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Original Article

Carbon in the Environment and the Characterization of Fire Regimes in the Past

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Abstract - The detection of carbon in ecological contexts has been used as an indicator of wildfire and forest fires, but its definition and characterization have been a problem, as it has been described by various terms, such as black carbon, charcoal, fusain, elemental carbon, soot, microcrystalline carbon, polymetric carbon, or graphite, etc. This paper is an effort to correct this situation. This research is focused on the comparison of terms for different forms of carbon found in the environment that might be associated with fire, as well as related aspects of changes resulting from, e.g., changes in the distribution of pollen or species (including animals) in regions of study. The variation in the use of terms complicates the understanding of the nature of fire in the past. In his definitive and comprehensive text, Edward D. Goldberg (1985) attempted to bring order and scientific discipline to the study of carbon in the environment. In recent years, a number of new techniques have been applied to this study, greatly expanding the contexts where carbon has been found and describing the processes involved in its production and the means of preservation and quantification. These advances have largely been made in the pursuit of discovering the history of ancient fire, yet at the cost of precise characterization of carbon from different contexts. In the context of current dramatic changes in fire intensity and magnitude, the nature of fire in the past is of great interest. This paper addresses this problem. A variety of terms are still being used to describe carbon in the environment. Carbon is generally considered now to be a marker or proxy for fire, rather than a result of other processes associated with the degradation of plant material (e.g., oxidation producing coal). This has affected ideas of wildfire in contemporary contexts.

Keywords - Carbon, Charcoal, Wildfire, Degradation, Preservation, Fire history.

1. Introduction

The current vast increase in fire intensity and extent has led some researchers to search past fire histories for the relationship between fire regimes and climate change. As most fire is produced by human agency, directly or by accident, current research has been focused on changing patterns of human attitudes toward fire over time and in relation to industrial and urban society (Chazan, 2017). The factor of past environmental contributions to fire regimes is central to understanding future regimes in climate change, and studies of the elements of these contributions depend on a difficult parsing of past evidence of fire (Wasserman & Mueller, 2023). The novel nature of my approach in this paper is to investigate the specific nature of fire evidence in the past and compare it to current theories regarding the preservation of this evidence and its interpretation.

The main objective is to point out deficiencies in the evidence and its interpretation. It has been argued that we should understand fire and climate in the past with more precision, the idea that climate change can be the major factor in the increase since the late 20th and early 21st century ignores the dramatic increase in human contribution to fire and to the creation of fire-adapted ecologies (Scott, 2020; Jones, et al., 2024). Several articles have been published reviewing the work done in the past 40 years on carbon in the environment, broadening our understanding since the publication of Goldberg's 1985 study. Most of these, like that by Galloway and Lindstrom (2023), focus on carbon presence and less on the chemical and physical nature of carbon and the context in which it is found. Some evidence places the increase in the past to begin in the Carboniferous (Scott, 2024). Fire, especially the way it introduces changes in both the thermal regime and the presence of water, has a number of chemical and biological changes.

New methods and instruments have been developed since 1985, which have sharpened definitions of fire evidence and the study of residues (Constantine & Mooney, 2021). Laboratory production of non-fire-derived charcoal aids in our understanding of carbon in paleoenvironments (Constantine et al., 2021a). Some of these rely on computer programs and algorithms designed from certain assumptions derived from empirical studies. For example, CharAnalysis has been relied upon to provide a basis for understanding the presence of different types of charcoal, as in primary and secondary (Galloway and Lindstrom, 2023). Many of these new methods have not lived up to their promise, as with CharAnalysis, where the data are being "overinterpreted" and where some of the assumptions on which the programs are built are supported (Anderson et al., 2022).

Nevertheless, new approaches and broader studies are producing a more specific understanding of the charcoalification process, especially in the study of different woods and temperatures (Braadhaart and Poole, 2008). As it is often the product of heat at temperatures below ignition, the preservation of charcoals in the fossil record is of great interest (Orvis et al., 2010; Mooney, 2011). Other complicating factors, including marine anoxic environments, associated metals, mold, and bacterial degradation, can turn wood black and mimic heat changes (Gao et al., 2018).

Ideas on biomass and wildfire generally argue a one-to-one relationship. More biomass results in an increased probability of fire and of an increase in fire intensity. The nature of biomass clearance is seldom discussed. There are several consequences to clearance. The most obvious is that which relates to the survival of animal life that depends on such vegetation not only for food but also for protection from predation. Increased soil heating is known to change local ecology (Qin et al., 2023; Tian et al., 2023; Xue et al, 2016; Nishar et al., 2017). Two other more significant aspects relate to wildfire directly. One is increased desiccation, and the other is increased heat and the lack of shade, which modify ground temperatures. These last two are significant in the distribution and variability of micro-environments that act to influence fire behavior once a conflagration grows in strength. Recent studies of the complexity of fire behavior are bringing new perspectives to the character of large fires (Beneduci and Mascali, 2024). The reduction of ground cover allows sunlight to act on areas for longer periods and with greater intensity. Measurements of recently cleared areas in Fairfax by workers directed by Firesafe agents showed an increase in solar radiation and heat gain to the thermal regime by 200 to 300% over previous measurements prior to clearing. Such increases have been reported in the past from cleared sites (Fowler & Helvey, 1981). Desiccation by increased exposure shows a very similar increase in drying, but also a concomitant effect of soil dissociation, which leads to increased runoff and erosion. Biomass removal and increased erosion are well studied in agricultural conditions (Pimentel and Krummell, 1987), as well as in forest conditions and natural areas (Kort et al., 1998). The unintended consequence of biomass clearing and prescribed burns appears to be increasing fire liability and increased erosion.

2. Determining Evidence of Fire in Past Environments

The nature of fire, or oxidation of organic materials, is determined by the source material that is consumed in combustion. This nature is constructed by the way organic materials are distributed in a mass of plant material, and the availability of oxygen to maintain combustion, a certain space for heat to be generated and combustion products to be carried off, and a limitation of moisture in either the substrate or the surrounding air. Without these characteristics of fire, the duration of fire and its temperature will be adumbrated. There have been reports claiming common fire regimes in tropical forests in the pre-Columbian period, but this is contradicted by more comprehensive work (Kaufmann and Uhl, 1990).

Table 1. Forms of carbon and carbon products of burning and various terms

Type of Carbon	Form	Product of	Particle Size
Particulate charcoal			
Charcoal* (A)			62-125um
Charcoal (B)			>250
Charcoal (C)			125-250um
PAH		<800C	
Pyro-PAH			
Alkylated PAH		<300C	
Black Carbon**		<800C	
Fusinite			
Semi-fusinite			
Structured fusain		>300C	
Glassy Carbon			
Amorphous carbon**			
Carbon dots			
Graphene			
Graphite			
Disseminated flake.	metamorphic		
Crystalline.	metamorphic		
Plumbago	metamorphic		
Amorphous.	metamorphic		
Carbon black++			
Coke+			
Lamp black***			

PAH: Polycyclic Aromatic Hydrocarbons. **amorphous or microcrystalline

Pyro-PAH: pyrogenic PAHs. *charred material blackened by fire (Zepp & Macko, 1997); **Black Carbon, a component of charcoal that is a fire-derived, highly aromatic to graphic carbon fraction (Kuhlbusch and Crutzen, 1995). ***a fine powdered soot from the incomplete combustion of carbonaceous materials. +a solid carbonaceous residue from low ash, low sulfur bituminous coal with carbon and ash fused together. ++graphitic carbon, often referred to as soot.

The variation of fractions of vegetable matter produced by fire in the environment is considerable, affected both by local conditions, including temperature and wind conditions, as well as the nature of the biomass burning and the temperature grade of the fire over the period of combustion. Zepp and Macko (1997) pointed out that the products of smoldering fire or low temperature fires include fatty acids, waxes, and alcohols, and that their transport into the atmosphere takes place by distillation at temperatures around the boiling point of water. This results in a lower pyrogenic signal (Zepp and Macko, 1997) but more of a biogenic signal. This causes a chemical problem of distinguishing between biomass that has been released and transported in association with dusts, discussed by Simoneit et al. (1977) and Gagosian et al. (1982/9 and those compounds emitted through the steam-distillation mentioned by fires (Zepp and Macko, 1997). Their analysis concluded that black carbon was the result of hot flaming fire, with about 80% remaining on the ground and 20% emitted with smoke. It is also resistant to microbial decay. However, microbial decay was suggested to explain the lack of significant samples earlier than the Pliocene (Goldberg, 1985).

Natural sources include volcanic eruptions, petroleum seepage, and smoldering coal deposits (Abdel-Shafy and Mansour, 2016). This presents both an opportunity and a problem as anthropogenic fire produces PAHs as well (Laflamme and Hiles, 1978) and since the invention of fire some 400,000 years ago (Caldararo, 2002) and the acceleration of the use of fire for hunting as the population increased significantly around 50,000 years ago and again with agriculture and sedentary life around 10,000 B.P., the differentiation of PAHa can only certainly be distinguished by distribution in the locale and context of fire and soil effects (Fowler and Helvey, 1981).

Some analyses have differentiated between PAHs on the basis of chemical source. Hutes et al. (1980) found that two types of PAHs could be identified in sediments from anoxic core samples. One type is derived from pyrene and chrysene and is associated with anthropogenic conditions, and a second type from natural sources such as retene and perylene and concentrated in lower sections of cores. A significant issue is the nature of fusain or fusinite and semi-fusinite. It has been identified with degradation by a number of avenues of plant matter, as well as evidence of slow oxidation or burning in paleoenvironments (Goldberg, 1985; Skolniok, 1952). Many recent authors have considered the issue closed and assigned fusinite forms to burning alone (e.g., Galloway & Lindstrom, 2023). This may relate only to structured fusains that retain cell wall, charcoal-like features (Goldberg, 1985).

Yet one has to consider whether the experimental conditions to study charcoal and carbon in non-combustion contexts can adequately simulate natural conditions. As the chart above demonstrates, there are various terms for carbon in the environment, and yet “charcoal” is usually considered a man-made product of pyrolysis, burning in anerobic conditions. Usually, those in favor of a man-made invention of charcoal point to remnants of plant structure in “charcoal” samples, yet this is typical of fossil carbonized plant remains termed “coal.” This is found especially in “peat bogs,” and variations can be related to the specific conditions of carbonization, depth in strata, heat, and pressure being the most important factors determined by Hilt’s Law, though variations have been noted (Sivak et al, 2008). Other fossilized remains of plant life and trees, especially, were usually ignored in the study of fire in the past. For example, silicified remains and “petrified trees” noted by Darwin (1839) in profusion in Chile, provide an additional source of information. Like other non-carbonized forms, and those that are not mineralized, like the so-called mummified wood and other plant tissue, these provide a common source of information on the evolution and distribution of plants (Mustoe, 2023, 2018).

One problem with this conclusion is that while residues like fusain and other fractions of coal can be produced experimentally by combustion, no experimental efforts have been applied to attempting to produce them by natural non-fire conditions. Harris (1958) created an early scheme to differentiate bituminous wood from charcoals based on a number of criteria, including morphology, condition, and chemical reactions. However, as with other coal deposits of various forms (e.g., coal balls, petrified peat, see Schoff, 1970), there is a lack of clear evidence of forest fire that can be extended over large areas of deposits and typifies the features we refer to today as “wildfire.”

Methods to correlate different forms of carbon in slides with pollen, sections in stratigraphic contexts, lake contexts, and other evidence considered of fire are difficult (Clark, 1988). If wildfire were so frequent and intense as is sometimes assumed, even in Harris’s (1958) view, we could hardly have found historic deposits of coal so extensive and massive. This conclusion appears apparent from comprehensive tests of samples from a variety of types of fossilized plant remains in different stages of oxidation and contexts (Leo and Barghoorn, 1970; Scott, 2024a). Schopf (1975) argued that the presence of charcoal could not be a single evidence of forest fire, as other biotic processes, for example, the stages of peat formation, can produce similar products. This relates not only to factors like atmospheric oxygen, moisture, and temperature, but also to the amount of plant biomass consumed by animal life (including microbes) and how much it contributes to the fossil carbon concentrations. It is obvious that fire is one factor, but it seems unreasonable to assume that it is a major factor (Glasspool and Gastaldo, 2024 and 2024a).

3. Historical and Paleontological Evidence

Studies of historical fire and strata from periods of climate change and significant die-offs related to transitions of life forms, as at the K/T transition (also known as the Cretaceous–Paleogene boundary or the Triassic–Jurassic extinction event, indicate peaks of carbon assumed to be associated with massive fires produced by volcanism or asteroid hits. But before and after these events, measurement of carbon demonstrates background carbon forms and stable conditions of fire evidence (Belcher et al., 2010). These represent extraordinary ignition events. Their association with massive amounts of vegetation that were under substantially dry conditions due to climate change is considered likely by some researchers (Belcher et al., 2010) or extraterrestrial events like asteroid hits.

The relationship between climate, biomass, conditions of ignition potential, and faunal reduction is poorly understood. I reviewed this problem in an earlier publication, but one element, biomass regrowth and reburn, especially as it relates to prescribed fire as a prevention, should be considered in light of fire size and speed. The recent Park Fire in Butte County, California, has burned over substantial areas (approximately 40%) that were reburned by the Camp Fire (2018) (Johnson, 2024). It is logical to assume that much of the biomass produced at any one time would be consumed or digested in one manner or another by animal sources.

Although dendrochronology usually refers to the science of dating sites by the use of tree rings as yearly indications of growth, variation of moisture and precipitation as well as temperature, it has been utilized to identify and date fine in prehistoric periods. The study of damage to trees as recorded in tissue repair has been taken over by fire research scientists as a modification of the dating role of dendrochronology (Gutsell and Johnson, 1996). These researchers have claimed that all scars found in trees are the result of fire, thus the term "fire scar." However, Caldararo's own study (2002) and that by Sutherland (2016) show that many forms of trauma produce tissue damage and repair in trees usually identified only as the result of fire. Gursell and Johnson (1996) also reported that fire scars only occur at certain heights in trees, yet this is contradicted by Caldararo (2002) and Sutherland (2016).

4. Chemistry, Imaging, and Definitions

As shown in Figure 1, carbon can be found to take a number of different forms related to conditions of its integration and organization in life forms, and or mineral accumulation, or the situation of burning. Discriminating between these forms and identifying their sources is still a challenge (Conedera et al. 2009). Other transformations can occur in particular contexts, as in the atmosphere, where these changes can take place in a gas phase or a particle phase (Atkinson et al., 1990). Some forms are created at very high temperatures, for example, glassy carbon and some other "amorphous forms" that are primarily crystallographic and mechanical in nature and lack "long-range crystalline order" (Uskokovic, 2021), that is, a regular pattern that repeats itself over the entire crystal. GC demonstrates a planar 2-dimensional structural element with all atoms sp2 hybridized and randomly distributed, and with dangling bonds present somewhat like amorphous carbon, but sharing more characteristics with amorphous graphite, except for its high temperature production. Another form is that of "carbon dots," which are of ultrasmall size and possess unique physicochemical properties. GCs are stable and resist graphitization, which requires high heat over several thousand hours. Rosalind Franklin was probably the first person to discover GCs in 1950, reporting a result of an experiment with a form of coke with a metallic lustre. It is known in a natural form as a Precambrian bituminous mineraloid called 'shungite' (Inostranzeff, 1880). This forms under high-grade metamorphism, while s form under lower-grade metamorphism (Jehlička & Rouzaud, 1992; Molak et al., 1998). All mined graphites today formed from metamorphism of carbonaceous sedimentary rocks (Robinson et al., 2017) and are found in the lower continental crust (Glover, 1996). In general, PAHs are also stable but can undergo catalytic hydrogenation under vacuum conditions (Cruz-Diaz et al., 2020) and yet are considered to be common in interstellar areas (Allamandola et al., 1987). Considerable differences are apparent in different forms, as between the Raman spectra of Natural graphite and glassy carbon. Alkylated PAHs persist longer than the parent PAHs they are produced from (Qian et al., 2022), though the pyrolysis of almost any organic compound can produce PAHs. The nature of the compound and the combustion conditions affect PAH yield and transition (e.g., PAHs to alkylated PAHs, see Neff, 1979; Zeep and Macko, 1997). This emphasizes the fact that PAHs are generally intermediate hydrocarbons and their chemistry depends on a number of factors (Smyth and Miller, 1987). The potential for masking the effects of fire by differences in deposition, preservation, and the partitioning of PAHs to vegetation can affect interpretation (Simonich and Hites, 1994).

Graphite is a naturally occurring form of stacked carbon layers, often referred to as a mineral form of carbon. It appears in a crystalline form of rings of six carbon atoms arranged in widely spaced horizontal sheets, thus in a hexagonal system as opposed to diamond, which crystallizes in an octahedral or tetrahedral system. However, Pauling (1970) refers to the two allotropic forms of carbon in nature in their elementary state as diamond and graphite. Both are crystalline, but some forms are imperfect, as in bort and black diamond (carbonado), which do not show the cleavage of diamond. Both possess a lower density than diamond and are rougher and harder (Pauling, 1970). Graphite has been formed by metamorphosis of sediments which contain carbonaceous material, that is, plant material, by the reaction of carbon compounds formed with hydrothermal solutions or by magmatic fluids. It is possible that it has also been formed by the crystallization of magmatic carbon. It appears in strata as masses or veins with crystalline gneiss, schist, quartzite, clay slates, and a variety of other materials. Other useful forms of industrial carbons include Graphene, produced from graphite by the Scotch tape technique. Carbon nanotubes can be produced at high temperature in carbon/transition metal combination similar to Buckminsterfullerine and fullerine structure as single or multi-walled nanotubes and have been found in coatings from fired ceramics produced in 2,600 B.P. old archaeological sites (Kokarneswaran, 2020). Buckminsterfullerine is the most common form of fullerine, which is naturally occurring with a fused-ring structure made of 20 hexagons and 12 pentagons with each of 60 carbon atoms bonded to its 3 neighbors. Fullerines are allotropes of carbon (different forms of carbon, diamond is one form) whose molecules are carbon atoms forming a mesh joined by single and double bonds, making forms as spheres, tubes, etc. Fire context is the most important element in our understanding of the extent of fire in paleo and ancient environments. Conedera et al. (2009) have made the most comprehensive examination of this issue. Where they find a lack of elements in a geological context, they have proposed "proxies" or substitutes that they consider to be useful to construct fire regimes in the past Conedera et al., (2009).

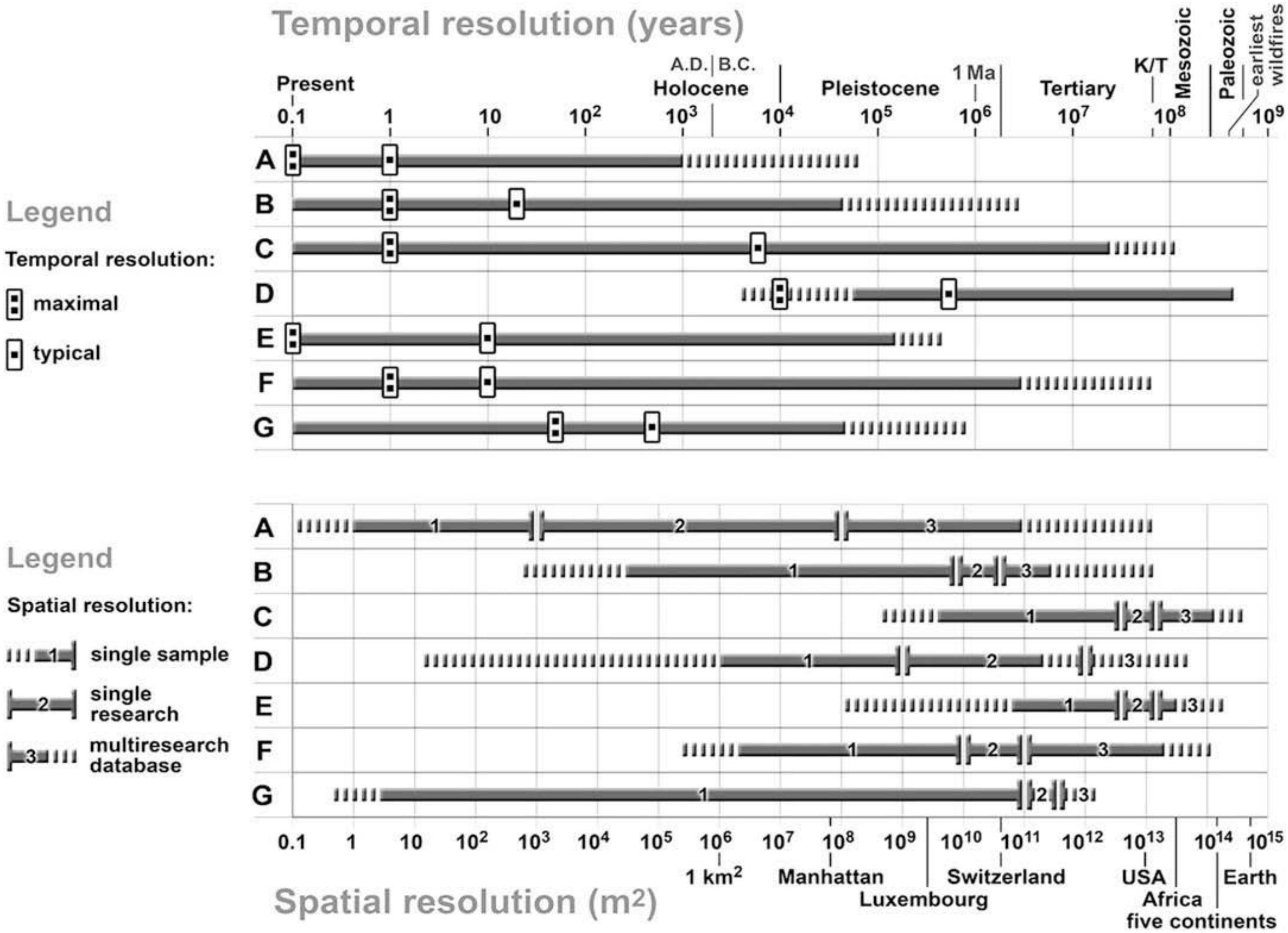

Fig. 1 Temporal and spatial resolution achievable with different approaches to fire history (Conedera et al., (2009))

A: dendrochronology and fire scars analysis; B: charcoal in lake sediments and peat bogs; C: charcoal and black carbon in marine sediments; D: fossil charcoal (fusain, fusinite) in sedimentary rocks; E: chemical markers and black carbon in ice cores; F: pollen-based fire history reconstruction; G: charcoal and black carbon analysis in soils.

Solid bars indicate the most common range, whereas dashed bars show the farthest extensions of the range. Modified from Delcourt and Delcourt (1991) and Swetnam et al. (1999), Conedera et al. (2009. Separate out charcoal and black carbon vs fusain and fusinite, assigning the latter to a fossil charcoal classification in sedimentary rock, while most researchers consider much of fossil carbon to be found in metamorphic rock (e.g., Goldberg, 1985). Also, note that studies of carbon in the environment have utilized different methods, and their comparability is difficult to achieve. The same applies to a variety of "proxies," including changes in plant life, animal species, and erosion. This is related to what Goldberg (1985) described as the difficulty of assigning source material to carbon compounds, as the temperature of formation in isotopic exchange reactions influences isotopic ratios. The other issue, mentioned above, is that PAHs can be produced by a number of mechanisms, some of which, such as heat without fire, were investigated in the early 1970s but have received little attention since (Zepp and Macko, 1997).

5. Conclusion

The information presented in this paper has been concerned with the varied conditions of the residues of fire in the geological and archaeological records. This review has argued that these residues, especially PAHs, are produced under varied conditions, including, but not limited to, fire. Oxidation of organic compounds and chemical interactions can be sources. Also, the conditions for preserving evidence of wildfire in these records are variable. While the proxies Conedera et al. (2009) do give an idea of possible fire in both antiquity and geological contexts over the past half billion years, they are only indicative and do not establish proof of the extent of fire or intensity. Their work is a major advance in our understanding and should be extended as they describe.

The same caution should be applied to suggestions of fire in indigenous contexts, as detailed in Caldararo's 2002 paper. Where we have good evidence of fire in these cases, it is in locations where Native peoples' diets and ecological relations have been modified by European contact and/ or the development of complex social adaptations like agriculture. More research and testing are needed. And just as we cannot attribute with confidence the current increase in size and intensity of wildfires to climate change or human activity and economic conditions, we cannot mandate certain methods of housing modifications without scientific studies as they can, suggest to many people that they can stay in their homes if they just produce an ad hoc "defensive space" that might endanger their lives and not even save their homes. However, the idea of defensive space is under question in this regard (Syphard and Keeley, 2019; Syphard et al., 2021). A certainty of the nature of biomass fuel and ignition has taken on a dominant position in forest and wildland fire policy. This has resulted in an increased use of prescribed fire, even while it is evident that this can produce more fire and contribute to fire-adapted landscapes. It has also promoted changes in forest management, for example, thinning, which is also unproven in its effects. Other factors are ignored due to their political sensitivity, as in the cases of limiting or stopping building in the urban/wildland interface or limiting human activities in forests and wildlands, both in recreation and commercial activities, especially logging (Levine et al., 2025).

Abbreviations

1. um as in millimeter, and by convention in 1959 also mm as micrometer
2. B.P. as in Before the Present
3. PAH. As in polycyclic hydrocarbons
4. K/T as in Cretaceous and Triassic
5. GC. As in glassy carbon
6. C as in Celsius

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