by Michael I. Bird

Fire in the earth sciences

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The earth sciences has a major role to play in elucidating the links between fire, humanity and the global environment. Currently, this emerging area of research is hampered by a lack of agreed definitions for the carbonaceous products of biomass burning, and a lack of agreed analytical protocols which make it impossible to directly compare the results of individual studies. With an appropriate suite of chemical and instrumental techniques in place, it will be possible to start untangling the complicated linkages between fire, climate, vegetation and humans.

As long as there has been reduced carbon, sufficient oxygen and a source of ignition, there has been fire. For many years earth scientists have reported evidence of fire in the geologic record, from the earliest occurrence of fusain in sediments of Devonian age to geochemical evidence of 'global wildfires' following a meteorite impact at the K/T boundary (Wolbach et al., 1988), to records of fire incidence inferred from charcoal abundance in marine and lacustrine sediments (Herring, 1986; Kershaw, 1986). The importance of fire in the modern world has been graphically demonstrated in recent months by the catastrophic fires which swept through the forests of Indonesia and Malaysia in the wake of an El Niño induced drought.

In the last decade, fire has received closer attention from many sections of the scientific community, including the earth sciences, following recognition of the role that anthropogenic 'biomass burning' plays in increasing the levels of greenhouse gases such as CO₂ in the atmosphere. Currently, one third of anthropogenic CO₂ emissions to the atmosphere are thought to derive from biomass burning sources, mostly from burning of forests and savannas in tropical regions. There is a certain irony in the observation that the tool which has underpinned the rise of *Homo sapiens* from stone-age to space-age, now also underlies a major threat to the global climate system from both fossil fuel combustion and anthropogenic biomass burning.

The link between humanities' ancestors and fire goes back at least 1.4 million years, as evidenced by the presence of stone tools, smashed animal bones and clay baked to several hundred degrees at Chesowanja in East Africa (Gowlett et al., 1981). While such evidence does not prove that homonids had the capacity to make fire at that time, a new find of intact hearths in Brittany does suggest that fire was actively being used by *Homo erectus* by at least 400,000 years ago (Monnier, et al., 1994). Determining the antiquity of humanities use of fire is important for two reasons: (i) there are implications for human social evolution because, as quoted by Balter (1995) "If they're (*H. erectus*) just burning meat to stuff in their mouths, they're a different kind of animal than if they're sitting around a fire talking while they do it", and (ii) through the acquisition of fire as a tool, humans gained a potent agent for environmental change.

The latter of these two is of relevance to the earth sciences, as it is only through an understanding of how fire regimes have evolved in response to 'natural' climatic forcing prior to any possibility of human influence, that we can hope to understand the degree to which

the imposition of anthropogenic fire regimes in the more recent past may have led to modifications of 'natural' ecosystems. Such information is of particular importance in view of the fact that there is a sound theoretical base for expecting fire-related changes in vegetation patterns to affect at least regional climate/paleoclimate (Shukla et al., 1990; Xue, 1993). This is because the type of vegetation cover is an important determinant of parameters such as albedo, moisture balance, rainfall, temperature and the length of the dry season.

In the case of Australia, for example, the imposition of an anthropogenic fire regime following Human occupation is considered by some researchers to have resulted in a massive alteration of vegetation from pyrophobic vegetation types such as *Casuarina* and *Araucaria* to the pyrophyllitic eucalypt-dominated ecosystems which cover much of the modern landscape (Singh and Geissler, 1985; Kershaw, 1986). In the words of Pyne (1991)—"With fire, the genus *Eucalyptus* and the genus *Homo* had a common cause and shared a common future" (p.21).

Several researchers have suggested that humans have been able to substantially modify their environment through the use of fire since pre-historic times (e.g. Emiliani et al., 1991; Miller and Magee, 1992; Bird, 1995). Such a view is not universally shared (e.g. Horton, 1982), and the impact of prehistoric anthropogenic burning on the landscape remains a contentious issue, largely because of a paucity of information on the nature of fire regimes before human occupation.

While the study of fire in the modern environment falls mainly within the ambit of ecology and atmospheric chemistry, the earth sciences has an important role to play in providing and interpreting long term fire histories both to determine the effect of large scale (glacial-interglacial) climate changes on fire regimes, and to provide a baseline against which to compare modern fire regimes. The earth sciences can also provide a measure of the importance as a global carbon sink of the carbonaceous products of biomass burning, and their role in the global carbon cycle. In both these cases, robust methodologies are required to be able to quantify the abundance of carbonaceous particulates produced by combustion, and the remainder of this paper attempts to outline the current status of research in this area.

'Elemental carbon' in the geologic record

Biomass burning produces a range of carbonized particulate materials known by a variety of terms including charcoal, soot, black carbon, fusain, microcrystalline graphite or elemental carbon. There is a comparably wide range of definitions for this material based on crystallography or chemical composition, or on its susceptibility to either thermal or chemical oxidation. In the discussion below, the term elemental carbon (EC) will be used as a general name encompassing all forms of carbon produced by combustion/pyrolysis.

While the first attempts to measure elemental carbon abundance in sediments were made in the 1970s (Smith et al., 1973), more recent recognition of the importance of being able to accurately measure EC abundance in a range of sample types has led to an upsurge of researchers working in the field. This interest has also led to a proliferation of techniques for measuring EC in soils, sediments and

aerosols. While this is a positive development, there are two major problems which will need resolution before reliable and unified progress can be made by the field as a whole:

Definition and measurement of EC

As noted above, EC is a continuum of compounds with a wide range of compositions that rarely approach the ideal of pure carbon with a graphitic structure. This means that most studies define EC according to the technique used in the study, and unfortunately there has been virtually no effort as yet, to compare results obtained using techniques or to formulate a standard set of techniques to ensure that results produced by different researchers can be reliably compared with each other.

A survey of the available techniques is presented in Table 1. In general, the techniques can be categorized into thermal oxidation, chemical oxidation or particle counting. A detailed analysis of the benefits and limitations of all techniques is beyond the scope of this paper, but it is worth making some general statements:

The particle counting techniques have the advantage of being able to 'see what you are dealing with', but do not measure the total EC content, only particles greater than a nominal size. It is not easy to discriminate between particles carbonized to varying degrees, and

it is also not possible to assess the possibility that particles may decompose or disaggregate over time to particles which are too small to be counted.

The oxidation techniques have the advantage of being able to measure EC of all particle sizes, but as is the case with the particle counting methodologies, do not measure total EC as some EC will inevitably be oxidized during the treatments. This is because the oxidation techniques operate on the basis that organic carbon will oxidize at a much faster rate than EC, such that only EC is left after a nominated duration of oxidation. As an example of the discrepancies which can arise using different oxidation techniques, Verardo and Ruddiman (1996) concluded that up to 90% of carbon in marine sediments in the equatorial Atlantic off Africa were EC, while Bird and Cali (in review) found an order of magnitude less EC was present in sediments a similar distance off the coast of Africa in the equatorial Atlantic on the Sierra Leone Rise. Both studies measured EC according to their definitions, but obviously were not measuring the same component of EC. Resolution of this discrepancy is important because one of the implications of the high EC contents reported by Verardo and Ruddiman (1996) is that EC burial in marine sediments is a major carbon sink. Further implications also flow on into all studies which attempt to estimate palaeoproductivity based on the

Table 1 Summary of techniques used for the determination of elemental carbon

study	pretreatment	oxidation	measurement	$\delta^{13}\text{C}$?	material
chemical techniques					
Skjemstad et al. (1993, 1996)	sonication/sieving	UV photo-oxidation	NMR, coulometry	no	So
Emiliani et al., (1991)	CD/SD	KOH/H ₂ O ₂ R.T., 24hrs	combustion / MS	yes	Se
Rose (1990), Odegaard (1993)	CD/SD	KOH/H ₂ O ₂ 55°C, 48hrs	particle counting	no	Se
Smith et al. (1973), Smith (1975)	CD/SD	KOH/H ₂ O ₂ R.T.	pulverising /IR spectr.	no	Se
Herring (1985)	CD/SD	KOH/H ₂ O ₂ R.T.	pulverising /IR spectr.	no	Se
Winkler (1994)	CD	hot HNO ₃	stepped combustion / MS	yes	Se
Verardo (1997)	CD	hot HNO ₃	gas chromatography	no	Se
Wolbach and Anders (1989)	CD/SD	Cr ₂ O ₇ /H ₂ SO ₄ , 50°C	weight loss / titration	yes	Se
Reullan (1996)	CD/SD	Cr ₂ O ₇ /H ₂ SO ₄ , 55°C, 72hrs	coulometry	no	So
Bo Lim and Cachier (1996)	CD/SD	Cr ₂ O ₇ /H ₂ SO ₄ , 55°C, 60hrs	coulometry	no	Se
Bird and Grocke (in press)	CD/SD	Cr ₂ O ₇ /H ₂ SO ₄ , 60°C, 72hrs plus KOH/H ₂ O ₂ 60°C, 8hrs	combustion / MS	yes	Se,So,Pl
'counting' techniques					
Clark (1988), Clark & Hussey (1996)	thin section prep	nil	particle area in thin section	no	Se
Kershaw (1985, 1986)	CD/SD	H ₂ O ₂	counting grain mounts	no	Se
thermal techniques					
Kuhlbusch and Crutzen (1995)	solvent extraction	thermal, 340°C, 2hrs	GC/mass-balance		Pl,Ae
Cachier (1989), Cachier et al. (1989)	filtration, CD	thermal, 340°C, 2hrs	coulometry	yes	Pl,Ae
Chylek et al. (1987, 1995)	filtration	stepped thermal 100-700°C	manometry/transmissivity	no	Ae
Fearnside et al., (1993)	determine biomass	burn biomass	weigh before/after	no	So,Pl
'proxy' techniques					
Venkatesan and Dahl (1989)	solvent extraction	nil	GC-MS of PAH's	no	Se
Killops and Massoud (1992)	solvent extraction	nil	GC-MS of PAH's	no	Se

note: CD = carbonate dissolution; SD = silicate dissolution; MS = mass spectrometry; GC = gas chromatography; PAH = polycyclic aromatic hydrocarbon; NMR = nuclear magnetic resonance; IR = infra-red; R.T. = room temperature; So = soil; Se = sediment; Pl = plant; Ae = aerosol

assumption that most of organic carbon in marine sediments is of marine origin.

Even if only those techniques based on acid-dichromate oxidation listed in table 1 are considered, it can be seen that while the same reagent is used in all the studies, the reaction times and temperatures are not consistent between studies, making it impossible to directly compare the results. Bird and Grocke (in press) further found that a series of EC standards produced from different plant materials and treated under identical conditions in acid-dichromate solution, oxidized at very different rates depending on the density and surface area of the original EC particles.

When dealing with changes in EC abundance in the sedimentary record, all techniques suffer from the fact that the transport of EC to the eventual site of accumulation is a complicated process affected by factors such as the efficiency of EC production at the site of burning, particle size effects on transport and variations in the intensity and direction of the transporting winds (e.g. Clark and Hussey, 1996).

Stability of EC in the environment

For measurements of EC abundance in the geologic record to have any meaning, the material must not be susceptible to significant degradation following burial. In the earth sciences it is generally considered that EC is inert, and that after it is produced it may be physically transported, but does not undergo significant chemical transformation. This contrasts strongly with the view held by archaeologists that at least in tropical environments charcoal does decompose on geological time scales (e.g. Yellen, 1986).

Given that EC is actually a continuum of combustion products, the assumption that EC is truly inert cannot be strictly correct, and it has not been adequately demonstrated that any component EC is truly inert. In reducing conditions such as characterize most marine sediments, EC may be relatively stable (Herring, 1986), possibly because reactive components are metabolized prior to burial, however this same stability may not be the case in oxidizing conditions such as pertaining in soil profiles and some terrestrial sedimentary sequences.

A recent study of a savanna plot in Zimbabwe that has been protected from fire for the last 50 years Bird (unpubl data) found that a significant proportion of EC is no longer present in the surface soil, compared with surrounding burnt savanna sites. There is also carbon-isotope evidence that large charcoal particles are gradually broken down into smaller particles and ultimately either being illuviated into deeper parts of the soil profile, oxidized by photochemical or biological means, or possibly translocated into the humic acid fraction of the soil carbon pool (Haumaier and Zech, 1995).

The conclusion that EC is not stable in oxidizing environments is supported by qualitative evidence from Australia which suggests that charcoal is commonly absent or sparse in the deeper levels of many archaeological sites, even though the sites were occupied during the deposition of the EC-poor levels, and higher in the same deposits EC is abundant (R. Jones pers. commun.).

The above statements must be considered speculative at this stage, but do reflect the very poor state of knowledge concerning the fate of EC in the environment and the pathways by which EC may in fact continue to be actively rather than passively involved in the carbon cycle after its formation. An example of where this knowledge becomes important is in the determination of EC abundances in soils. Skjemstad, (1986) has suggested that a significant component of many soils is EC (up to 30%), and that if EC in soil profiles is not taken into account, then the amount of 'active' carbon in the soil maybe considerably over-estimated. This conclusion is predicated on the presumption that the EC is actually inert, and while on shorter time-scales this may be reasonable, it has yet to be demonstrated that this is true on decadal time-scales.

Conclusions

The growth of interest in EC in recent years testifies to its importance in a variety of spheres of environmental research of relevance to the earth sciences, but like any emerging field, research efforts are currently disjointed and disparate. The current problems of definition and consistency in measurement can be addressed by inter-comparison of techniques using standard samples, with a view to subsequent standardization on one or more agreed analytical protocols. The addition of H/C and C/N ratio measurements as well as carbon-isotope measurements (^{13}C and ^{14}C), can potentially facilitate a much greater understanding of what is actually being determined as EC by different techniques, as well as the source of that material. The concern as to the degree to which EC is 'inert' can be addressed by carefully designed field and laboratory studies.

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Hutchison 'Young Scientist' Fund

William Watt Hutchison, "Hutch" to his many friends around the world, was a Scots-born Canadian geologist who served Canada and the IUGS in myriad dynamic and creative ways. Most notably, he served as the IUGS Secretary General (1976-1980) at a pivotal time in its history, and as IUGS President (1984-1987). The same boundless energy, enthusiasm, skill in communications, and ability to foster teamwork that characterized his work with the IUGS also carried him to preeminent scientific administrative positions in the Canadian Government, where he served as Director General of the Geological Survey of Canada and as Assistant Deputy Minister of Earth Sciences. His distinguished career was terminated in 1987 by his untimely death at the age of 52, following a painful struggle with cancer.

One of Hutch's last wishes was to establish under IUGS auspices a memorial foundation intended to promote the professional growth of deserving, meritorious young scientists from around the world by supporting their participation in important IUGS-sponsored conferences. The first 3 beneficiaries of the Hutchinson "Young Scientist Foundation" attended the 28th International Geological Congress (IGC) in Washington, D.C., in 1989.

Currently, income earned as interest on the Hutchison fund is insufficient to sustain comparable grants every four years without seriously eroding the principal. For that reason, the IUGS made no grants from the fund for the 30th IGC, preferring instead to strengthen the fund by allowing it to earn interest for a longer period of time and by appealing for donations from the international geologic community. It is expected that grants from the fund will again support deserving young scientists to attend the 31st IGC in the year 2000. The Hutchison "Young Scientist Foundation" is a worthy cause that honors a fine, caring man and a distinguished, public-spirited scientist and administrator. The foundation also celebrates and promotes those things that gave Hutch the most professional satisfaction: geology, international scientific collaboration, and stimulating young minds.

The IUGS welcomes contributions to the Hutchison "Young Scientist Foundation." Please send donations to:

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