types in wet regions can sustain combustion at higher moisture levels than those in dry areas.

The FBFM duality of arid to semi-arid *versus* sub-humid to humid climate was fully embraced by Aragoneses et al. (2023) using a strict rule: the presence or absence of at least one dry summer month as distinguishing criteria. The Mediterranean, European Black Sea, and Steppic biogeographic regions were classified as arid/semi-arid, and the rest of Europe as sub-humid/humid. However, annual rainfall is extremely variable in the Mediterranean climate, roughly from 200 to 1200 mm (Philandras et al., 2011). Thus, the arid/humid dichotomy is an extreme simplification that exaggerates aridity and has far-reaching consequences regarding fuel model allocation. It would have been advisable to work at a higher-resolution spatial level and use and combine other criteria, namely Koppen-Geiger climate classification, net primary productivity, and data from fuel inventories (e.g., Davide et al., 2020).

Furthermore, Aragoneses et al. (2023) state that “…we assigned to each fuel type a given FBFM and the related fuel parameters that most fitted the average conditions in the field, according to expert knowledge”. Fuel models were conceived by Rothermel (1972) as “stylized”, i.e. nearly abstract assemblages of fuel parameters, set at values minimizing the error between simulated and observed rate of spread, rather than representations of average fuel conditions in the field (Burgan, 1987; Cruz and Fernandes, 2008; Ascoli et al., 2015). It follows that the fuel model best matching observed fire behaviour in a particular fuel type can be inconsistent with vegetation physiognomy and structure, and that multiple fuel models may display comparable errors when predicting observed rate of spread (Sá et al., 2023). In any case, it is difficult to understand to what extent could expert knowledge appraise average conditions in the field, given the absence of field work and the enormous geographical scope and variety of vegetation types. After mapping the FBFM, the authors also mapped the corresponding fine dead fuel loadings and surface fuel depths. Their purpose in doing so is unclear, but it may induce misunderstanding, as readers may take the mapped values at face value and assume they portray fuel conditions in the field, when in fact they are nominal and are not expected to match or even approach the reality (Rothermel, 1972; Cruz and Fernandes, 2008; Ascoli et al. 2015).

Difficulties in assigning a single fuel type and fuel model at the 1-km^2 scale, where different fuel types contribute to fire behaviour, are manifest. The authors could have used field observations to quantify the corresponding uncertainty, which is important information that can be integrated into probabilistic simulations of fire propagation, e.g. Benali et al. (2021). The low data quality associated with the user imperfect knowledge of the mechanisms driving fire behaviour may lead to unrealistic fire predictions and fire risk assessments fraught with uncertainties (Benali et al., 2016).

The crosslinks in Table 5 of Aragoneses et al. (2023) and the resulting map reveal issues with the expert-based association of fuel models to fuel types, particularly those that occupy the largest area in Europe. A relevant example is fuel type 41 'herbaceous cropland', which covers the largest surface area (1,779,000 km^2), mostly in wet and semi-humid bioclimatic areas. This fuel type was assigned to various agricultural crops, from mown meadows to forage grasses, cereal fields, rice-farming, pastures and grasslands, which characterise the intensively-used farmland of central-northern Europe. According to Aragoneses et al. (2023), the fire behaviour of fuel type 41 is well predicted by the GR4 fuel model in the arid/semi-arid and by the GR6 fuel model in sub-humid/humid regimes, respectively. Simulating fire behaviour with the Rothermel package in R (Vacchiano and Ascoli, 2015) for GR6 and a "moderate moisture scenario", i.e. 9% for dead fine fuel and 90% for live grass (Scott and Burgan 2005), suitable for central-northern Europe, and a wind of 15 km hr^{-1}, a rate of spread of 53.5 m min^{-1} is obtained, rising to 82.5 m min^{-1} with a wind of 20 km hr^{-1}; substantially higher values would be obtained assuming higher grass curing levels. Under very similar conditions, a 710-ha grassland fire in the Netherlands — the largest in the country in at least 50 years — spread at just 18.5 m min^{-1} (Stoof et al., 2020). Those predictions thus appear to grossly overestimate fire spread rate in the cultural landscapes of central-northern Europe. Even higher overpredictions are expected for most of the UK, Ireland, and Norway, due to the allocation of heavy and tall grass fuel models (GR8 and GR9), in what seems to be a consequence of the bioclimatic modelling approach, i.e. fuel-depth overestimation, see Fig. 7 in Aragoneses et al. (2023).

Similarly, fuel type 1122 (covering 452,000 km^2, 84.1% in the humid bioregion) is associated to fuel models TU4 and TU3, respectively in the arid/semi-arid and humid/sub-humid regimes. Associating a faster fuel model (TU3) to the humid rather than the arid biogeographical region is dubious, and more so because TU3 is describing deciduous broadleaved forests, strongly overlapping with beech forests in central-northern Europe and with mesophytic deciduous forest in southern Europe (Barbati et al., 2007). These closed forests are characterized by litter comprised of large and fast-decomposing leaves, moderate loads of downed dead woody fuel, and scattered understory (e.g., Ascoli et al., 2020; Heisig et al., 2022) under mesic conditions, and seldom support intense fire behaviour (Maringer et al., 2016). Their association with TU3, one of the highest-intensity FBFM, will thus substantially overestimate fire behaviour under such fuel conditions. Similar problems arise with fuel type 1212, which covers 861,000 km^2, 93.4% of which in the humid bioregion. The TU2 fuel model associated with the humid region produces a fire-spread rate that is 2-10 times faster than TU1, linked to arid regions. This assignment overestimates fire spread in closed short-needle conifer forests where the fuel bed is dominated by litter, including those of spruce and fir, which are among the least flammable in Europe (Tanskanen et al., 2007; Xanthopoulos et al., 2012).

Aragoneses et al. (2023) did not compare their crosswalks or benefited from those suggested by prior work at the local or regional levels. As an example, the proposed crosswalk differs from the one outlined by Alcasena et al. (2016) for a southern European region, who have ascribed mowing hay meadows and grazed pastures to fuel model GR2 and beech forests to the timber litter fuel model TL2. Likewise, Spadoni et al. (2023) assignment of farmland and broadleaved deciduous and short-needle conifer cover types in Italy to fuel models — respectively the GR1 fuel model and TL fuel models— is sounder, realistically downgrading the fire behaviour potential implicit in their EFCS counterparts.

A last relevant concern about Aragoneses et al. (2023) approach is that the fuel modification inherent to recently burned areas is ignored, as well as the impact of time since fire on fuel model selection. For example, most of the extensive area of pine and eucalypt stands burnt in 2017 in Portugal is classified by Aragoneses et al. (2023) as medium height grasslands. This fuel model assignment incurs in a large error, because the burned area is mostly covered by tree and shrub regeneration. While the authors claim that accurate and updated fuel maps are needed, they do not integrate vegetation disturbances in their framework and the patterns of vegetation recovery with time since disturbance, thus ignoring the correspondent dynamic changes in fuels. Finally, the land-cover base map used is from 2019, but the process and plan to update the fuel models map is not discussed, nor how it can affect the reliability of the product for operational fire management purposes.

5 Data availability

No new data were used in the study.

6 Conclusion

Our main conclusion is that the generic claim of Aragoneses et al. (2023) regarding the EFCS as widely applicable in Europe is not warranted. From the operational viewpoint, the insufficiency of the coarse mapping resolution (1 km) adopted is apparent, because by definition it hinders fire behaviour simulation, regardless of the intended application of the results. However, the use of smaller mapping units, such as ~1 ha, would still have been insufficient to achieve acceptable fire simulation outcomes due to the fuel modeling issues we have identified.

A basic concern in the EFCS is the disconnection between the fuel type concept and the structure of the hierarchical system and, consequently, between the categories identified and actual fuel types. Fuel depths of shrublands and grasslands play a relevant role in the EFCS hierarchy, but were estimated through a bioclimatic modelling approach based on empirical equations developed for specific mediterranean environments, hence not generalizable. The assignment of fuel models was conditioned by the coarse resolution of mapping and fuel-depth estimation, plus by arbitrary decisions, namely rigidly assuming a humid versus arid duality, and ascribing timber-understorey fuel models to forest types where fire behaviour is determined by litter. The compounded end result was the considerable overestimation of fire behaviour potential across the large fraction of Europe that is occupied by farmland, pastures, and low-flammability forests.

Overall, the degree of applicability and reliability of the proposed European fuel map does not encourage its adoption by fire researchers and fire managers alike. Future work efforts should therefore develop and apply approaches tackling the current insufficiencies and resulting in more capable fuel mapping procedures and truly operational products.

Author contribution

PMF wrote the initial draft of the manuscript, which was subsequently developed by all authors. PMF and NGG carried out the data analyses.

Competing interests

The authors declare that they have no conflict of interest.

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