

Review

# Criteria-Based Identification of Important Fuels for Wildland Fire Emission Research

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**Abstract:** Studies of the emissions from wildland fires are important for understanding the role of these events in the production, transport, and fate of emitted gases and particulate matter, and, consequently, their impact on atmospheric and ecological processes, and on human health and wellbeing. Wildland fire emission research provides the quantitative information needed for the understanding and management of wildland fire emissions impacts based on human needs. Recent work to characterize emissions from specific fuel types, or those from specific areas, has implicitly been driven by the recognition of the importance of those fuel types in the context of wildland fire science; however, the importance of specific fuels in driving investigations of biomass-burning emissions has not been made explicit thus far. Here, we make a first attempt to discuss the development and application of criteria to answer the question, "What are the most important fuels for biomass-burning emissions investigations to inform wildland fire science and management?" Four criteria for fuel selection are proposed: "(1) total emissions, (2) impacts, (3) availability and uncertainty, and (4) potential for future importance." Attempting to develop and apply these criteria, we propose a list of several such fuels, based on prior investigations and the body of wildland-fire emission research.

Keywords: biomass burning; combustion; emissions; fuels; fuel selection criteria; wildland fires

# 1. Introduction

# 1.1. Terminology and Scope

We use the terms "wildland" and "wildland fire", as defined by the National Wildfire Coordinating Group [1], with "wildland" referring to "An area in which development is essentially non-existent, except for roads, railroads, powerlines, and similar transportation facilities. Structures, if any, are widely scattered." and with "wildland fire" referring to "Any non-structure fire that occurs in the wildland". This terminology indicates a distinction between wildland fires and the use of open fires to burn agriculture waste or refuse. Although these and other biomass-burning emissions are of great importance to atmospheric sciences and public health, here, we concern ourselves with the relatively uncontrolled wildland fires that represent the dominant influence on ecosystems, the atmosphere, and people.

# 1.2. Background of Fuels Classification

The importance of wildland fire is recognized across most areas of earth and environmental sciences [2], due to its major societal, economic, ecologic, and human health and wellbeing impacts. Quantifying fire processes and effects, and their interaction with other, non-fire processes, is consequently the focus of much effort within many disciplines. Within the broad scope of wildland fire science, this effort has resulted in remarkable progress in predicting the behavior of wildland fires.

The pioneering work of Rothermel [3] is widely regarded as having ushered in the age of numerical prediction of the movements of wildland fires, and, currently, many modeling schemes exist to forecast the growth of large fires [4,5]. Factors such as meteorology and its interactions with fires, and the contributions of radiation and convection determine fire dynamics [6] and control fire growth and movement to varying, but generally substantial degrees. Recognizing the dominant influence of fuels and their varying properties on the characteristics of wildland fires, wildland fire researchers have developed abridged fuel classification schemes that create broad categories of fuels across biomes and permit inputs to a variety of models designed to predict fire behavior and effects, and the production and fate of smoke and emissions. For example, Rothermel outlined 11 fuel types for input into his eponymous fuel-spread model [3]; Albini expanded on this work to generate 13 wildland fuels classifications [7]. A later, more complex scheme created and incorporated 40 fuel types [8]. All these systems have the goal of improving model predictions of fire behavior, particularly fire spread; they are therefore based on fuel characteristics, such as arrangement, rate of drying, and other factors that contribute to the ignition and spread of fires across fuel beds [9]. As such, they are largely focused on fuels important to the flaming combustion phase, while largely ignoring fuels that mostly burn in the smoldering phase [10]. A few fuel components, e.g., "Southern Rough" (e.g., "Southern Rough"; [7]) refer to geographic areas where substantial contributions by individual plant species (or groups of species) can be inferred. However, no fuel classification scheme exists to guide research that focuses on the properties of emissions produced by wildland fires either in North America or elsewhere [10].

#### 1.3. Importance of Fuels Prioritization for Emissions Research

Investigations of the physics, chemistry, transport, fate, and effects of wildland fire emissions are collectively in a state of rapid growth, driven by needs for prediction of fire processes and effects and enabled by advances in experimental design [11–14], and in measurement and analysis technology [15–17]. In particular, societal needs for information concerning the effects of wildland fire emissions on air quality, visibility, and public health [18–21], and on global climate [22–24] and in return, the effects of human-caused landscape modifications and climate change on fire emissions [25,26], are promoting and influencing fire emission research [12].

The modeling of wildland fire emissions generally requires detailed, fuel-specific emission factors to quantify primary atmospheric emissions that can be used to assess the impacts of wildland fire emissions on global and regional climate, human health, regional air quality and visibility, and other areas [27,28]. Detailed databases giving unified access to the results from laboratory and field emissions studies (e.g., measurements of fuel-specific, fuel-based emission factors for speciated gaseous and particulate matter (PM) emissions) grow only slowly, due to the expensive nature of detailed emission studies, and the difficulties of presenting the results of very different studies in a unified manner [29–31].

The importance of accurately predicting wildland emissions means that the number of these studies for various types of wildland fuels continues to grow. For example, a Google Scholar search (conducted on 3 March 2020) for "laboratory fire emissions" yielded a near-exponential increase of the annual number of publications from 1985 (488 publications) to 2018 (12,200 publications) corresponding to a 25-fold increase in publication rate over this 33-year period. These studies are conducted in order to provide inputs for models addressing air quality, visibility, human health [19,32], and climate change [33,34].

We contend that—due to the growing magnitude of effects from wildland fire emissions on climate and health in some regions of the globe [35] and resource constraints limiting the rate at which detailed emissions studies can occur—determining the most important wildland fuels for future emission research is needed, to guide future efforts in this area of work. We approach this goal with the objectives of (1) developing selection criteria and (2) applying these criteria to compile an initial list of important wildland fuels for experimental studies of wildland fire emissions.

#### 2. Developing Criteria for Fuels Prioritization

Here, we concern ourselves with the characterization of near-field emissions from the combustion of biomass in wildland fires, i.e., the smoldering and flaming combustion of live and dead vegetation and organic matter in the upper layers of soil—collectively known as wildland fuels. Unlike fuels classifications developed for other aspects of wildland fire, no scheme exists currently for assessing the relative importance of some wildland fuels over others with respect to combustion emissions. It is known that the emissions produced from the combustion of these fuels vary considerably as a function of fuel properties and environmental conditions [36], and a growing body of literature describes the types and relative quantities of emissions across a range of different fuels and varying characteristics within a single fuel type, e.g., arrangement, density, moisture (e.g., arrangement, density, moisture; [10]), as function of environmental conditions, e.g., temperature, relative humidity, wind velocity (e.g., temperature, relative humidity, wind velocity; [37]). Note that emissions and their toxicity are greatly dependent on the combustion phase (e.g., flaming, smoldering, [36]), which itself is a function of fuel and environmental conditions [38–41].

We first discuss two possible approaches (i.e., splitting vs. lumping) for creating a list of criteria, to identify priority fuels for combustion emission research that acknowledges the variety of effects from wildland fires on humans and on anthropogenic and natural systems. One immediate challenge facing such an effort is to include criteria reflecting the range of socio-cultural, human health, ecological, and climatic impacts, and to mitigate the varying quality and availability of data from around the globe. Indeed, the drive to better understand the influence of wildland fire emissions on these factors is the very reason that a first-order prioritization of important fuels is so challenging. This is followed by discussion of an initial list including the criteria of (1) total emissions, (2) impacts, (3) availability and uncertainty, and (4) potential for future importance.

#### 2.1. Splitting Versus Lumping: Two Possible Approaches

For developing inventories of combustion emissions data for wildland fuels, two divergent approaches immediately become apparent. The first is to select individual components of a "fuelscape"—the fuels found in an ecosystem or landscape of interest—and consider each individual species, and even the variety of plant parts within a species—foliage, bark, small or large branches, litter, and so on—and to quantify the emissions characteristics for each of the many environmental factors known to affect combustion, as mentioned above. Here, the assumption is that during the combustion of a fuelscape, total emissions can be calculated with a properly weighed sum over its combusted components. However, we are not aware of any verification of this assumption for realistic fuelscapes. For the purposes of this study, we refer to this approach as "splitting."

A contrasting approach considers all of these major elements together, burning an arrangement including the major plant species and their component parts together with litter, duff, and soil—i.e., an approach that "lumps" together all of the constituents of a wildland fuelscape. Such an approach aims to ensure that the fuel arrangements and combustion processes comprise those found in a given fuelscape and assumes that the combustion products from such an arrangement qualitatively reflects those found in nature, by being represented in laboratory emissions profiles from that fuelscape.

Ideally, emissions from wildland fuel combustion would be assessed across a variety of variables known to influence combustion and emissions, both fuel properties (e.g., arrangement, density, moisture) and environmental conditions (e.g., temperature, relative humidity, wind velocity)—just as Rothermel [3], Albini [7], and others have done—to develop and refine fuels classification systems for fire-behavior models. Additionally, individual plant species within a vegetation community or portions of organic soil horizons (e.g., Oa, Oe, Oi, or otherwise according to factors such as mineral content, depth, or other determinants of combustion), would also be analyzed, due to their known differences in combustion dynamics and emissions produced; these differences certainly can be expected to extend to the various components of individual plants, since leaves, small and large branches, bark, and stems

all should be expected to vary chemically and physically in their combustion emissions as they do in vivo (as well as in mortem).

Alternatively, a "lumping" approach for fuels selection should capture the variation found in an ecosystem, community or region, and ensure that its major components are represented, in order to ensure that at least the identities of emissions species (of both gaseous and particulate) are discovered in analysis, even if their relative abundance is acknowledged to vary with a number of fuel characteristics. The moisture content, arrangement, density, and combustion phase should represent those conditions realistically encountered under a scenario of a wildland fire in a given area, for similar reasons. Such characterizations can support management decisions and the study and prediction of climate and health impacts when emissions occur from broad fuel types, and the effects and interactions of emissions with the atmosphere can be compared across the biomes from which they originate. The essence of this approach is to ensure that all emissions constituents created by wildland fires in a given area are identified, and to some degree also quantified.

Both the "splitting" and "lumping" approaches have their benefits and drawbacks. In addition, both approaches suffer from the uncertainty of scaling emission factors with fire size, from small-scale laboratory fires to mega fires. This has led to concerns in the biomass-burning-emissions community, regarding the ability of laboratory-based experimental burns to accurately replicate conditions and emissions observed in real wildland fires, e.g., [42–44], and in-depth understanding of scaling laws and atmospheric processes may be necessary for laboratory-based methods to yield accurate quantitative extrapolations to wildfires. Therefore, the usefulness of either approach may be limited for deriving quantitative biomass-emissions estimates for real-world wildfires.

Examining the emissions of individual fuelscape components under varying combustion environments could support the development of tools to precisely predict the production of many combustion products from wildland fires, especially in situations where the constituent elements of a burned area are well-characterized or can be readily reconstructed. Additionally, powerful forecasts of changes to wildland fire emissions could rely on data resulting from this approach, giving a picture of changes under scenarios of changes to climate, hydrology, fuel loads and composition, and many other factors for well-characterized landscapes. However, the advancements yielded by this approach would be both slow and resource-intensive, because achieving a comprehensive characterization of even a low-diversity plant community would require many combustion experiments per plant species—even multiple trials for each part of a plant—as other factors affecting combustion chemistry are varied, (e.g., [45,46]). In addition, the splitting approach ignores the combustion interactions between different components as they burn next to each other, exchanging energy and influencing each other's emissions.

By contract, the "lumping" approach prioritizes acknowledges that our understanding of emissions from wildland fires in large parts of the world remains limited and prioritizes expediency in addressing this first-order deficiency. Additional problems of the "lumping" approach include the limited ability to reproduce spatial fuel arrangements found in the wild in the laboratory. This is especially true for tall fuelscapes, including fuel ladders [47].

Ultimately, the splitting approach—the detailed characterization of emissions at the fine scale of individual fuel constituents and their variation—will tell us much more than coarse-scale estimates using the lumping approach, enabling the prediction of changes to emission impacts as a function of changes in fire regimes and climate. As emissions-characterization research advances to produce more comprehensive inventories and analysis costs are reduced, and as fire models advance in their ability to ingest an increasing resolution of fuel constituents and combustion environments toward yielding more detailed emissions-products data, the splitting approach will become a more useful means to providing highly quantitative information on biomass combustion emissions. However, fine-scale emissions studies achieve their results at the expense of applicability across large areas; and we argue that the value of such an approach in supporting atmospheric science research at large spatial scales is presently subordinate to gaining a first approximation of representative emissions, and their variation, from areas where wildland fire emissions have the greatest impact on the factors mentioned above.

For the splitting approach to be truly useful for large fires, more knowledge on scaling issues [48,49] and on the interactions between multiple adjacent combustion processes is needed.

Here, we propose and present a prioritization of ecologically representative assemblages of wildland fuels, which below we refer to as wildland fuels, or simply fuels. These assemblages and their prioritization can be used for studies both utilizing the splitting and the lumping approaches.

#### 2.2. Total Emissions

The first step in determining whether a given fuel assemblage is important for emission research is, generally speaking, to determine the relative emission contribution of wildland fires in that assemblage to total wildland fire emissions. A logical first step is to choose candidate fuels from among a list of those whose combustion emissions are among the highest. These emissions occur in gaseous and particulate forms, and estimates of these emissions at regional to global scales are generally made using remote sensing techniques, often deployed from satellites for near-global coverage [50]. In these cases, emission estimates are provided on the basis of their origin at a range of spatial scales up to the subcontinental, e.g., the Global Fire Emissions Database (e.g., Global Fire Emissions Database; [51–53]); however, data on wildfire occurrence and land cover information allow these emissions to be assigned to a particular biome, land cover class [54], and, in some cases, even individual fires or clusters of fire activity in a particular ecosystem [55]. Emissions of one type measured remotely or directly can be combined with known fuel-based emissions factors [31] for ecosystems, biomes, or fuels, to provide estimates of a variety of emissions classes, such as C [56] or N [46], and entire satellite data archives refined with these data and modeling can be used to estimate continental-scale emissions over several decades [57]. Laboratory and small-scale field combustion experiments contribute to libraries of additional trace gases and particulate matter [58] that can be used to refine these estimates.

#### 2.3. Impacts

The impacts of emissions from wildland fires occur across the breadth of disciplines that consider fire, including human health, economics, biogeochemistry, and climate science. Within these disciplines, useful metrics for choosing important fuels include assessments of human health [32,59,60], economic impacts [61–63], and atmospheric radiative forcing potential of emissions [24,52,64,65]. Where information allowing quantitative comparisons of impacts may be difficult to obtain, substitute metrics might be considered. For example, the economic and human health impacts of wildfires may be more easily quantified for some areas than for others, and direct impacts are more easily estimated than indirect impacts.

Due to a lack of consistently detailed information on fire impacts, data on area burned [51,53,66] can provide useful indications of biomes and fuel types in which fires cause substantial impacts, especially when these data are combined with human population density [61]. However, these data generally are derived from orbital platforms [67], which can lead to inaccuracies resulting from cloud cover and limitations in detecting and characterizing smaller fires [68].

#### 2.4. Availability and Uncertainty

Emissions and impacts are obvious criteria in attempting to list and rank potential fuels for investigation. However, we propose that additional criteria, much less difficult to quantify, are important to include. One of these is the degree to which prior emission research has been undertaken for a particular fuel or fuel assemblage, or the existence of studies whose findings would complement emissions characterizations and expand understanding of a fuel and its role across atmospheric and other elements of fire sciences. This criterion promotes the possibility for further work to complete a characterization of a fuel or fuel assemblage begun by others, so that comprehensive studies, for a given landscape, already begun might thus be enhanced. As techniques for emissions characterization studies detailing the contribution of individual components within a fuel assemblage—progressing toward a

"splitting" strategy—these studies will provide important foundations and guidelines. We refer to this criterion as the availability of detailed emissions characterization research.

We further propose to include under this criterion opportunities that ongoing campaigns will provide to investigate emissions from wildland fires. Currently, one of the most significant of these is the Fire and Smoke Model Evaluation Experiment (FASMEE), which was developed to improve fire and smoke models using a series of large prescribed fires [12,13,69]. Other recent or ongoing campaigns, such as WE-CAN [70], and FIREX-AQ [71], can leverage information from laboratory or field-based biomass-emission studies, where fuels are explicitly identified and measured, and thereby both benefit from and contribute to the selection of specific fuels according to this criterion.

It should be noted that despite considerable progress in fire ecology, and the discipline's contribution to our understanding of fire impacts on ecosystems and non-human species, there does not yet exist sufficiently broad information on these impacts to support a robust global intercomparison of the fuels in the systems that have been examined. Added to this deficit is the difficulty of reconciling the negative ecological impacts of fire occurrence [72] or alteration in severity [73–75] with those related to its suppression, collectively considered as topics related to altered natural fire regimes. Owing to the results of studies in various well-characterized ecosystems, however, some fuels can be contributed for consideration in a list of important fuels. The purpose in doing so is to begin forming a comprehensive understanding of the multifaceted role of wildland fire, as it simultaneously influences vegetation, hydrology, atmospheric processes, and linked atmospheric-terrestrial cycles, such as carbon dynamics. Therefore, in addition to availability, we also propose that a situation can exist whereby the need for emissions data for a given fuel exists, but little or no prior work on such a fuel has been undertaken. We propose that uncertainty, for a given wildland fuel, can also create a need to prioritize that fuel for inclusion in future studies, and we therefore include it as a facet of this criterion.

#### 2.5. Potential for Future Importance

Anthropogenic and other changes in climate will continue to manifest as changes to wildland fire activity in many parts of the world through the 21st century [76–79]. These changes may be driven by increases in fuel amount via net primary productivity growth, fuel availability by changes to nighttime temperature and humidity and drought dynamics, changes to human land-use patterns, and lengthening fire seasons in areas where the onset of spring snowmelt and autumn snow govern fire activity. While climate change is likely to affect all global ecosystems to some extent, the degree to which climate change will alter fire activity, and the resulting impacts, varies at sub-continental scales [80]; see also [81] for a discussion of interactive climate, atmospheric CO<sub>2</sub>, and human population effects on emissions from wildfires. Acknowledging the absolute and relative values of projected changes to fire activity and impacts, under likely scenarios of altered climate, provides a way to identify fuels whose importance to biomass emission research will rise in the coming decades. We finally propose the inclusion of the potential for future importance as a criterion for selecting wildland fuels.

#### 3. Applying the Criteria

#### 3.1. Magnitude of Carbon Emissions

For recent and historical emissions of gases and PM, we used the Global Fire Emissions Database (GFED) [52], Wildland Fire Emissions Information System (WFEIS) [28], and the Global Fire Atlas [82], along with a number of recent studies on global and regional emissions from wildland fires as sources for information to produce candidate fuels for inclusion [64,83–99]. These resources differ in scope and scale: GFED provides global assessments of fire emissions using satellite data on burned area, vegetation productivity, and overall C emissions, as well as some trace gas and aerosol emissions, with specific emissions factors applied [27,58,100] to provide estimates of individual emission components at the subcontinental, biome scale. WFEIS uses burned-area maps from 1984 to the present, including the same Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data products on burned

area [66] as GFED, fuel loading (i.e., biomass) from the USDA Forest Service's Fuel Characteristic Classification System (FCCS) [FCCS, 9], and fuel consumption models from CONSUME [101] to produce emissions estimates by year for each of several different ecoregions for the Continental USA and Alaska.

Nearly  $1.5 \times 10^7$  ha of boreal forest may burn every year [34], representing 151-202 Tg of C emissions annually, compared with global averages of 936 Tg C from forests and 3950 Tg from global biomass burning [100]. Russia contains about two-thirds of the world's boreal forests [34], and 30% of the world's C is in boreal zone forests [102,103].  $1.2 \times 10^7$  ha of boreal forests burn in Russia annually [34], while Kasischke et al. [104] estimate  $4 \times 10^6$  ha burned in non-Russian boreal forests. Van der Werf et al. [52] estimated that during 2001–2009, most C emissions (44%) were from grassland and savanna fires, while an additional 36% came from fires in tropical forests and extratropical forest fires contributed 15%. Kasischke et al. [105] estimate average total C emissions were 106–209 Tg yr<sup>-1</sup> between 1995–2003 from boreal forests and high-latitude peatlands. An updated emissions intercomparison study by Andreae [58] found tropical forests and savanna-grassland fuels to contribute the highest amounts of total emissions from biomass fires in these ecosystems. These prior studies indicate a consensus for recommending wildland fuels from tropical forests, boreal forest ecoregions, high-latitude peatlands, and grasslands and savannas—especially African savanna fuels (due to the quantity of emissions from fires in these ecosystems [106])—for emissions research, as indicated in Table 1.

**Table 1.** Five examples of wildland fuels considered according to the "Magnitude of fire emissions" criterion. Fuels are listed with dominant or common global locations of occurrence, and information on total emissions (generally either total C or CO<sub>2</sub>, depending on source).

Fuel Type (Biome, Community, Source)	Location	Emissions <sup>1</sup>	References
Tropical Forest	S. America, Africa	$4670 \text{ Tg yr}^{-1} \text{ CO}_2$	[52,58,106]
Savanna/Grasslands	Sub-Saharan/Southern Africa	$3980 \text{ Tg yr}^{-1} \text{ CO}_2$	[52,58,82,83]
Boreal Forest	Russia, Canada, Alaska USA	$690 \text{ Tg yr}^{-1} \text{ CO}_2$	[34,52,82,100,105]
Temperate evergreen forests	NW USA/SW Canada	470 Tg yr <sup>-1</sup> $CO_2$	[52,58,100]
Peatlands	Russia; N. Europe, N. America, SE Asia	$270 \text{ Tg yr}^{-1} \text{ CO}_2$	[52,55,58,105]

<sup>1</sup> Where emissions from a given fuel are provided in multiple literature sources, the source supplying the figure provided in the table is listed first, followed by additional sources providing additional estimates or further information on combustion emissions from the fuel.

### 3.2. Impacts of Fire Emissions: Economic and Regional Air Quality and Public Health

Our consultation of published studies generated candidate fuels for inclusion based on impacts to economies, and regional air quality and public health (Table 2). These impacts result from the generation of large amounts of aerosols in proximity to human population centers, especially primary and secondary PM and  $O_3$  from NO<sub>x</sub> and VOC emissions [107,108]. These studies found large amounts of particulate matter (PM) emitted as a result of burning in temperate evergreen and boreal forests [31], and of  $O_3$  produced in regions comprising tropical forests and peatlands, grasslands, and savannas in sub-Saharan Africa, and boreal forests [108]. Acute health and economic impacts resulted from the emissions of fires in chaparral, eucalypt, and temperate evergreen forests; the impacts of wildfires in chaparral and eucalypt forests on human life and property is especially noteworthy in recent years in Australia, California USA, Spain, and Portugal [57,59,63,109–111], where eucalypt and chaparral-type vegetation communities dominate. A combination of high human population density in Southeast Asia and the production of high amounts of PM from fires in the tropical peatlands occurring in this region [112–114], mean that high impacts to air quality are associated with significant human health impacts from fires in regions of South America and sub-Saharan Africa dominated by tropical forests.

Fuel Type (Biome, Community, Source)	Location/Region of Impact	References
Tropical Forest	S. America, Africa	[20,52,58,106]
Savanna/grasslands	Sub-Saharan/Southern Africa	[20,52,58,83]
Peatlands	Russia; N. Europe, N. America, SE Asia	[52,55,58,105,108,112-114]
Temperate evergreen forests	NW USA/SW Canada	[52,58,100,109]
Mediterranean and N. American Chaparral	Mediterranean Europe; California USA	[59,60,63,110]
Eucalypt Forest	Australia; Portugal	[110,111]

**Table 2.** Examples of wildland fuels whose emissions cause sufficient impacts to air quality and public health to merit priority consideration for biomass burning emission research.

#### 3.3. Availability/Uncertainty

Comprehensive, detailed emission characterizations are available from a number of prior studies for several wildland fuels. These include several wildland fuels from North America: the Northwestern USA, Southwestern USA, and Southeastern USA coniferous forests; boreal mixed-conifer forests, and chaparral [27,118–121] (see also [30,31,45,122–134] for multiple examples of output from the Fire Laboratory at Missoula Experiment (FLAME) that resulted in the characterization of emissions from numerous fuels during successive campaigns). Considerable experimentation has occurred on smoldering combustion emissions in tropical and high-latitude peats, resulting in a rich library of information concerning peat soil combustion emissions across biomes [29,55,135–142], which can be combined with information on hydrologic and ecological effects [40,143–145], as well as laboratory studies of the physics and dynamics of smoldering combustion to achieve a multifaceted understanding of peat fire dynamics, impacts, and effects [146–150]. Thus, in addition to wildland fuels collected from tropical and high-latitude peatlands, commercial Irish peat is included in this list, because the level of prior characterization for this biomass fuel makes it akin to a benchmark for emissions studies in peat [151]. For similar reasons, emission research efforts also should focus on fuels from fires at the heart of large, coordinated campaigns such as FASMEE [13], WE-CAN [70], and FIREX-AQ [71]. In some instances (e.g., FASMEE), characterization of fuels in burn units is an integral part of study designs linking fuels, fire behavior, and smoke movement and chemical evolution [13]. In others, an emphasis on the airborne chemical measurements of wildland fire smoke means that more attention to the nature and characteristics of the fuels and combustion regimes that produce them will improve the applicability of results.

At the other extreme, application of emissions and impacts criteria may initially suggest a given fuel type which the literature surveys reveal to be poorly characterized, or even not investigated at all. Stockwell [152] highlights the problem of undersampled, yet globally significant, wildland fuels. Combined uncertainties in consumption and detailed emissions information imply difficulties in projecting fire impacts for some regions; these uncertainties appear to be particularly high in boreal forests [153,154]. Meanwhile, the widespread practice of wildland fuels mastication, meant as a means of reducing fire growth and risk in some areas [155], has led to the rapid development of a novel type of biomass fuel widespread in areas prone to wildland fires: fractured, relatively dense fuel particles whose tendency to undergo sustained combustion differs markedly from its original constituents [156]. Although fire behavior and effects in masticated fuels have been studied in the laboratory and field [157–159], the growing use of mastication as a fuels treatment combined with the tendency of treated areas to lie near population centers, and in regions where high population density and high fire activity coincide, indicate that this fuel type should be considered for future emissions research. Finally, in the USA prescribed fires are an important land-management strategy for maintaining ecosystems and reducing undesirably high fuel loads, and also constitute an important category of wildland fire. Furthermore, prescribed fires often are conducted in areas with significant human population density, such as the Southeastern USA, where the widespread occurrence of fire-dependent ecosystems also has led to considerable research on the effects of fire on their dominant

species and ecosystems. As a result of the high amount of  $PM_{2.5}$  emitted from these areas [97,120], the inclusion of these fuels is warranted, even though prescribed fires are anthropogenic in nature (and also consume wildland fuels, the focus of this effort). A summary of fuels for consideration according to either multifaceted characterization and availability of comprehensive information, or the existence of other non-emissions characterization that would be complemented by the investigation of these fuels in emissions studies, is listed in Table 3.

**Table 3.** Wildland fuels listed below have been well-characterized in regards to growth, behavior, and effects of fires, or in other aspects of their combustion emissions and, consequently, additional work for which may complete a comprehensive picture; alternatively, this list also includes fuels for which little emissions research has been carried out, but where other factors indicate a need for such work to be performed.

Fuel Type (Biome, Community, Source)	Location	Characterization Type	References
Boreal and tropical peat	Russia; N. Europe, N. America, SE Asia	Laboratory (Emissions); Field (Ecological)	[55,104,135–145]
Mixed-conifer	Northwestern USA; Southern Rocky Mountains/Wasatch USA	Laboratory (Chemical); Field (Physical, Ecological)	[13,30,119]
Commercial Irish Peat	Ireland	Laboratory (Physical)	[146-150]
Masticated fuels	Worldwide; N. America	Laboratory (Physical)	[155–159]
Southeastern ("Southern Rough")	SE USA	Laboratory (Physical, Chemical); Field (Physical, Chemical, Ecological)	[98,121,160]

#### 3.4. Future Potential

To apply our criterion of potential emissions, we used studies indicating the potential of certain regions to experience increases in fire activity corresponding to the likelihood of greater emissions or their impacts. In Table 4, we list five examples of fuels from regions where increases in fire activity or impacts are projected to occur. In general, changes to wildland fire activity projected for the next several decades are mainly due to factors related to climate change, with warmer and drier conditions leading to longer fire seasons, increased in area burned [161], and increased fuel consumption (and therefore greater emissions) for areas especially in mid- to high-latitude regions [79]. Notably, these regions include: (1) the western USA [76,77,162,163], comprising areas of conifer, mixed-conifer, chaparral, and shrubland; (2) Australia [164,165], comprising vast grasslands and eucalypt forests; and (3) boreal regions with their vast forests [33,34,166–169]. Ecosystems in these regions include peatlands which will be subject to increased fire activity and C release due to climate factors; peatlands in low-latitude regions are more likely to experience increased fire activity, due to anthropogenic factors, such as draining and swidden agriculture methods [170]. Peatlands contain between one-fourth and one-third of the world's terrestrial carbon, and when burned release the vast amounts of C that have been accumulated over centuries to millennia, compared to other fuels which represent C sequestered over years to decades [55,171–173]. As a result of their C pool size and age, and the potential for increased contribution to emissions in the future [174,175], it is therefore important to consider these fuels as well. Finally, the same anthropogenic factors likely to be responsible for increased tropical peatland fire activity are at work in the tropical forests of Africa and the Amazon [176–179], with their effects on fire activity, emissions, and impacts likely to increase [180–183]. Due to the vast area of these forests and the amount of potential C release from fires in these ecosystems, emissions work including fuels representative of the Amazonian and sub-Saharan rainforests will help to inform projections of future effects of their emissions on global climate, regional processes such as cloud formation, and public health in rapidly-developing cities and suburban areas of the global tropics.

Fuel Type (Biome, Community, Source)	Location	Type of/Reason for Projected Increase	References
Tropical Forest	S. America, Africa	Climate-driven fire activity; Land-use changes	[170,176–183]
Boreal and tropical peat	Russia; N. Europe, N. America, SE Asia	Climate-driven fire activity; Land-use changes	[79,174,175]
Boreal Forest	Russia, Canada, Alaska USA	Climate-driven fire activity	[33,34,79,166–169]
Mixed-conifer	Western N. America	Climate-driven fire activity	[26,76,77,162,163]
Eucalypt	Australia	Climate-driven fire activity	[164,165]

**Table 4.** Fuels whose contribution to total emissions, impact on climate, human populations, or regional or global processes is likely to increase in the future are listed below.

## 3.5. Results of Joint Application of the Criteria

When all criteria, discussed above for potentially selecting wildland fuels, are considered, a number of fuels are indicated as potentially important according to multiple criteria. Although quantitative comparisons across multiple criteria are impractical for a number of reasons, a simple means of compiling priority fuels is to consider those whose importance lies across multiple criteria. Table 5 summarizes the globally important fuels for biomass-burning emission research we have identified according to the criteria and information sources above and represents our generally recommended list of priority wildland fuels.

**Table 5.** The wildland fuels listed below represent the application of multiple criteria (Emissions, Impact, Availability/Uncertainty, and Potential).

Biome	Location	Criteria	References
Boreal Forest	Russia, Canada, Alaska USA	Emissions; Impact; Availability; Potential	[28,33,34,52,79,100, 102,104,105,166–169]
Peatlands (Boreal)	Russia; N. Europe	Emissions; Impact; Availability; Potential	[28,52,105,138,141, 143,144]
Peatlands (tropical)	SE Asia	Emissions; Impact; Availability; Potential	[112,115–117,138,139, 141]
Savanna/grasslands	Sub-Saharan Southern Africa	Emissions; Impact; Availability; Potential	[20,58,82,83,106]
Temperate evergreen forests	NW USA/ SW Canada	Emissions; Impact; Availability; Potential	[52,58,100,109]
Tropical Forest	S. America, Africa	Emissions; Impact; Potential	[20,52,58,106,170, 176–183]
Chaparral	California USA; Mediterranean Europe	Impact; Availability; Potential	[57,59,63]
Eucalypt Forests	Australia; California USA	Impact; Potential	[52–54,59,110,111, 164,165]
Southeastern ("Southern Rough")	SE USA	Availability; Potential	[16,98,119–121]
Masticated Fuels	W and SE USA	Availability; Potential	[155–159]
Commercial Irish peat	Ireland	Availability	[146,148–151]
FASMEE fuels	Utah USA; SE USA	Availability	[12,13,136,137,142]

#### 4. Discussion

Translating this list of proposed important fuels for wildland fire research to practice amid the reality of finite resources will expose the experimenter to the complex balance of achieving deep, statistically robust (i.e., well-replicated) datasets versus breadth (representation of the range of moisture levels, physical arrangement, and variations in composition), as described above.

By focusing attention on a relative few, important assemblages of wildland fuels, we expect that these findings will be useful in a number of ways. First, investigators or teams in the areas of atmospheric chemistry and physics lacking a strong background in wildland fire science may find value in our list, since previously there has been relatively little information, other than expert opinion, to guide the selection of wildland fuels for emissions studies. Second, a common list of important fuels may lead to the rapid accumulation of emission information to serve as a foundation for more detailed studies (splitting) within a broader fuel assemblage. Lastly, we hope that our proposed list of criteria stimulates debate and discussion concerning those factors that determine importance, and that our attempt to prioritize fuels for emissions studies may inspire similar efforts in other disciplines, in the same way that our work has been inspired by the efforts of Rothermel and other pioneers of fire science to classify wildland fuels.

Further, our experiences suggest that lacking a wider set of guidelines, the progress of wildland fire emission research is unnecessarily slowed while researchers occasionally work on some "clusters" of closely related fuel types, while leaving others, seemingly of importance, relatively ignored. It is our hope that a first attempt to move toward a widely-recognized list of high-priority wildland fuels will help increase the availability of globally important wildland fuels emission data, thus improving our collective ability to support large-scale estimates of the interactions of wildland fires with climate, the atmosphere, and human society.

#### Refining the Criteria for Future Use

Despite its initial appearance of simplicity, the question, "Which are the most important fuels to use for emission research?" easily becomes a difficult topic. This difficulty is partly due to the varying amounts and types of data that can be used in efforts to answer the question, while applying criteria as different in their nature as health impacts and radiative forcing is a strategy destined for contentious debate. In this effort, we have proposed a list of criteria by which the constellation of wildland fuels can be judged. While we deem those fuels selected in their application to be "important," we do so in full recognition that the criteria should vary according to the emphasis of a given study, even over time, such a list of criteria and the results of their application will differ with changing fire regimes, climate, and patterns of human population growth, as well as the perceptions and values that continue to shape humanity's ancient relationship with fire. A greater objective than the resulting list of important fuels above has been to propose a framework to unify fuels selection in fire emissions research, and it is in this area we hope our efforts will prove to be least ephemeral.

Previous investigations on the emissions from wildland fuels have cited model inputs for fire management, atmospheric smoke transport, and climate, or public health, as justifications; hence, a number of candidates have been implicitly introduced as criteria to be used in determining which wildland fuels should be chosen over others when devoting limited resources to the characterization and study of their emissions. However, to date, no explicit effort has been made to organize criteria that should be used for evaluating and prioritizing wildland fuels for emission research. We believe this effort is the first attempt to do so, and as with many such efforts, we acknowledge that the presentation of these criteria is likely to stimulate discussion, and perhaps disagreement regarding the ones we present here, and the proposal of new ones. These outcomes are among our intended outcomes from this initial effort, and we look forward to the further development of this initial effort by the wildland-fire emission community as this field continues to develop rapidly.

While a number of additional or alternative criteria for evaluating and prioritizing wildland fuels for emission research can be envisioned, we chose to keep the list of selection criteria to a relative few.

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One major reason to exercise care in the type of criteria chosen results from the variety of scope and scale of the various analyses and outputs available for use in applying these criteria: the differences between GFED and WFEIS indicated above, for example, could lead to selection bias in favor of fuels located in areas covered by a lower-area but higher-resolution analysis, for example, potentially resulting in over-representation from areas studied more extensively (for example, fuels and their emissions from North America appear extensively studied, compared to those from Africa.). Already, the criteria of human impact leads to relatively narrow geographic focus on eucalypt fuels from Australia or chaparral fuels from California, USA for example; the likelihood that others may identify other candidates that could have been chosen in addition or instead of these will illustrate the reasons for our choice.

## 5. Conclusions

For the near future, the cost and difficulty of characterizing emissions will continue to limit the ability of these studies to estimate the impact of the above factors and their variations on emission products. Over time, improvements to technology and ever-growing datasets will enable greater exploration of factors influencing emissions; this work will include not only such fine-scale factors as those above, but it will also allow for work on fuel assemblages (e.g., varieties of species compositions and architectures). Therefore, the work we present here—to identify schemes for prioritizing fuels upon which researchers should focus—should experience evolution, and each major development in this area should prompt the re-examination of both the criteria and fuels themselves. For instance, large campaigns integrating fuels and emission measurements from the field with laboratory work can drive especially rapid progress when they incorporate high-resolution information on fuel composition, characteristics, and links between combustion conditions and chemistry, e.g., [121,184]. Efforts by the research community to support such efforts by bolstering existing studies of emissions from their constituent fuels, and to provide comprehensive research on other priority wildland fuels such as those we propose here, will provide an accelerating influence.

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