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Abstract

The nature, dynamics, and policy-relevance of the charcoal sink of biomass burning on the Australian continent were investigated. In a manner analogous to the decomposition of plant biomass and the formation of humus, biomass burning has the potential to generate a sink for atmospheric CO_2 by the production of refractory charcoal. While both compounds are resistant to biodegradation and thus long-lived, the analogy is not exact. From the instant of formation, charcoal is highly inert whereas the humus fraction of soil carbon is generated only as a metabolically resistant fraction that slowly accumulates after repeated cycles of decomposition and by physical protection by clay complexation. Thus, with respect to the quality of carbon sinks, newly formed charcoal is more stable than newly formed soil carbon.

The quantitative aspects of charcoal were addressed by modelling the charcoal production rates of contemporary biomass burning, which included redistribution and residence time, then inferring continental pool size. The modelling employed, while probabilistic, was simple and transparent with the predictions tested against available field measurements.

Biomass burning on the Australian continent was divided into four fire types, Managed and Unmanaged forest fires, (tropical) Grassland fires, and the Clearing fires of converting woodlands to crops and pastures. Statistical descriptions of burned area for each fire type over an 18-yr period were used to calculate charcoal production rates. The median annual charcoal production rates for the four fire types were 0.14, 0.13, 5.6, and 1.9 MtC yr^{-1}, respectively. The tropical grasslands, which currently experience the most extensive annual burning, are also the largest source of charcoal. The median charcoal production for all fires types aggregated was 8.3 MtC yr^{-1}. This is equivalent to the sequestration of ≈ 30MtCO_2 yr^{-1}, or 8.5 % of Australia's 1990 baseline CO_2 emission rate.

Predictions were made of the charcoal abundance and variability in the 0-1 m profile for the tropical grasslands and agricultural lands based on the last 5000 yr of burning. For validation, these predictions were tested against two sets of field measurements for the agricultural lands, and one for the tropical grasslands. For the agricultural lands, the predicted median charcoal abundance was 29 tC ha^{-1}, and the agreement with the two sets of field measurements was good but with a consistent model over-prediction of 30 %. For the tropical grasslands, the predicted median charcoal abundance was 8 tC ha^{-1}, and here the agreement was excellent. The calculated charcoal pool sizes for the agricultural and tropical grasslands were 2 GtC and 1 GtC, respectively.

The characteristics of soil carbon and charcoal were compared as operational carbon sinks within a hypothetical version of the Kyoto Protocol. The characteristics were origin, nature, dynamics, sequestration rate and carbon cost, and verification and compliance. In terms of stability (security) of the carbon sequestered and of the carbon costs involved, charcoal appears a superior sink to that of soil carbon. In terms of rates of sequestration of recalcitrant carbon and its verification, charcoal and soil carbon are equivalent as sinks. A significant point is that a large charcoal sink is currently in operation as part of contemporary land management. Considering only the tropical grasslands, the location of the most extensive burning, this charcoal sink is sequestering carbon at an estimated median rate of 5.6 MtC yr^{-1}, equivalent to ≈ 21 MtCO_2 yr^{-1} or 6 % of Australia's 1990 baseline CO_2 emission rate.

Introduction

We begin with a summary of the phenomenon of biomass burning. At the instant of burning, the biomass (fuel) carbon exposed to fire has three possible fates: it is either volatilised to carbon dioxide (CO_2) and numerous other minor gas species, or it is carbonised to (pyrogenic) char, 'charcoal', or 'black carbon'. These carbonised particles are deposited on the soil surface or are incorporated in the particulate phase of smoke. The third fate is that the biomass remains unburned. The predominant fate is volatilisation with the last fate, unburned, being uncommon.

The second fate of the fuel carbon, carbonisation or incomplete oxidation, is the focus of this report. Carbonisation produces char, a diverse mixture of carbon structures that range in complexity from graphite-like carbon to high molecular weight aromatic rings, most of which are highly resistant to physical and chemical decomposition and are known to persist in soils for thousands to millions of years (Kuhlbusch and Crutzen, 1996; Skjemstad *et al.*, 1996). It follows that the more resistant to decomposition these compounds are, the longer they will persist in soils or sediments. Such long residence times could result in a char carbon sink. Furthermore, because the source of the carbon was atmospheric CO_2, which was converted to carbohydrates and other carbon species by the plant process of photosynthesis, this char carbon pool represents a sink for atmospheric CO_2.

The above core argument – that carbonisation of a small fraction of biomass carbon produces inert carbon compounds with long residence times that have the potential to generate a carbon sink - is qualitatively indisputable because the mechanisms invoked are well known. No matter how paradoxical it may seem, biomass burning has the potential to generate a sink for carbon from the atmospheric CO_2 pool into soil and sediment pools. This argument is not original having been proposed decades earlier, possibly initially by Seiler and Crutzen (1980) and subsequently refined by Kuhlbusch and Crutzen (1995, 1996), Kuhlbusch *et al.* (1996), Kuhlbusch (1998a) and Schmidt and Noack (2000).

The challenging uncertainty of the core argument resides with its quantitative aspects: under what circumstances can the char sink potential be realised, what is the size and persistence of the char sink, and where is it located?

The objective of this document is to explore these uncertainties, to present a summary assessment of the nature, size and dynamics of the biomass burning char sink for the Australian continent. The motivation is to inform two separate audiences. One audience comprises the national and international policymakers who carry the responsibility for mitigating enhanced greenhouse effect (EGE) climate change. Given the objective of minimizing the increase atmospheric concentrations of greenhouse gasses (GHG), especially those of carbon dioxide (CO_2) and methane (CH_4), members of the community of nations accept and execute an annual prescribed accounting of carbon emissions (sources) and sequestrations (sinks) (Keenan, 2002). This mutually agreed prescription for accounting correctly focuses on the largest single source of greenhouse gasses, CO_2 from fossil fuel burning, and on other anthropogenic sources and sinks only. Non-anthropogenic (biogenic) sources and sinks of CO_2 and CH_4 are excluded. The proscription of biogenic sources and sinks can be criticised because the distinction between anthropogenic and biogenic sources and sinks of GHG is not sharp (Winiwarter, 1999) and it detracts from the real goal of stabilising GHG whatever their source, not just complying with a mutually agreed set of rules. At time of writing, early 2003, the char sink of biomass burning is not accepted as a carbon sink within the internationally agreed accounting rules.

In this report, we argue that the attributes of the char sink are such that it should be considered for inclusion in the agreed accounting of carbon sinks. Our argument is an extension of the core argument presented above. Biomass burning generates a relatively inert form of carbon that is subsequently incorporated within soil organic matter or buried within sediments. The longevity, size, and dynamics of this carbon sink appear to rival other sinks currently accepted, such as those of plant biomass or soil carbon that are the consequence of dedicated landuse and management activities. Furthermore, this pyrogenic carbon sink is a direct result of biomass burning, and in Australia, for example, the overwhelming proportion of biomass burning, whether measured by area or biomass consumed, is an integral part of contemporary or traditional land management. Therefore, the carbon sink is effectively anthropogenic in origin and presumably eligible for consideration by the international community. A similar situation exists in many nations with tropical savannas.

The second audience for this assessment is the research community that is interested in the size and dynamics of the soil organic carbon (SOC) pool. In abundance terms, char is a significant contributor to the total SOC pool, particularly in Australia where it averages ≈ 25 % over all soil types. The dynamic behaviour of the char fraction differs sharply from that of the other components of the total SOC pool because its physical and chemical properties confer very much larger residence times than that of the other components. These differences become particularly significant in the forecasting of SOC futures under different land management systems using multi-compartment models, such as ROTHC (Coleman *et al.*, 1997; Skjemstad *et al.*, 2001).

As will be demonstrated, the qualitative or mechanistic aspects of this analysis of the char sink are robust. In contrast, the quantitative components – how much and where – are less certain, principally because of the paucity of field data for the Australian continent. Our strategy in generating this assessment is to first consider the qualitative aspects – that biomass burning is a carbon sink – and then address the quantitative components by considering the size and dynamics of this sink. Where addressed, quantitative uncertainty is transparently treated.

Carbon chemistry of biomass burning

Two dynamically interacting biogeochemical carbon pools are the atmosphere, of size 750 GtC, and the biosphere, the terrestrial plant biomass with a size of 560 GtC (Schlesinger, 1997). The chemistry (but not the energetics) of the principal interchange of carbon can be simply and generally written thus:

$$CO_2 + H_2O \leftrightarrow CH_2O)_n + O_2 \qquad (1)$$

Carbon enters the biosphere via plant biomass from the atmosphere as CO_2, through the reductive process of photosynthesis, the forward reaction of equation (1). The generic chemical composition of most plant materials, such as carbohydrates, cellulose and lignin, can be simplified as $(CH_2O)_n$ and it is thought that the process of photosynthesis has been on Earth for approximately 3.5 Gyr (Nisbet and Sleep, 2001). The reverse reaction is respiration (metabolism) where carbon-containing compounds are oxidized to CO_2 and H_2O. This occurs either within the plant biomass itself (autotrophic respiration), which accounts for ≈ 45 % of carbon fixed by photosynthesis, or within the bodies of biomass-feeding organisms, such as fungi, bacteria, and animals (heterotrophic respiration), which accounts for the remaining 55 % of carbon fixed. This continuous and reciprocal flow of carbon through photosynthesis and respiration provides the mass and energy flux upon which the biosphere is structured.

It follows from equation (1) that any persistent difference in relative photosynthetic and respiration rates will result in changed carbon pool sizes, either biospheric or atmospheric. Over geological timescales, there have been huge changes in this balance. The largest of these began with the Carboniferous period (350 My BP) when there was a very large increase in the global biomass of land plants, especially in freshwater swamps, with a simultaneous sequestration of atmospheric carbon from the atmosphere into the biosphere. Then with changing geological conditions globally, this biospheric carbon pool was buried and subsequently transformed to coal and other kerogens that currently serve as the principal source of fossil fuels (Schlesinger, 1997).

Now, considering the release of carbon from biomass by respiration: if some $(CH_2O)_n$ compounds have physical or chemical properties that resist metabolism by decomposing organisms, then they will accumulate. One example on geological timescales is the biopolymer lignin, a component of wood. When it first appeared as part of the invasion of land by plants that began in the Devonian period (400My BP), it accumulated and consequently influenced global atmospheric oxygen concentration because it was not readily metabolised (Robinson, 1990, 1996). A similar and more dynamic situation exists with the humus fraction of the SOC pool. Humus is a mixture of compounds that are highly resistant to decomposition by organisms. Humus is a major fraction of total SOC, accumulating in the deeper sections of the soil profile where it is additionally protected from bacterial oxidation. Essentially, the largest component of the soil carbon store is a metabolic residual – bacterial and fungal detritus – that for most plant communities represents a carbon pool several fold larger than that of the litter and standing biomass from which it was ultimately derived over millennia (Schlesinger, 1997).

The metabolic component of equation (1) is more completely written as:

$$(CH_2O)_n + O_2 \rightarrow CO_2 + H_2O + C_{humus}. \qquad (2)$$

The residual humus carbon pool is denoted by C_{humus}. The significant points to be made here are that metabolic inertia confers longevity in the soil such that the humus fraction eventually becomes the major component of the SOC pool. In addition, the SOC pool is one focus of effort to sequester atmospheric CO_2 into the biosphere, and which currently enjoys international approval.

We now draw a parallel between humus and pyrogenic char. In terms of their intrinsic chemical potential for sequestering atmospheric CO_2, they are analogous rather than homologous. The chemistry of biomass burning can be simplified as a unidirectional process, thus:

$$(CH_2O)_n + O_2 \rightarrow CO_2 + H_2O + C_{char}. \qquad (3)$$

Plant compounds are oxidized (at high temperatures) to CO_2, H_2O and carbonised to a residual char (C_{char}), Figure 1 and the Frontispiece. The proportion of fuel carbon that is converted to char is determined by the combustion conditions, a mix of physical conditions and chemical activity that lies between the ends of flaming and smouldering combustion - see Graetz (2002).

In overall carbon terms, biomass burning and respiration/decomposition compete for biomass. Furthermore, from equations (2) and (3), the overall consequences of biomass burning are qualitatively equivalent to those of respiration, in that plant biomass is oxidized leaving only a small residual, which accumulates because it is biochemically inert. Thus, the two phenomena differ only in their respective rates of change, biomass burning being very much faster than decomposition. However, in contrast to photosynthesis and respiration, which is at least 3.5 Gyr old, the phenomenon of biomass burning is much, much younger. A prerequisite for fire on land was fuel, i.e. the invasion of the land by plants, and the first fossil records of burned plant material (fusain) occur in the late Devonian period, approximately 380 Myr ago (Robinson *et al.*, 1997). Thereafter, the fossil record of biomass burning increases with increasing plant biomass (fuel, type and amount), and sources of successful ignition (lightning) until the domestication of fire by members of the genus Homo approximately 1.5 Myr ago (Pyne and Goldammer, 1997). It is currently estimated that most of the landscape fire on Earth is anthropogenic, and that this proportion is increasing (Dwyer *et al.*, 2000).

Figure 1: The passage of a grass fire front in northern Australia illustrating the amount and location of char production. It is obvious that while most of the (dry) grass fuel is burned, there is an equally obvious layer of char left on the surface of the soil and on green unburned vegetation. The black smoke plume contains material convected from the surface as well as soot formed by gas-to-particle conversion.

Terminology

Before we begin substantiating the core argument of this report, it is essential that we first declare and define the terminology used. The nomenclature of the many carbon compounds formed during biomass burning is unsystematic and thereby confusing. The principal reason is that such carbon compounds have been a focus of research within the disciplines of geology, archaeology, and atmospheric chemistry for a century or more. Consequently, a number of terms were generated and used in the literature to identify various products of fire and heating. These terms are confusing because the same term may refer to different materials in different disciplines. To address this difficulty, Jones *et al.* (1997) proposed a unified nomenclature based on physical and chemical properties, and the relevant (edited) definitions are reproduced in Table 1.

The definitions in Table 1 are informative but insufficiently exact because the products of incomplete combustion form a continuum in chemical and physical properties from partially charred plant materials to fully graphitised black carbon particles. The assigning of boundaries is therefore arbitrary. Nonetheless, the five fire products of interest here are charcoal, black carbon, ash, soot, and smoke.

Table 1: A selection of definitions of fire-affected carbon compounds selected from a larger list compiled by Jones *et al.* (1997).

Fire–altered	Plant material that has had its chemical composition altered because of heating in a fire (pyrolysis). Organic carbon is progressively decreased in the residue with increasing combustion efficiency, leaving non-combustible mineral matter.
Black carbon	A fire-derived polymeric, aromatic to graphitic carbon fraction in fire-altered material or smoke particulates. It absorbs radiation, and is highly resistant to biodegradation and chemical oxidation.

Charcoal	Any black-coloured plant-derived material that has had its chemical composition and ultrastructure significantly altered as a result of heating in a fire, and retains recognizable anatomic structure of the parent plant, even if only in a fragmentary form. For example, secondary wood that is chemically altered has homogenized (previously-stratified) cell wall ultrastructure, but retains its three-dimensional anatomical structure.
Ash	The mineral-rich powdery residue remaining on-site after a fire.
Smoke	All visible matter emitted by a fire, comprising visible gases, volatiles, and smoke particles.
Soot	Particles emitted with smoke and formed via gas phase processes; gas-to-particle conversion. Particle size ranging from sub-micrometer (mainly) up to less than 1.0 µm.

In the beginning of this report, we used the words ‘pyrogenic char’ and ‘black carbon’ because they are evocative and thus helpful to the reader unfamiliar with this topic. The char obvious on the soil surface in Figure 1 is a mixture of two principal types of compounds formed during the carbonisation process identified in Table 1 above. These are charcoal and black carbon, and their properties are compared below.

Charcoal

Charcoal is derived from plant material that has had its chemical and ultrastructure altered by heating. Shafizadeh (1984) showed that at ≥ 400°C, plant material undergoes considerable chemical change with carbohydrate structures being converted to fused aromatic ring structures with the loss of carbon dioxide/monoxide and water. The fused aromatic rings form basic structural units of three or four graphitic layers randomly organised in charcoal, or may form soot, spherical ‘onion-like’ particles, in the gaseous phase of smoke (Schmidt and Noack, 2000). The graphitic structures are not true graphite, i.e. an exclusively-carbon crystalline allotropic polymer, because they contain elements, such as oxygen and nitrogen. These elements permit the formation of other functional groups within the graphitic structures, such as carboxyl groups and heterocyclics (Skjemstad *et al.*, 1996; Knicker and Skjemstad, 2000). Despite this significant chemical rearrangement, plant anatomical detail, such as cell walls, phytoliths, and conducting vessels, remains largely intact and identifiable - see Figure 2.

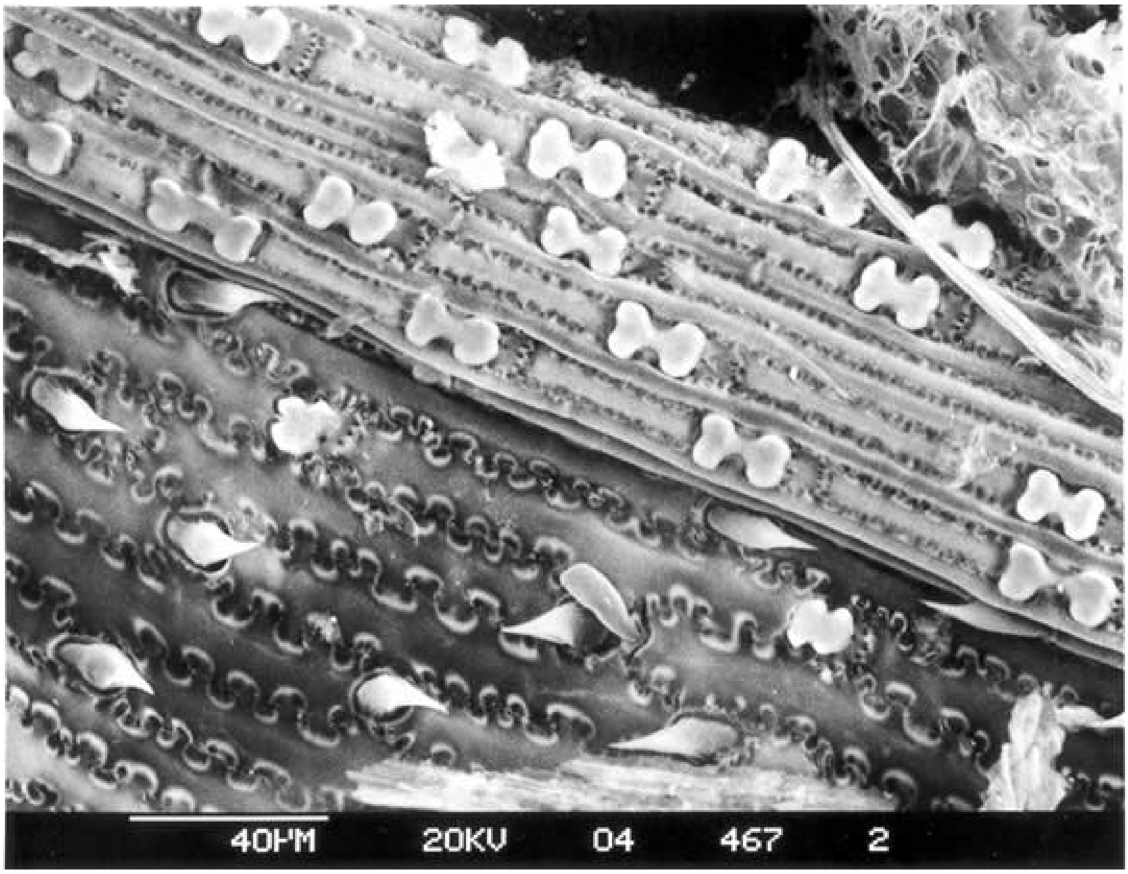

Figure 2: A scanning electron micrograph of tropical grass (Sorghum sp.) charcoal illustrating the residual, detailed cell wall structure, preserved in part by the pervasive presence of silica. Note in particular the extracellular dumbbell and spike-shaped bodies, phytoliths, which are mostly opaline silica. This plant silica, which is unaffected by burning, is later used to calculate the carbonised fraction of the fuel biomass.

Black carbon

As illustrated in Figure 2, one of the physical properties (morphology) of charcoal particles can easily be interpreted in terms of plant cell anatomy. However, based on the defining chemical description given in the previous paragraph, the presence of graphitic structures, the term charcoal also includes the black carbon fraction as defined by Jones *et al.* (1997). Black carbon (BC) particles have very different physical properties from charcoal: they are smaller, spherical or in grapelike clusters, and retain no plant structural features. Black carbon is a component of both surface charcoal and the smoke plume where it is also formed in gas phase chemistry (Kuhlbusch, 1998a, b). Black carbon is a subject of considerable interest to atmospheric chemists and climate modellers because its physical characteristics determine its optical properties. As a globally ubiquitous aerosol, black carbon strongly absorbs solar radiation. This influence on the atmospheric radiation balance is estimated to contribute about 15 – 30 % of contemporary global warming (Jacobson, 2001). Like charcoal, black carbon is of interest to carbon modellers because of its chemistry, the graphitic-like structures that confer chemical inertia and thus low biodegradability.

Usage

To make clear our intended definition, we recap the core argument presented at the beginning of the Introduction. At the instant of burning, one of the fates of the biomass (fuel) carbon is to be carbonised remaining either as a black residue on the soil surface, or being formed in the gas phase of the smoke and later precipitated. This carbonised fraction of the fuel carbon was formed under limiting oxygen concentrations, and comprises a diverse range of compounds. The term **char** is used to refer to this diverse range of carbon compounds.

Some of the char may be susceptible to degradation by abiotic agents, such as ultraviolet radiation (UV), or far more likely, decomposed by microorganisms. The size and fate of this labile component is also of interest in this report. *That which remains unaltered by virtue of its resistance to chemical change will be a mixture of charcoal and black carbon*. The chemistry of these two materials is almost identical, and because only chemistry can currently be used to quantify abundance, we are currently unable to measure the size of their separate contributions. However, based on expert assessment that charcoal is predominant over black carbon, from this point on in the report, we will use the one word, **charcoal**, *to designate the mixture of two chemically inert carbon compounds that collectively contribute to the carbon sink of biomass burning*. In contrast, European scientists favour the term black carbon (BC) to describe chemically recalcitrant carbonised compounds formed during biomass burning; see, for example, Kuhlbusch (1996, 1998a) and Schmidt *et al.* (2001). The terminology differs but the essential chemically inert pyrogenic carbon compounds referred to are the same.

Char, charcoal and carbon

In terms of mass, char and charcoal are not all carbon. In the field, the carbon mass fraction of char is determined by the fuel type (grassy versus woody) and by the burning conditions (fleeting or prolonged). For grassy fuel, the bulk of the char residue is ash (mostly silica) such that the carbon content is low, 10-30 %. After separating the charcoal from the char, the carbon mass fraction of charcoal is much higher: for grassy fuels, it is usually ≤ 65 %, whereas for wood charcoal, the fraction is in the range 70-80 %. The highest charcoal carbon contents, ≈ 80 %, are found in the soot formed in the smoke plume of grass fires; see Table 2 of Kuhlbusch (1998b). The non-carbon mass in charcoal is almost all oxygen, with a trace of nitrogen both of which are integral parts of the carbon structures. The carbon mass fraction becomes an important consideration in the issue of burning efficiency that is dealt with later.

Biomass, char and charcoal

Figure 3 illustrates a proposed relationship between the carbon pools discussed above, as well as a quantitative indication of their importance. On burning, more than 90 % of the biomass carbon is instantly volatilised to CO_2. The char residue on the soil surface is a mixture of carbon compounds reflecting the variation in comprehensiveness of pyrolysis. The less complete is the pyrolysis, the more labile will be that char fraction. Even so, because of its physical properties, this labile char fraction is still far more resistant to biodegradation than the unburned biomass. On timescales of tens of months, this labile fraction is metabolised by microorganisms, a process that is not yet well understood. Because of its chemical inertness, the charcoal fraction containing charcoal and black carbon remains. Subject to redistribution, the charcoal fraction is incorporated into soil or sediments where it can persist for millennia. At whatever rate, the ultimate loss of charcoal from these buried pools is suspected to be mostly via microbial or chemical oxidation processes. This process is also not yet well understood but charcoal cannot be truly inert because historic and contemporary production rates would soon lead to charcoal as the dominant form of carbon in almost all soils and sediments. We will return to this issue.

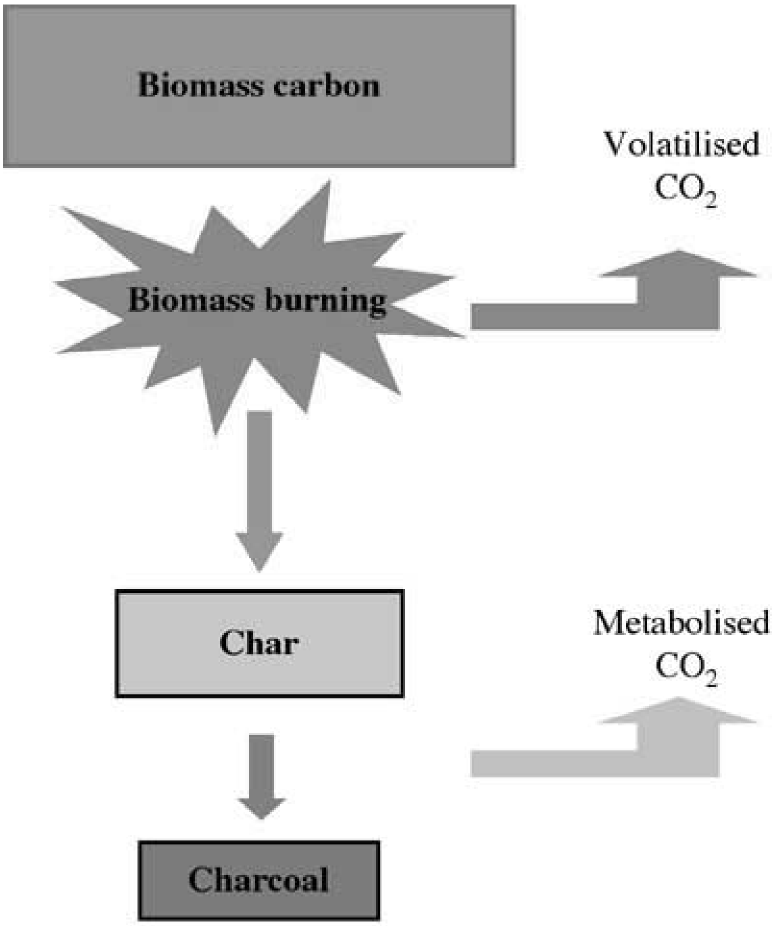

Figure 3: The flow of carbon from the biomass fuel through the pools identified in the above text. The size of the boxes (pools) and flows (arrows) is only indicative.

Formation, transport and deposition

Setting aside the labile component of char and considering only the core components of charcoal and black carbon, we note that while chemically very similar, their physical differences significantly influence their post-fire fate. These two components are compared across the processes of production, transport, and deposition in Figure 4.

Charcoal and black carbon are formed during pyrolysis, the temperature-driven chemical decomposition of the fuel. Both are formed at the surface under conditions of flaming combustion (high temperature and oxygen concentration) and smouldering combustion with lower temperatures and reduced oxygen levels - see Schmidt and Noack (2000). The formation of black carbon is favoured over charcoal during flaming combustion, and vice versa – see Kuhlbusch and Crutzen (1996). Black carbon is also formed in the plume of heated gases immediately above the fire by complex free radical chemistry that results in gas to particle conversion, thus contributing a black colour to smoke - see Schmidt and Noack (2000). Soot is the common name for the black carbon particles so formed with a size range of ≤ 1.0 µm from biomass compared with ≤ 50 µm from fossil fuels. Biomass burning smoke particulates comprise black carbon, small charcoal fragments, as well as unburned or partially charred plant material convected aloft in the plume, Figure 4. Depending upon particle size and circumstance, both charcoal and black carbon may be widely transported from the fire site by wind and water, or interred locally. Charcoal from grassy fuel is easily macerated by wind and rain to particle sizes comparable with that of black carbon formed in the smoke plume. Carbonaceous aerosols from biomass burning are globally ubiquitous (Cooke *et al.*, 1999). The profiles of charcoal deposited in ocean sediments or the cryosphere can be interpreted in terms of historic burning events. As examples, the charcoal profiles in million-year old ocean sediments demonstrate burning episodes that can be connected with the advent of the genus *Homo* in Africa (Bird and Cali, 1998, 2002). On historic time scales, Holdsworth *et al.* (1996) used ice cores from the Yukon and Greenland spanning 1850-1910 to document the episodic burning event that was the Pioneer Agricultural Revolution in North America.

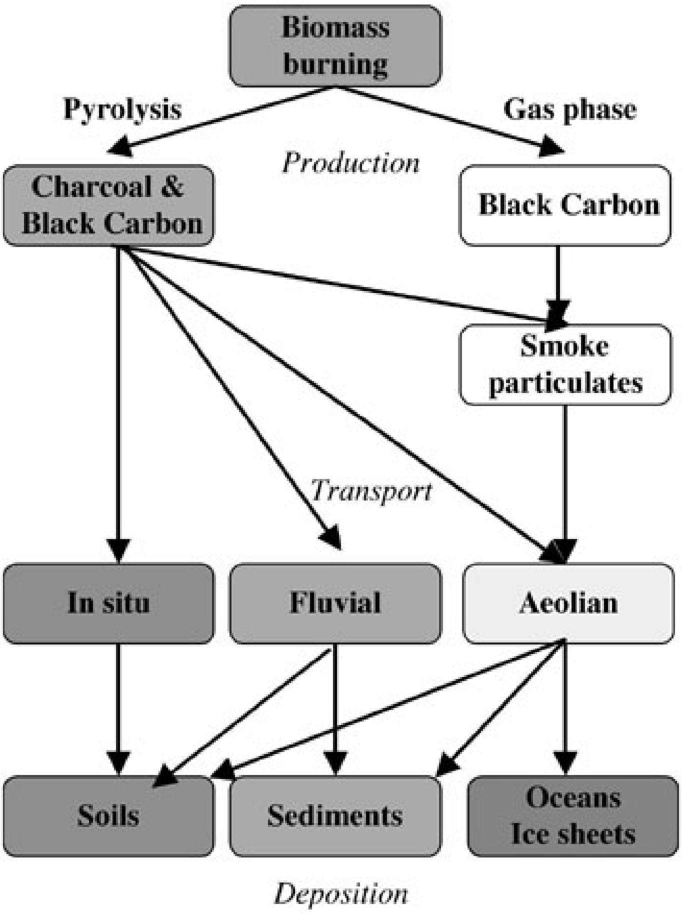

Figure 4: The production of charcoal and black carbon, and its transport and deposition post-fire, after Kuhlbusch and Crutzen (1996). Both components of char can be widely distributed, particularly black carbon formed within the smoke plume which, as an aerosol is globally ubiquitous. Charcoal and black carbon can be found in soils, freshwater and marine sediments and in the cryosphere. Diagram box size is not indicative of flux or mass.

Orienting questions

The argument presented in the Introduction has two parts. The first is this qualitative argument: In a manner analogous to the decomposition of plant biomass and the formation of humus, biomass burning has the potential to generate a sink for atmospheric CO_2 by the production of refractory charcoal. The second quantitative part is the objective of this report: to substantiate the potential of charcoal as a carbon sink by addressing the issues of how much, how long-lived, and where is the sink?

Consequently, this report is structured by the following questions.

1. How can charcoal be measured?
2. How to quantify the charcoal pool size and dynamics for the continent?
3. What is the production rate of charcoal?
4. What are the policy implications of our findings?

The measurement of charcoal

Laboratory

Regardless of from where the samples were harvested, soils, sediments or ice, the determination of the charcoal content will also be primarily a laboratory measurement. Despite the relatively simple chemical structure of charcoal, products of incomplete combustion form a continuum from partially charred plant materials to fully graphitised black carbon particles, Table 1. Methods of analysis, therefore, have proven difficult to develop with different methods often determining different components of this continuum depending upon the disciplinary interest. Many methods for quantifying the abundance of charcoal in a sample have been proposed. Such methods include the optical/microscopic methods of the palaeo-environmental disciplines (Rhodes, 1998; Figueiral and Mosbrugger 2000), or thermal and chemical based laboratory methods. Optical methods rely on the characteristic morphology and sometimes lustre of charcoal pieces. This widely used technique is reliable only for charcoals of large particle size (> 5 µm) as are typically found in archaeological studies. For charcoals of smaller particle size, such as are commonly found in soil samples, they can be difficult to identify and therefore to reliably estimate using microscopy (Schmidt and Noack, 2000).

Thermal analysis methods rely on the relative stability of charcoal to heat in an oxidising atmosphere compared with other natural forms of carbon. Thermal separation may be preceded by chemical extractions to remove interfering species (Kuhlbusch, 1998b). Chemical methods rely on oxidation of charcoal structures to recognisable chemical units (Glaser *et al.*, 1998) or the selective removal of other forms of carbon leaving only the charcoal material that can then be estimated. These methods rely on the use of oxidising acids such as nitric (Verardo, 1997) or chromic acid (Bird and Gröcke, 1997) or high-energy ultraviolet photo-oxidation (Skjemstad *et al.*, 1996, 1999a). Other rapid indirect methods using Fourier transform infrared spectroscopy (FTIR) are also being developed (Janik *et al.*, 1998). Schmidt *et al.* (2000) compared a number of these techniques and found that the *estimates could differ by as much as a factor of 500 or more*. They concluded that it is essential that a reliable set of standard materials be established for inter-laboratory comparisons of analysis methods.

The charcoal analysis methodology that underpins all the data presented in this report is that developed over the last decade within CSIRO Land and Water, Adelaide laboratories, by one of the authors (JOS). The analysis method is based on the oxidation of the more chemically labile materials with UV photo-oxidation and subsequent analysis of the residue by solid-state ^{13}C NMR. Because of its highly aromatic nature, charcoal can be readily detected with NMR once other aromatic materials such as lignins and tannins are removed. A full description of the method is given in Skjemstad *et al.* (1999b). This methodology has the advantage of concentrating the charcoal material so that other estimates such as the content and nature of nitrogen within the charcoals can also be investigated (Knicker and Skjemstad, 2000). This treatment is also relatively gentle, since no strong oxidizing agents are used, and allows the morphology and particle size of the charcoals to be determined.

It is clear from the analytical procedure described above that the highly condensed aromatic structures present in charcoal will be extremely resistant to microbial decomposition (Skjemstad *et al.*, 1998) and therefore should persist in soils and sediments for millennia. This recalcitrance has significant implications for the dynamics of carbon in soils, particularly since *methods for soil organic carbon estimation cannot effectively discriminate between charcoal and other forms of organic carbon* (Skjemstad and Taylor, 1999). Skjemstad *et al.* (2001) showed that in Vertisols under exploitive cultivation, charcoal did not vary over periods of 50 years or so, despite the fact that other soil carbon fractions significantly decreased over this period. It was also demonstrated that charcoal, which could represent nearly 50 % of the total organic carbon, equated well with the inert pool of the Rothamsted soil carbon turnover model, ROTHC - see Jenkinson (1990). Charcoals maintain a C/N ratio similar to that of the plant material from which they are formed (Knicker *et al.*, 1996). Soils high in charcoal, therefore, can contain over 20 % of their nitrogen content within the aromatic charcoal structure in the form of nitrogen containing heterocyclic components (Knicker and Skjemstad, 2000). It must be assumed that this nitrogen is as stable and unavailable as the carbon within these structures. Thus, the charcoal fraction also represents an inert pool of N. Therefore, the importance of charcoal in stabilising both carbon and nitrogen against decomposition in soils and sediments demonstrates the need for a universal and simple method to accurately measure this material in soil carbon turnover studies.

Field

The first stage in the charcoal cycle begins with the deposition of char on the soil surface immediately post-fire; see the Frontispiece, and Figure 1. Sample harvests of the char are an obvious first step in the collection of material for chemical analysis, and for estimation of the mass abundance of charcoal formed and when compared with the pre-fire fuel abundance, the fraction that was carbonised. Note that for convenience, char and charcoal are equated. The validity of this is discussed below.

There are but few reports of char harvesting. A systematic and careful study was undertaken by Hurst *et al.* (1994) using collecting trays distributed before an experimental fire in tropical grassland. This technique is possible only for small fires under controlled experimental conditions. In contrast, the most common situation is opportunistic sampling, seizing the sampling opportunity presented by the presence of a fire. In these situations, simple manual or mechanical char collection techniques are used, such as reported by Stronach and McNaughton (1989) for grass fires, and Fearnside *et al.* (2001) for forest fires. A simple technique of char collection using a small vacuum cleaner was developed by Kuhlbusch (1995) for use in grassland fires. This technique was used to sample the char from a variety of fires in tropical Australia - see Figure 5. While perfectly adequate for collecting char, there are problems in measuring the mass of char per unit area. Regardless of the care taken, we found that the char samples were always contaminated with very fine sand that could not be removed by simple sieving. Thus, the use of this gravimetric technique for measuring char (charcoal plus ash) abundance is discounted.

Figure 5: An illustration of char harvesting in the field using a small vacuum cleaner and a bicycle rim as a circular quadrat. The fire was in tropical grassland but in the pre-harvest quadrat, (eucalypt) tree leaves are obvious in the char mass. In spite of much practice and attention to technique, all of char samples harvested were significantly contaminated with very fine surface sand so that gravimetric measurement of char was compromised.

The fraction of the fuel carbonised is a critical variable in calculating char production of during biomass burning. Given the difficulties with estimating this in the field using the gravimetric method described above, an alternative chemical composition approach was used. This approach compares carbon to silicon ratios (C/Si) in unburned plant material and in the char, and employs the assumption that the inert element Si is conserved during the burning process.

Silicon is a component of plant tissues, particularly in tropical grasses where it occurs as silica (SiO_2) in discrete structural objects called phytoliths - see Figure 2. Phytoliths are distinctive and well preserved, thereby serving as a valuable fossil record for the reconstruction of past vegetation community structure and dynamics (Stromberg, 2000). With laboratory measured values of the C/Si for plant (R_{plant}) and char (R_{char}), and assuming that the inert element Si is conserved during the burning process, the ratio of carbon in the char to that in the plant (C_{char}/C_{plant}, the carbonised fraction) is R_{char}/R_{plant}. The values for the carbonised fraction obtained by this method for tropical grasses are in good agreement with the few published values. The use of the carbonised fraction for calculating char production is outlined in Appendix A.

Char and charcoal

In the Definition Section above, it was proposed that char was principally charcoal with a fractional contribution of other pyrogenic carbon compounds, which, in contrast to charcoal, were labile and degradable either by abiotic agents, such as UV radiation, or by microbial metabolism - see Figure 3. In published values for char harvesting in the field, the separation of char and charcoal is usually not made; char is equated to charcoal. Because published values will form a central part of our estimation strategy, a reasoned argument about the relationship between char and charcoal for Australian biomass burning is required.

For biomass burning on the Australian continent, which in terms of char production is overwhelmingly the burning of tropical grasslands, we propose *that char is charcoal*; that is, the proportion of labile carbon compounds in the char is insignificantly small (≤ 5 %), where significance is judged by the much larger overall uncertainty associated with the measurement of char mass.

We support this proposition with two pieces of evidence, and provide an alternative explanation to a published study that reports a high charcoal degradation rate. The principal evidence is in the recently published laboratory study by Baldock and Smernick (2002) of the relationship between the degree of heat treatment/charring of macerated wood and its subsequent decomposition during incubation. They found that the decomposition rate of the samples treated at temperatures ≥ 200 °C was 2 % of controls, with similar or lower values for the higher temperature treatments, see Figure 7 of Baldock and Smernick (2002). That is, high refractivity of carbon (fuel) compounds was induced by heat treatment at ≥ 200 °C, a low temperature compared with > 400 °C usually experienced during combustion in the field.

The second piece of evidence is the link between the measured increase in resistance to decomposition and the change in the H:C mol ratio - see Table 3 of Baldock and Smernick (2002). The H:C ratio of unburned fuel materials, such as cellulose or lignin, is ≈ 1.5. This ratio rapidly declined with increasing temperature of the heat treatment in the above experiment. At 200 °C, when high refractivity was conferred on the char, the H:C ratio had fallen to ≈ 1.0; at 350 °C when the consequent decomposition rate was negligible, the ratio was ≈ 0.5. Kuhlbusch and Crutzen (1995) defined black carbon, demonstrably an extremely refractive form of carbon, using molar H:C ratio values of ≤ 0.2. Further, based on sound chemical principles, they proposed that the lower the H:C ratio, the greater the resistance of the charred material to chemical and biological decomposition. Therefore, a plausible conclusion is that, because during the biomass burning temperatures are predominantly greater than 400 °C (smouldering combustion), it is highly probable that any char formed will have molar H:C ratios of ≤ 0.5, the values achieved by the mild treatments applied by Baldock and Smernick (2002). Because of low H:C ratios, the resistance to chemical and biological decomposition of the char formed will be very high.

The crucial test of the above argument would be measurement of H:C ratios of the numerous field-collected char samples, see Figure 5 above. Unfortunately, access to the precision instrumentation required was not available to the authors and these measurements of H:C ratios could not be made.

Bird *et al.* (1999) report field measurements that they interpreted as demonstrating high charcoal decomposition rates, a confronting finding. The study was a comparison of the concentrations of ‘oxidation-resistant elemental carbon (OREC)’ in a (sandy) savanna soil at Matopos in Zimbabwe. The treatment was fire exclusion (for 50 yr) contrasted with frequent burning (1-5 yr). OREC (equivalent to charcoal) was measured only in the 0-50 mm soil horizon. The half-life of soil OREC loss from the 0-5 mm interval was calculated as ≈ 100 years, while that for larger particles (2000 µm) just 50 years. The conclusion of the authors was that “a significant proportion of OREC can undergo natural degradation in well-aerated environments on decadal/centennial timescales suggests that only a fraction of the total production of OREC from biomass burning and fossil fuel combustion is likely to be sequestered in the slow-cycling 'geological' carbon reservoir**”.**

We offer an alternative explanation for the decline in soil charcoal abundance in the soil of the unburned plot. It is that in the topmost layer of (a sandy) soil, the physically fragile char will be progressively macerated by animal activity and the impact of raindrops. Then in the absence of stabilizing clay particles, these very small particles will be illuviated down the soil profile driven by a monsoonal hydrology. There are small charcoal particles in all soils, not just sandy soils. Skjemstad *et al.* (1996) found charcoal particles as small as those of clay (2 µm) and commonly, > 90 % of soil charcoal resides in particles that are smaller than 53 µm (Skjemstad *et al.*, 1999b). This alternative was considered and rejected by Bird *et al.* (1999) for reasons that are not clear. Sampling only the topmost layer (0-50 mm) of a sandy soil in a monsoonal environment is a weak evidence base on which to conclude that the decline in charcoal abundance can only be the result of decomposition. It is not a compelling interpretation.

In summary: the plausible overall conclusion we draw is that char sampled in the field is equivalent to charcoal determined in the laboratory. Whatever fraction of the total char carbon that resides in labile compounds, it is small and insignificant compared with the independent uncertainties associated with identifying charcoal and estimating its production. We reiterate the comparisons revealing that existing (laboratory) techniques for the measurement of charcoal can differ by a factor of 500 or more (Schmidt *et al.*, 2000).

Charcoal pool size and dynamics

Given the task of estimating the size and dynamics of the continental charcoal pool, the preferred strategy is a basic and direct one – calculate pool size first, then dynamics. The estimation of pool size has two steps. First, stratify the continent using some relevant criteria, then use the existing database of soil charcoal measurements to derive a mean charcoal abundance (mass area^{-1}) for each stratum, and finally scale up by summing over all strata, the product of area and charcoal abundance. Exactly this strategy was used to estimate SOC for regions, continents and globally (Batjes, 1997). Unfortunately, this basic and transparent strategy cannot be employed because the available database of soil charcoal measurements is small, much smaller than for SOC. Furthermore, the distribution of the available charcoal samples is not (spatially) systematic; rather it is heavily biased by localised research interests and is thereby inadequate for a defensible stratification of the continental landmass. Thus, a reasonable assessment of the task in hand is that it is overwhelmingly data limited.

To overcome the above-mentioned data limitations, an alternate strategy is used wherein we begin with the dynamics, and from that infer the size of the continental charcoal pool. The dynamics of charcoal is taken to comprise production, redistribution, and residence time. All three components will be model-based, and the predictions of these models can be tested using the available field measurements. This strategy is attractive in that the modelling is transparent and its validation against observations extracts maximum benefit from this scarce resource.

Uncertainty and a probabilistic methodology

Besides the size and dynamics of the continental charcoal pool, there remains a third objective: an explicit treatment of the uncertainty associated with all estimates. Uncertainty is well illustrated by the two questions that drive scientific research: ‘What do you know, and how well do you know it?’ ‘What do you know?’ refers to the uncertainty associated with the conceptual framework or model of the system under investigation. ‘How well do you know it?’ refers to the uncertainty associated with values given to model variables. We address the objective of the explicit treatment of the uncertainty by employing a probabilistic methodology throughout that is demonstrated by the following simple, but realistic, example.

The CO_2 emitted from prescribed forest fires is given by.

$$E = A\,M\,f_v\,\phi \qquad (4)$$

where

- E Mass of CO_2 emitted ($tCO_2\ yr^{-1}$)
- A Burnt area ($ha\ yr^{-1}$)
- M Fuel (dry) mass abundance ($tdm\ ha^{-1}$)
- f_v Burning efficiency, the mass fraction of the fuel volatilised (0 –1, dimensionless)
- ϕ Emission factor, the mass ratio of CO_2 produced/fuel consumed ($1.6\ t\ t^{-1}$).

Even though the above equation is a simple multiplicative inventory model, existing knowledge of the values of three variables in it is inexact. There is a dearth of relevant published values for A, M, and f_v. Nonetheless, it is possible to transparently generate best estimates and their credibility is determined by their associated uncertainty. Uncertainty and variability are frequently and incorrectly interchanged. Variability is an inherent property of the behaviour of systems, simple or complex. Whereas uncertainty as defined here is a property of any description of such systems. Uncertainty is illustrated by the two questions that drive scientific research: ‘What do you know, and how well do you know it?’ The former refers to the uncertainty associated with the conceptual framework or model of the system under investigation whereas the latter refers to the uncertainty associated with values given to model variables.

Using a probabilistic approach with the multiplicative inventory equation above, the difficulty that key variables are poorly known can be addressed thus. While it is not possible to know the exact fuel loads in prescribed forest fires, sufficient recorded or expert understanding exists to set the probable upper and lower limits of the fuel load as well as describe the likely distribution of values within that range, such as normal or lognormal. In this way, the fuel load value can be transparently modelled using a probability distribution function (pdf). If required, the pdf is simply updated given additional information. It follows that because the variables in the inventory model are represented by pdf, and their product, the calculated emission will also be presented as a pdf. In this way, we calculate what we know, as well as how well we know it. We believe this strategy addresses the significant issues in using multiplicative equations with varying degrees of uncertainty that were highlighted by Robinson (1989)

In this particular example taken from Graetz (2002), the pdf for the variable A ($ha\ yr^{-1}$) was modelled by a normal distribution truncated by the minimum and maximum-recorded values,

Figure 6. Similarly, the fuel load (M, tdm ha^{-1}) pdf was modelled using a lognormal distribution truncated by the minimum loading (5 tdm ha^{-1}) that would warrant prescribed burning, Figure 6.

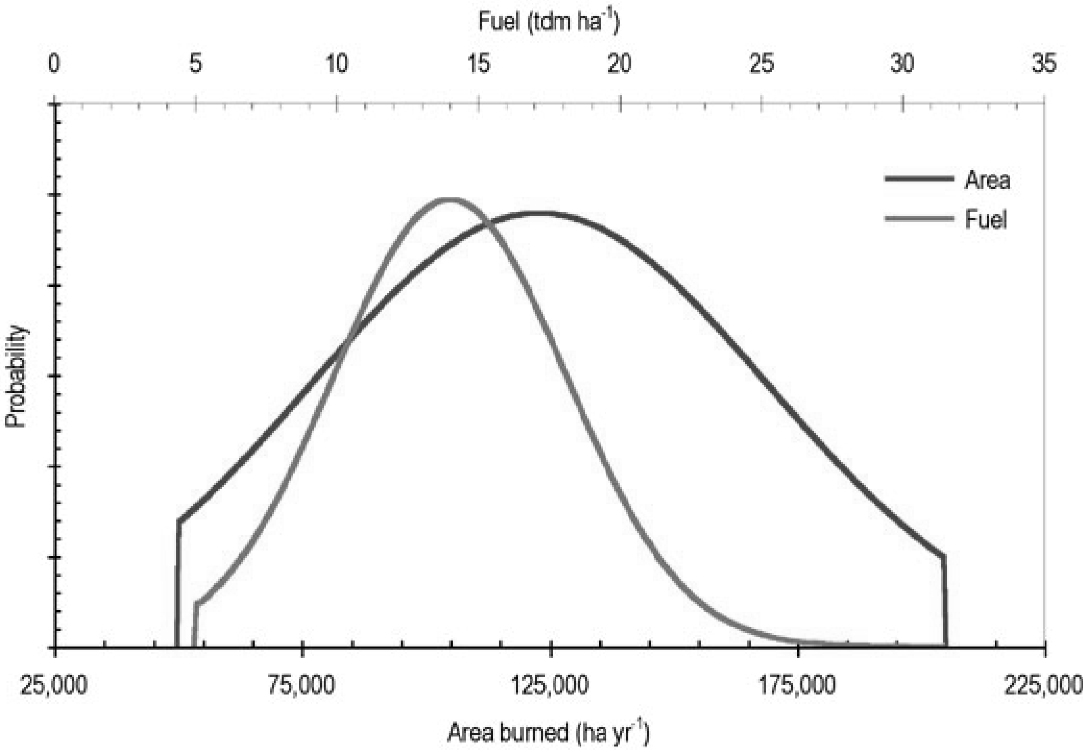

Figure 6: The shapes of the truncated probability distributions (pdf) used to model area burned and fuel loading.

Using Monte Carlo simulation techniques, these two pdf along with that for burning efficiency (f_v), a probabilistic estimate of CO_2 emission rate can be generated - see Figure 7. The emission rate is presented both as a pdf (discrete points) and as a cumulative probability distribution (cdf) to illustrate that the obvious Monte Carlo sampling noise in the former does not detract from the interpretation of the latter. In this illustration, only 200 samples were used to calculate the pdf of CO_2 emission rate. In the calculation of char production to be presented below, 10, 000 iterations are used within the Analytica software package (Lumina Decision Systems, USA). For brevity, the char pdf output is summarized by the 5, 25, 50, 75, and 95 percentiles that describe the distribution shape. In particular, the interquartile range is particularly informative because it captures 50 % of the observations, Table 2. Nonetheless, if required, all intermediate pdf are available from the authors.

Table 2: A statistical summary of the example CO_2 emission pdf in Figure 7. Median values are in bold.

Percentile	CO_2 emission rate (ktCO_2 yr^{-1})
5	1,100
25	1,800
50	**2,500**
75	3,400
95	4,700

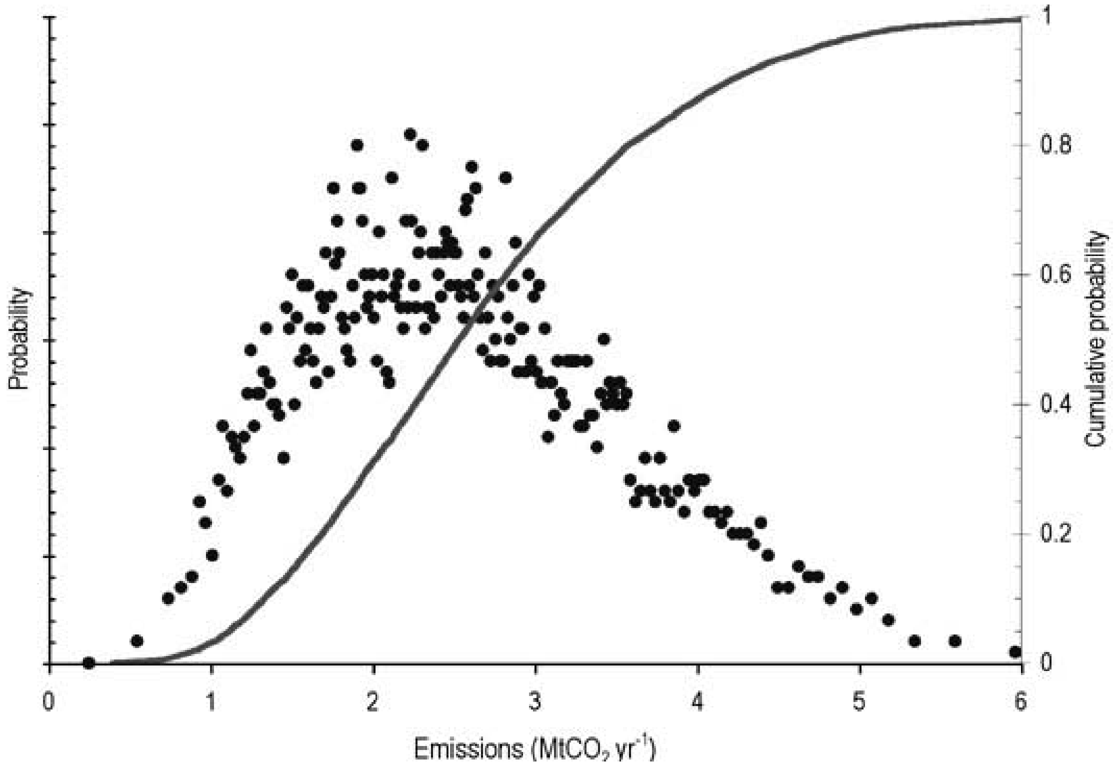

Figure 7: The shapes of the calculated distributions for CO_2 emission rates presented as probability (discrete values) or cumulative probability (continuous).

Charcoal production

In this Section, we present a transparent calculation of the annual production of charcoal. The units of aggregation are continental and annual.

Charcoal production model

The charcoal production rate on burned landscapes is given by,

$$C_{char} = A\ M\ (1 - \square_{\square}) \qquad (5)$$

where

C_{char}	Charcoal production rate (tC yr^{-1})
A	Burned area (ha yr^{-1})
M	Carbon abundance (tC ha^{-1}) of the biomass fuel exposed to fire
$\square_{\square}$	Burning efficiency, the fuel fraction that is volatilised (0 – 1, dimensionless).

Only the three variables A, M, and $\square_{\square}$ are required for the calculation of charcoal production. All three require additional comment. Burned area (A) is taken to be that area of landscape burned, and not just the total area of a fire footprint. M is the carbon abundance of the fuel that is exposed to fire. In forest fires, a proportion of the fuel (f_u), particularly the coarse woody debris, is exposed to the fire but remains unburned the so-called third fate. Last, the burning efficiency or completeness of combustion term ($\square_{\square}$) determines the (small) fraction of the fuel carbon that is carbonised ($\square_c$). The implicit relationship is

$$\square_{\square} + \square_c + f_u = 1.0. \qquad (6)$$

Equations (5) and (6) are the charcoal production models underpinning all contemporary fire types.

Based on available records for the 18-yr period, 1982-2000, one of us (RDG) conducted an analogous exercise to calculate CO_2 emissions from biomass burning for the continent (Graetz, 2002). In this exercise, continental biomass burning was stratified into four types:

Managed and Unmanaged forest fires, Grassland fires and Clearing fires. For each fire type, the annual area burned (A), the fuel mass carbon abundance (M), and the burning efficiency (□□) were determined and assigned a probability distribution function (pdf). A probabilistic approach was followed to explicitly capture the uncertainty in the representativeness of the three variables in the multiplicative production model, see equation (5) above. Because the variables in the charcoal production model are represented by statistical distributions, their product can also be presented as a statistical distribution - see Graetz (2002) for details of the fire stratification, the eighteen-year base dataset, and the various pdf. To reduce the clutter of detail in this main text, the reasoning and manipulation associated with the variables (A, M, □□□□□□□□□□□□□□□□□ is confined to Appendix A. Lastly, this strategy of probabilistic calculation is based on these two assumptions: the time series of burned area (A) for the various fire types are all stationary series, and the three variables (A, M, □□) are uncorrelated

Charcoal production in Managed forest fires

Managed forest fires are deliberately lit by state agencies as part of prescribed burning programs to reduce the probability of Unmanaged fires - ‘bushfires’. Using the variables derived and applied in Appendix A, the carbon consequences of Managed forest fires are summarised in Table 3. Because the distributions of estimated charcoal production are quasi-normal, the median values (bold) are informative values. The burning of forest litter fuel at the rate of ≈ 2.5 MtC yr^{-1} results in a short-term emission of ≈ 9 MtCO$_2$ yr^{-1} and a charcoal production rate of 143 ktC yr^{-1}, or the equivalent sequestration of 524 ktCO$_2$ yr^{-1}.

Table 3. A continental summary of the carbon consequences of Managed forest fires in terms of fuel burned (MtC yr^{-1}), charcoal produced (ktC yr^{-1}), and the overall conversion ratio. Median values are in bold.

Percentiles	Fuel carbon burned	Charcoal production	Charcoal / Fuel carbon
5	1.8	57	0.03
25	2.2	98	0.04
50	**2.5**	**143**	**0.06**
75	2.8	207	0.08
95	3.2	354	0.13

Charcoal production in Unmanaged forest fires

Unmanaged forest fires are ‘bushfires’ in woodlands and forests. The annual area burned by these fires is ≈ 30 % less than for Managed fires but because of their high burning intensity, these fires also combust part of the canopy biomass. Using the variables derived and applied in Appendix A, the carbon consequences of Unmanaged forest fires are summarised as Table 4.

Table 4. A continental summary of the carbon consequences of Unmanaged forest fires in terms of fuel burned (MtC yr^{-1}), charcoal produced (ktC yr^{-1}), and the overall conversion ratio. Median values are in bold.

Percentiles	Fuel carbon burned	Charcoal production	Charcoal / Fuel carbon
5	0.5	38	0.04
25	0.9	78	0.07
50	**1.3**	**133**	**0.10**
75	2.0	226	0.14
95	3.5	504	0.24

As can be appreciated from the interquartile ranges in Table 4, the distribution of charcoal production values is strongly positively skewed driven by the extreme values of area burned. Even so, the median values are informative and parallel the values for Managed forest fires,

Table3. The median charcoal production for the continent is 133 ktC yr^{-1}, or the equivalent of 488 $ktCO_2$ yr^{-1}.

Charcoal production in Forest fires

Managed and Unmanaged forest fires share the same fuel type, fine and coarse woody canopy litter, and vary only in intensity of the burning process. In terms of area and charcoal production, they substantially differ from the two fire types yet to be considered Grassland and Clearing fires. The combined carbon consequences of these two fires are summarized as Table 5. The median fuel carbon consumption by both forest fire types is 3.9 MtC yr^{-1} producing 0.3 MtC yr^{-1} of charcoal, equivalent to the sequestration of 1.1 $MtCO_2$ yr^{-1}.

Table 5. A continental summary of the carbon consequences of Managed and Unmanaged forest fires combined in terms of fuel burned (MtC yr^{-1}), charcoal produced (ktC yr^{-1}), and the overall conversion ratio. Median values are in bold.

Percentiles	Fuel carbon burned	Charcoal production	Charcoal / Fuel carbon
5	2.7	138	0.04
25	3.4	218	0.06
50	**3.9**	**302**	**0.08**
75	4.6	424	0.10
95	6.1	735	0.15

Charcoal production in Grassland fires

Grassland fires are a tropical phenomenon. The overwhelming majority of area burned (> 98 %) is in either the tropical savannas or the hummock grasslands (‘spinifex’) of the desert sandplains. These fires are mostly deliberately lit in the Dry Season (April - October) as part of contemporary or traditional land management. Using the variables derived in Appendix A and substituted into a production model appropriate to this fire type, the annual production of charcoal from Grassland fires is summarised as Table 6. The median annual charcoal production for the continent is estimated as 5.6 MtC yr^{-1}, equivalent to the sequestration of ≈ 21 $MtCO_2$ yr^{-1}. This is larger than the combined total char production from forest fires (Table 5) by a factor of ≈ 20.

Table 6. A continental summary of the carbon consequences of Grassland fires in terms of fuel burned (MtC yr^{-1}), charcoal produced (MtC yr^{-1}), and the overall conversion ratio. Median values are in bold.

Percentiles	Fuel carbon burned	Charcoal production	Charcoal / Fuel carbon
5	74	1.7	0.02
25	108	3.5	0.03
50	**142**	**5.6**	**0.04**
75	187	9.0	0.06
95	281	17.5	0.10

Charcoal production in Clearing fires

Managed and Unmanaged forest fires as well as Grassland fires are phenomena of carbon-resilient landscapes. That is, the fuel that is burned in these three fire types is replaced by natural processes within a few years. For Grassland fires, the replacement time is months. Thus, the carbon storage of these landscapes fluctuates in a resilient manner in response to fire; there is no permanent change. Fire competes with decomposition for biomass. Without fire, total plant biomass would increase with the accumulation of litter, as would the rate of decomposition until a new dynamic equilibrium evolved. On a time scale of years, the CO_2 emissions from these three fire types are not net transfers from the biospheric to atmospheric carbon pool. These fires do not add CO_2 to the atmosphere in the same way as does the combustion of fossil fuels (Graetz, 2002).

In terms of the carbon resilience, Clearing fires are a distinct class because they are used to transform landscapes, and thus to significantly and enduringly diminish the size of the landscape carbon pools, as well as its net primary productivity (NPP). Consequently, Clearing fires add CO_2 to the atmosphere in an analogous manner to the combustion of fossil fuels, Graetz (2002). For Australia, it is the land management activity of clearing that provides the largest source of pyrogenic CO_2 from transformed landscapes. Here, woody vegetation is mechanically felled and burnt to transform this landscape into those more financially productive, such as crops or pastures.

Using the variables derived in Appendix A and substituted into a production model appropriate to this fire type, the annual production of charcoal from Clearing fires is summarised as Table 7. The median charcoal production rate for the continent is calculated to be ≈ 1.9 MtC yr^{-1}, equivalent to the sequestration of 6.8 $MtCO_2$ yr^{-1}.

Table 7. A continental summary of the carbon consequences of Clearing fires in terms of fuel burned (MtC yr^{-1}), charcoal produced (MtC yr^{-1}), and the overall conversion ratio. Median values are in bold.

Percentiles	Fuel carbon burned	Charcoal production	Charcoal / Fuel carbon
5	12.1	0.7	0.04
25	17.4	1.3	0.06
50	**23.0**	**1.9**	**0.08**
75	30.9	2.8	0.11
95	48.1	4.9	0.16

Contemporary charcoal production

Combining the models for the four fire types, the estimated median total fuel carbon burned is 172 MtC yr^{-1}, which is twice the current fossil fuel usage, which generates a charcoal production of 8.3 MtC yr^{-1}, and which is equivalent to a sequestration of 30 $MtCO_2$ yr^{-1}, or 8.5 % of Australia's 1990 baseline CO_2 emission rate, see Table 8.

Table 8. A continental summary of the carbon consequences of all fire types in terms of fuel burned (MtC yr^{-1}), charcoal produced (MtC yr^{-1}), and the overall conversion ratio. Median values are in bold.

Percentiles	Fuel carbon burned	Charcoal production	Charcoal / Fuel carbon
5	99.9	3.7	0.02
25	136.9	5.9	0.04
50	**172.1**	**8.3**	**0.05**
75	218.4	11.8	0.06
95	313.4	20.0	0.10

The relative contributions of the four fire types to the overall total are, in descending order, Grassland (72 %), Clearing (24 %), Managed (2 %), and Unmanaged (2 %).

Historic charcoal production

In the above Section on Clearing fires, estimates were derived for the annual fuel usage and charcoal production rate, Table 7. Clearing fires have been a source of charcoal since the introduction of agriculture to the Australian continent (ca. 1800) so it is of interest to estimate cumulative total charcoal production since the availability of official statistics for the area of land converted.

Based on official statistics for crop and pasture areas, such as Table 14.17 in the 1997 edition of the Australian Year Book, we use the value of 95 Mha for total area of forest and woodlands that were cleared (and burned) in the period 1860, when colonial statistics began, until 1980, the start of available statistics of area burned. Using the same distribution of fuel carbon abundance (M) used for Clearing fires, the median value for estimated total charcoal production from historic clearing, 1860-1980, is 370 MtC, see Table 9.

Table 9: A statistical summary of modelled total fuel carbon burned (GtC) and charcoal produced (MtC) from historic Clearing fires for the entire continent, 1860-1980.

Percentiles	Fuel carbon burned	Charcoal production
5	2.6	151
25	3.6	256
50	**4.6**	**370**
75	6.0	545
95	8.9	947

We note that it is highly likely that the above estimated median total charcoal production from agricultural land conversion is significantly underestimated. The fuel carbon (M) values used are representative of the woodlands currently being cleared. The high value forests and woodlands cleared at the beginning of the agricultural expansion would have had much higher fuel carbon densities, perhaps as much as 50 % greater. We also note that the annual rates of clearing varied substantially during the 1860-1980 period with the annual rate peaking at ≈ 3 Mha yr^{-1} in the 1970s.

Bearing both of these points in mind, the historic clearing values provide four interesting perspectives. First: the median estimated fuel carbon burned in this agricultural conversion period was ≈ 4.6 GtC giving an average annual rate of 38 MtC yr^{-1}, which is approximately half the current fossil fuel usage rates of ≈ 80MtC yr^{-1}. Second: the average annual charcoal production rate over the 120-yr period is ≈ 3 MtC yr^{-1}, almost twice the current estimated rate of 1.8 MtC yr^{-1}, see Table 7. Finally, the average abundance of charcoal generated and deposited in the new agricultural lands by 120 years of Clearing fires is ≈ 4 tC ha^{-1}, and the total permanent transfer of carbon from the landscape to the atmosphere was >> 16 $GtCO_2$. These perspectives will inform the following discussion of the distribution and size of the continental charcoal pool.

Pre-historic charcoal production

The objective of this Section is to transparently estimate the charcoal production rates from Aboriginal burning. The topic of the Aboriginal use of fire, its extent, frequency and consequences, remains contentious. The evidence base is small and isolated, in contrast to the political consequences, which are high. To meet our objective, three estimates are required: when, where, and how much burning occurred as the result of Aboriginal landuse. We derive our estimates informed by the recent and comprehensive review of Kershaw *et al.* (2002).

When: The evidence for the presence of Aboriginal people is strongest beginning 40 ka BP and one component of that evidence is an increase in charcoal (Kershaw *et al.*, 2002). Since then, the continent was completely colonised and the density and distribution of people fluctuated in response to very significant variations in climate. There is no doubt that fire was used from the initial occupation. However, we nominate 5 ka BP as the baseline for charcoal production based on three independent strands of evidence. The existing records suggest that during the Holocene (10 ka BP) fire activity was relatively constant until the arrival of Europeans (Dodson and Mooney, 2002; Kershaw *et al.*, 2002). At about 6 ka BP, sea levels stabilised after a long period of (global) adjustment from the last glacial period. Consequently, large areas of highly productive coastal regions were lost and the displaced people concentrated around the existing coastline and the nearby hinterland. This movement of people and the changed fire regimes they brought with them would undoubtedly have had a significant impact on the vegetation. As one illustration, Hopkins *et al.* (1993, 1996) document the changes in fire-sensitive rainforest species and fire-tolerant Eucalypts in coastal far north Queensland. Finally, based on independent data, a demonstrably significant and synchronous intensification of Aboriginal occupation and landuse began about 5 ka BP (Kershaw *et al.*, 2002). To these three archaeological strands of evidence, we add one additional chemical factor: based on our experience, we estimate the residence time of charcoal in soils as less than 5000 yr - in the range 3000-4000 yr for clay soils, whereas for sandy soils it may be as small as short as 500 yr (J. Skjemstad, 2003, private communication). Thus, if we are correct in these estimates, contemporary soil charcoal levels will be equilibrating on millennial time scales.

Where: As demonstrated by Fensham (1997), reconstruction of the fire regimes of pre-contact Aboriginal landuse from direct observations – explorer's records – is difficult. Nowhere in Australia do we have defensible estimates of the area of landscape burned during pre-contact Aboriginal landuse. As estimated in previous Sections, the two largest charcoal sources from contemporary burning are the Grassland and Clearing fires. Therefore, the locations wherein we can compare our estimates of current charcoal production with the soil pool are the tropical grasslands and the cleared agricultural lands. The extensive tropical grasslands are but sparsely documented while the best records of fire regime are for south-eastern Australia that will serve for the earliest-cleared agricultural lands.

How much: the archaeological charcoal record is quantitatively focused in time but not in space. The site where the charcoal record is preserved is rarely typical of the surrounds where the burning took place. It is not possible to use this type of record to calculate charcoal production (tC ha^{-1}) for landscapes. Therefore, our only option is to reason production equations based on the values used in previous Sections and guided by archaeological interpretations of Aboriginal landuse.

We propose that a general pre-historic charcoal production rate is given by,

$$D_{prechar} = M\, I^{-1}\, L\, \square_c \qquad (7)$$

where

$D_{prechar}$	Pre-historic charcoal deposition rate (tC ha^{-1} yr^{-1})
M	Carbon abundance (tC ha^{-1}) of the biomass fuel exposed to fire
I	Between-fire interval (yr)
L	Proportion of the landscape burned
$\square_c$	Fraction of the fuel carbon that is carbonised.

As with previous estimates, the task is the assigning and justifying the four variables of equation (7). Beginning with south-eastern Australia that was amongst the first-cleared agricultural lands, we reason that Aboriginal burning was most common in the woodlands, heaths, and grasslands and never in the closed forests. The fires were primarily for hunting and access and were managed to burn only the understorey grass and litter. The between-fire interval (I) at any one site was by current tropical standards, long, such as 5 to 10 yr. The proportion of the landscape burned term (L) is to capture both the selectivity and skill of Aboriginal fire management of small areas of high value, as well as the episodic conflagration. The values chosen are listed and justified in Appendix A.

Two estimates can be derived from equation (7). The first is the annual charcoal deposition per unit area averaged over the entire landscape, $D_{prechar}$, assuming no redistribution. The other is the cumulative charcoal production (tC ha^{-1}) over the last 5000 years, assuming no redistribution or oxidative loss, Table 10. The median charcoal deposition rate is just 10 kg ha^{-1} yr^{-1}, which over 5000 years accumulates to 50 tC ha^{-1} assuming no redistribution or oxidative loss. In the Historic charcoal production Section above, the clearing episode was estimated to have deposited just 4 tC ha^{-1} with the latter value regarded as an underestimate.

Table 10: A statistical summary of modelled prehistoric charcoal production for the agricultural lands of south-eastern Australia. The deposition rate (tC ha^{-1} yr^{-1}) is a landscape average. The cumulative production (tC ha^{-1}) is over the last 5000 years. Both values assume no redistribution or oxidative loss. Median values are in bold.

Percentiles	Deposition rate	Cumulative production
5	0.003	20
25	0.006	30
50	**0.010**	**50**
75	0.016	80
95	0.032	160

The estimations are repeated for the tropical grasslands, Table 11. They are comparable to those for the agricultural lands. A median deposition rate for grasslands of 9 kg C ha^{-1} results in a cumulative production of 43 tC ha^{-1}. Note that all values assume no redistribution or oxidative loss.

Table 11: A statistical summary of modelled prehistoric charcoal production for the grasslands of tropical Australia. The deposition rate (tC ha^{-1} yr^{-1}) is a landscape average. The cumulative production (tC ha^{-1}) is over the last 5000 years. Both values assume no redistribution or oxidative loss. Median values are in bold.

Percentiles	Deposition rate	Cumulative production
5	0.002	12
25	0.005	26
50	**0.009**	**43**
75	0.014	71
95	0.028	141

These values can be compared with charcoal deposition rates for contemporary Grassland and Clearing fires, Table 12. The modelled deposition rate for contemporary Grassland fires is 15 times larger than that for prehistoric burning. This difference reflects the moderating influence of the two factors of between-fire interval (I) and proportion of the landscape burned (L) that were introduced in equation (7) to contrast prehistoric and contemporary fire regimes and to compensate for an absence of burned area values. We note that at the patch scale, the actual charcoal deposition rate in prehistoric grassland fires is identical to contemporary fires, ≈ 150 kgC ha^{-1} yr^{-1}. However, we argue (via our modelling variables) that less-frequent prehistoric fires covered a smaller proportion of the landscape than contemporary burning. The result is that the landscape-averaged value in Table 10 is 15 times less than current burning value in Table 12.

Table 12: A statistical summary of modelled charcoal deposition rates (tC ha^{-1} yr^{-1}) for contemporary Grassland and Clearing fires. Both values are landscape averages that assume no redistribution or oxidative loss. Median values are in bold.

Percentiles	Grassland	Clearing
5	0.05	2
25	0.09	3
50	**0.15**	**4**
75	0.23	6
95	0.43	10

The charcoal deposition rates for prehistoric burning and contemporary Clearing fires are not strictly comparable. The former repeatedly burned only the understorey whereas the latter was a once-only burning of all aboveground biomass. Therefore, we predict that two charcoal signatures could be found in the soils of the agricultural lands of south-eastern Australia reflecting the nature and timing of these two contributions.

Charcoal redistribution

We reiterate our strategy: given systemic data limitations, we attempt to achieve our objective of estimating the size of the continental charcoal pool by beginning with the dynamics - production, redistribution, and residence time - and from that infer pool size. In the previous Section, annual production rates were calculated for four contemporary fire types, as well as for historic agricultural clearing fires during the period 1860-1980. The objective of this Section is to quantify the redistribution and residence time of charcoal in the landscape into a set of geographically specific predictions that can be tested against existing measurements of charcoal distribution and abundance.

A framework

The basic qualitative framework of charcoal redistribution is Figure 4. This framework of considerations is simplified to Figure 8 as follows. The focus is the largest current sources of charcoal production, Grassland and Clearing fires, which in aggregate contribute 96 % of total char production. The gas phase black carbon (soot in smoke) production and transport is ignored because it is a very small component. In addition, because the most plentiful measurements of charcoal distribution and abundance available are for soils, we consider only charcoal in soils of the tropical grasslands and the agricultural lands. This charcoal was interred either in situ or redistributed by wind and water, Figure 8.

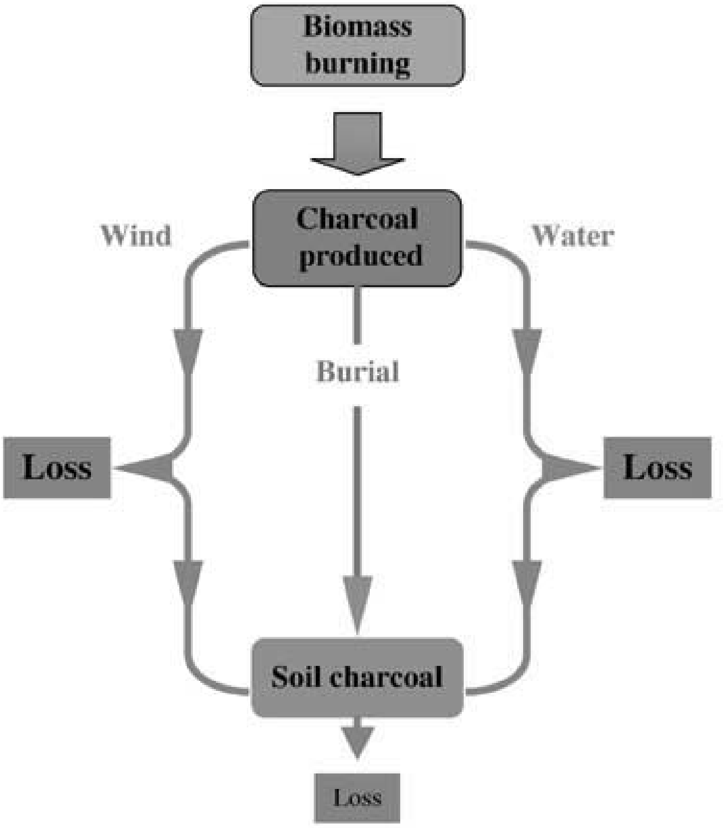

Figure 8: An illustration of the three pathways by which charcoal is either buried or transported from the fire site by the agents of wind and water. During the transport process or by elution from the soil profile, charcoal can be lost from the system under consideration. In either case, the loss is principally the result of physical and not chemical processes, such as UV oxidation or biodegradation.

In comparing our estimates of charcoal production with that stored in the soils, three possible losses must be considered. As part of charcoal redistribution by water, a fraction will be lost from the land surface via organised drainage to the ocean. Similarly, as part of the redistribution by wind, a fraction of the charcoal produced may be lost from the continent by deposition in the surrounding oceans. Finally, under conditions of high rainfall and sandy soils, charcoal also may be eluted from the upper layers of soils to beyond the depth of customary measurement, as well as be lost via microbial or chemical oxidation, see Figure 8. Thus to reconcile the charcoal production estimates generated in the previous Section with available measurements of the soil charcoal pool, estimates of the size of the three potential losses should be considered in advance.

Wind: redistribution and loss

“Visual observations of a burned savanna … showed that a large proportion of the black-coloured residue was transported off site in the absence of rain within three to four weeks” (Kuhlbusch *et al.*, 1996). This is the common experience as observed on ground or from space. For reasons of particle size, the burned areas of grasslands lose their surface charcoal faster than burned wood. In the absence of rain, the burial and dispersal of charcoal must be by wind.

All charcoal is light and brittle, particularly that from grass fuel, and thus it can be rapidly broken down to smaller particles by wind-driven short-distance movements. Wind appears very effective in burying surface char. As the surface char particles are moved by wind, so also are the surface soils particles so that their combined small-scale redistribution results in rapid burial.

Wind will also transport surface char. Kuhlbusch *et al.* (1996) found that post-fire, 10-30 % of surface charcoal was less than 1 mm in size, a property that in conjunction with its low density would make it readily entrained and transported by wind even in the sparingly treed savannas. In the treeless spinifex sandplains of Central Australia, the burial and transport of post-fire char can be both rapid and complete, see Figure 9.

Figure 9: An area of spinifex sandplain in the Tanami Desert burned a few (≤ 5) days earlier wherein the surface char was buried or transported by the passage of a small-scale tornado or ‘willy-willy’.

The published measurements of wind-transported char are small with that for Australia limited to just one review of data. Boon *et al.* (1998) surveyed the organic matter content of rural dusts collected in Australia. The carbon determination method was loss on ignition, an imprecise technique that overestimates the organic carbon component. Nonetheless, from the data reviewed by Boon *et al.* (1998) the compelling conclusion is that the carbon concentration of sampled dusts is very high with a mean of 32 % compared with that of the source soils that are < 1%. This selective winnowing indicates the transport potential of wind for organic matter, including char. Unfortunately, no measurements were made or are now possible of the nature of the organic carbon particles. Even so, given the small size of the particles, it is highly likely that a significant proportion (≥ 30 %) of the particles is charcoal.

Finally, we note that redistribution of charcoal by wind is not the same as charcoal loss. Charcoal is lost if it is transported (as aerosol in smoke) from the land surface and deposited in the ocean. In northern Australia, the aerosol from the tropical grassland fires (and from smoke) is transported south-east to north-west on the Dry Season winds to be rained out somewhere over South-east Asia. Andreae and Merlet (2001) estimate the emission factors for BC from savanna and extratropical forest fires as ≈ 0.5 gm kg^{-1} of dry matter burned. Thus, the carbon in smoke is ≈ 0.1 % of the fuel carbon burned, a trivial component given other much larger uncertainties.

To summarize, wind appears to be a significant agent in the burial and transport of the fine charcoal from grassland fires, and probably much less so for the coarser fragments from forest and clearing fires. The burial and redistribution is rapid and most probably follows an initial in-situ fragmentation. It is likely that the scale of the dispersal is relative to just that of the burned area. Based on the emission factors of Andreae and Merlet (2001), the charcoal lost by transportation as a BC aerosol over scales very much larger than the burned areas is too small to be considered. Nonetheless, we suspect that it is a more significant carbon budget term in the smoke from spinifex fires because that smoke is always very dense and very black. The foliage of spinifex (*Triodia* sp.) contains high concentrations of resins and is highly flammable; even in a green condition, it can be ignited with a match during light rain.

Water: redistribution and loss

Because the density of water is a factor of 1000 greater than that of air, the momentum of moving water will pulverise and move charcoal particles far more readily than will moving air. In addition, the density of charcoal is < 1.0 and fragments readily float (Nichols *et al.*, 2000) with the overland flow of water being organized into drainage patterns with the majority of the continent being drained to the ocean. Casual field observations support this contention: charcoal is readily fragmented by raindrops and easily transported by overland flow, even when the water film is only millimetres in thickness. In the tropical grasslands, a common observation is that with the first (light) rains of the wet season, the smallest of tributary drainage lines run with black water. From the global generality of charcoal deposition and accumulation within drainage basins and near-shore sediments, the compelling conclusion is that water is a significant agent in the redistribution of charcoal on historical to geological time scales (Kuhlbusch, 1998a).

However, there is little quantitative evidence with which to estimate charcoal loss; the proportion of charcoal formed during a fire that is transported away from the burn site and (eventually) redeposited in terminal drainage basins or near-shore sediments. Here we define loss with reference to the alternate for the charcoal, in-situ burial. Thus, charcoal in the soils of directed drainage systems (e.g. floodplains), or in terminal drainages (swamps and lakes), is regarded as lost from the landscapes whereon it was formed.

It can be easily imagined that the loss fraction would be higher for the small, fragile charcoal particles from grassland fires compared with the larger, robust (and buoyant) charcoal fragments from the woodier fuel fires hypothesised for the agricultural burning. Because there are no guiding published values, we estimate that the loss fraction of charcoal by water will lie in the range 0.20 (grass plus woody fuel) to 0.75 (grass fuel only). We justify the high value for grass fuel by noting that the high-intensity, high-volume storm rains at the beginning of the Wet Season will most likely resuspend and transport the fine charcoal particles.

Soil: reservoir and loss

The soil is the reservoir that contains most of the charcoal pool. Even though it has the largest set of measurements available, data remain limiting. As indicated in Figure 8, the soil charcoal pool is fed by three distribution pathways, two of which represent a loss. In addition, a loss path from the soil charcoal pool is indicated in Figure 8 and this path comprises two separate processes.

The first loss path is physical: small charcoal particles are moved from the surface to deeper soil layers (and out of the traditional measurement zone) by percolating water. This loss is plausible given that ≈ 80 % of charcoal particles in soil are too small to be detected by optical microscopy because more than 95 % of the particles are ≤ 53 μ□, and in clay soils, some 50 % of charcoal particles are ≤ 2 μ□. Because of the physical interaction between charcoal and clay minerals, the percolation loss rate will be inversely related to the soil clay content: high clay levels restrict loss rates. Although this relationship is not yet quantified, our qualitative experience is that charcoal loss by percolation becomes significant with clay levels below 30 %.

The percolation of charcoal particles through the near-surface soil profile, perhaps into a groundwater layer, is a most likely loss from the tropical grass landscapes because the charcoal particles are uncharged and already small at formation. Further, the duration and depth of rainfall is conducive to mass movement, particularly within the sandy soils derived from repeatedly-weathered sediments. Earlier, we offered this explanation of the field experiment of Bird *et al.* (1999).

The second loss is chemical: charcoal is oxidized, most probably by a combination of microbial and chemical agents. This loss must occur otherwise, given plausible rates of burning, the carbon of the global vegetation would have been largely transferred to the soil charcoal pool well within the last million years. There is an analogous absence of relevant published measurements of the oxidation rate of charcoal in soils, and this rate is a key factor in the determination of pool size. Although charcoal has been dated with ages from millennia (soils) to millions of years (sediments), these ages principally are a reflection of the environmental setting, the burial conditions, such as oxygen availability, and not of a true decomposition rate (Schmidt and Noack, 2000). As a first attempt and based on plausible values from the literature, we estimate the residence time for charcoal to be 3000–5000 yr, with no differentiation between agricultural and tropical grassland soils.

Predicted charcoal pool sizes

Redistribution and oxidative loss

In the previous Section, loss rate as the result of the percolation of water were estimated for charcoal accumulation into agricultural and tropical grassland soils. In addition, a broad range of residence times (3000-5000 yr) was specified for both soils where residence time (yr) is the size of the soil charcoal pool (tC ha^{-1}) divided by the input flux (tC ha^{-1} yr^{-1}). With these two additional factors and the previously calculated prehistoric charcoal deposition rates, Tables 9 and 10, the contemporary soil charcoal pool size can be predicted in broad terms for agricultural and tropical grassland landscapes. These predictions can then be tested against available soil charcoal measurements.

The predictions are based on the prehistoric rates of charcoal deposition calculated earlier, Tables 9 and 10. The relationship is:

$$P = D_{prechar}\,(1 - Loss_{water})\,T_{residence} \qquad (8)$$

where

P	Contemporary landscape-average charcoal abundance (tC ha^{-1})
$D_{prechar}$	Pre-historic charcoal deposition rate (tC ha^{-1} yr^{-1})
$Loss_{water}$	Charcoal fraction lost via water transport (0.20 – 0.75)
$T_{residence}$	Residence time (yr)

As with previous calculations, probabilistic techniques were employed in the implementation of equation (8). The charcoal fraction lost via water transport was modelled for prehistoric agricultural fires as a lognormal distribution (median 0.25, geometric standard deviation 1.5) truncated to ≤ 0.75. The complement was used for grassland fires. The residence time was modelled as a normal distribution (mean 4000, stdev 500) truncated 3000-5000 yr. The predicted landscape average charcoal densities for the two types of country are summarised in Table 13. For the (now) agricultural lands of south-eastern Australia, the predicted values, which are adjusted for redistribution and oxidative loss, are ≈ 50 % of the unadjusted values in Table 10. The values for the tropical grasslands are ≈ 20 % of the unadjusted values.

Table 13: A statistical summary of landscape-average charcoal densities (tC ha^{-1}) predicted for contemporary agricultural areas of south-eastern Australia, and for the tropical grasslands. The values in parentheses are from Tables 10 and 11 and are not adjusted for redistribution and oxidative loss. Median values are in bold.

Percentiles	Agricultural	Grassland
5	8 (20)	2 (12)
25	17 (30)	5 (26)
50	**29 (50)**	**8 (43)**
75	47 (80)	15 (71)
95	96 (160)	34 (141)

Specific predictions

The available archives of soil charcoal measurements are limited. Nonetheless, because they were collected independently of this work, they have value for validation of our charcoal predictions. The following are specific predictions that can be tested against soil charcoal measurements for either the agricultural or the tropical grassland landscapes:

1. All soil profiles will contain charcoal, and its abundance (mass area^{-1}) will always be less than that of (non-char) organic carbon (OC).
   This prediction is to demonstrate that, (a) charcoal is ubiquitous on landscape scales, and (b) that its abundance, like that of non-char organic carbon, is coupled to biomass production at that site.

2. Profile ratios of charcoal to OC will be constant within one (broad) climatic or soil type.
   This prediction builds on part (2) of the first by linking fire frequency, and hence charcoal production, with the climatic (and nutrient) control of biomass fuel production. For a given type of country, the ratio of char to non-char carbon in the soil will be an integrated consequence of the fire regime. Alternatively, for a given fire regime, the ratio will change in response to the climate and soil (nutrient) factors

that determine biomass production.

3. The median and the distribution of measured profile integrals (0-1 m) of charcoal densities (tC ha^{-1}) should form a constant fraction of the predicted values in Table 12. This is the crucial test. We have predicted both the abundance and its variability. If the differences between predicted and observed are systematic, i.e. additive and multiplicative in nature, then they can be plausibly explained given the assumptions employed. In contrast, if the differences between predicted and observed are both large and random, then the only explanation is that the modelling is inadequate and does not capture the processes governing production and distribution.

Measured charcoal pool sizes

Agricultural lands

Most of the available soil charcoal datasets have been collected in the agricultural lands, both the cultivated croplands and the cleared (but uncultivated) improved pasturelands. All of these datasets were collected for purposes other than validating the three specific predictions made above. Consequently, the sampling employed will commonly be biased, such as by concentrating only on one of the several components of the landscape, such as drainage lines, or cultivated areas. Moreover, this bias is rarely recorded. This poses a problem in assessing how representative (of an entire landscape) are the sampled soils.

To test the three predictions, a systematic, unbiased sampling of all landscape components of a region is required - uplands, bottomlands, and everything in between. This sampling strategy has rarely been employed and only two suitable datasets are known to the authors. These data were collected under the direction of Dr Michele Barson of the Bureau of Rural Sciences, Federal Department of Agriculture, Fisheries and Forests of Australia (AFFA). The survey used for the agricultural lands, hereafter known as the St George-Duaringa gradsect, was conducted to support a program of quantifying the environment determinants of soil organic carbon. To achieve this objective, a transect is located along a climatic gradient, hence the name gradsect (Ludwig and Tongway, 1995). One hundred and fourteen profiles (to 1.0 m) were systematically located at 8-km intervals along public roads from the townships of St George in the south to Duaringa in the north, both within the State of Queensland. This gradsect spanned five degrees of latitude (23°-28°S) and encountered 17 principal profile forms (PPF or type) using the classification of Northcote (1979). In terms of climatic factors, the gradsect end-points had mean annual rainfall and temperatures of 496 mm and 20° C in the south, and 311 mm and 22° C in the north. The principal, and possibly the largest, bias in the selection of sampling sites was that inherent in the location of the public roads. While very efficient in terms of sampling, this gradsect is marginal in terms of location within the continental landuse pattern by being on the arid margins of cropping.

The complete dataset comprised 114 profiles, of which 110 were excavated to 1.0 m depth. All of the profiles of this subset were sampled with the following five levels (m): 0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.5, and 0.5-1.0. The variables measured for each level were as follows: organic carbon (OC, %), charcoal (%), total organic carbon (TOC, charcoal + OC, %), bulk density (BD, mass vol^{-1}), nitrogen (N, %), and clay (%). Each of these variables was converted to a weighted profile mean, then, using the bulk density value, the mass per area value (to 1.0 m), was calculated. These units, traditionally called mass densities, were used to test the three predictions above.

The first prediction - that all soil profiles will contain charcoal - is supported. All profiles recorded charcoal but two had densities $\leq$ 1 tC ha^{-1}, values below valid detection. The measured charcoal densities were in the range 0 – 72 tC ha^{-1}, lognormally distributed with a median of 17 tC ha^{-1}, see Figure 10. The second part of the first prediction – that charcoal abundance will always be less than that of organic carbon – is also generally supported. Considering all profiles in aggregate, the respective OC and charcoal means are 54 vs. 22 (tC ha^{-1}), are significantly different ($P << 0.001$). However, of the 110 profiles, 17 had higher densities of charcoal than of OC. For these 17 profiles, seven showed differences that were small, ≤ 5 tC ha^{-1}. For these 17 profiles, no attributes obviously explained their abnormally high charcoal densities.

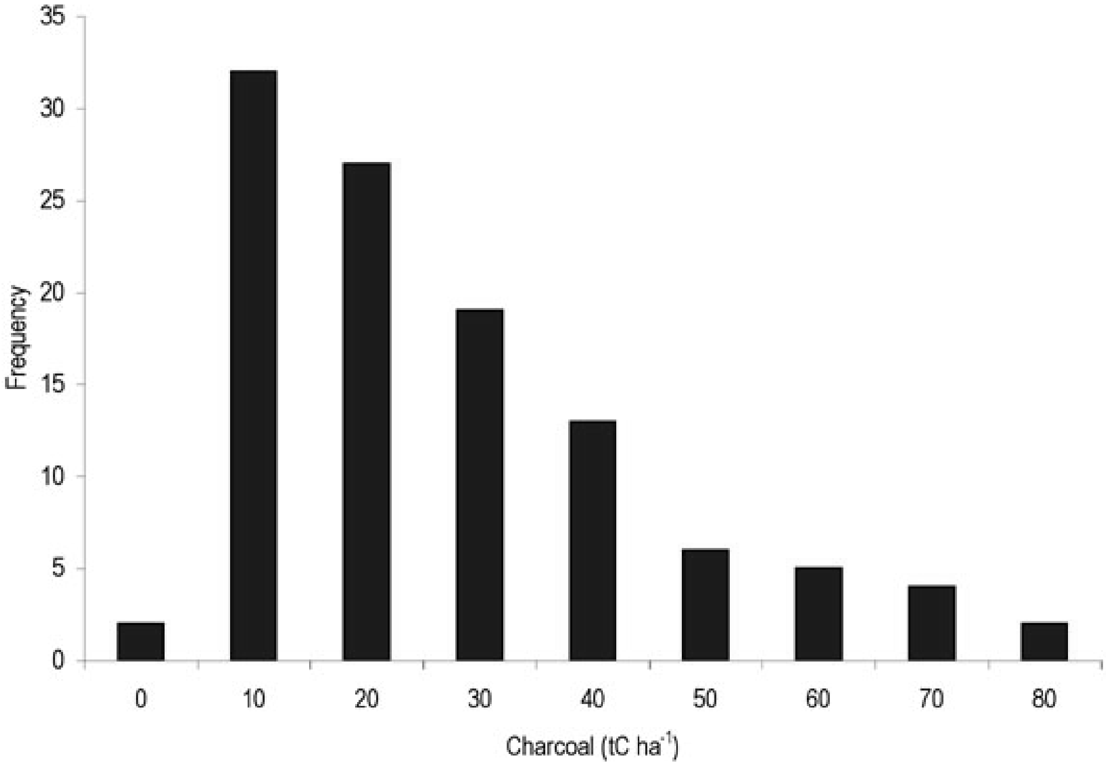

Figure 10: The class/frequency distribution of measured soil charcoal densities from 110 profiles of the St George-Duaringa gradsect. The distribution is distinctly lognormal with a median abundance of 17 tC ha^{-1}.

The second prediction - profile ratios of charcoal to OC will be constant within one (broad) climatic or soil type – was also supported at all profiles aggregate d. A regression forced through the origin gave an overall ratio of charcoal to OC of 0.34 ($P<<0.001$). That is, charcoal represents 25 % of TOC. However, the variation in the ratio was high and approximately 50 % of values fell in the range 0.17 – 0.77. Grouping the profiles by soil type indicated that the lowest ratios (≈ 0.2) occurred in the Dr3 soils whereas the highest ratios (≥ 1.0) were recorded in the Db1 and Gn1 soil types. No measured variable was a significant predictor of charcoal/OC ratio. Charcoal abundance was positively correlated with clay percentage ($P < 0.01$), and OC abundance was positively correlated with both nitrogen levels ($P < 0.001$), and clay percentage ($P < 0.001$).

The first two predictions addressed are of interest because they test the plausible assumptions that underpin our modelling. However, their validity is not of great moment. This is reserved for the third and last prediction. This forecast - the median and the distribution of measured profile charcoal densities (tC ha^{-1}) should form a constant fraction of the predicted values in Table 13 – is critical because it tests predictions of both the abundance and variability of charcoal across the landscape.

Charcoal abundance and variability within the landscape are simultaneously compared by plotting and regressing the predicted and field measured charcoal percentiles, see Figure 11. If the variability (distribution shape) is adequately predicted for the 5, 25, 50, 75, and 95 percentiles, then a linear relation will be possible, as here in Figure 11. In addition, the adequacy of the prediction of abundance will be demonstrated by the slope of the regression;

ideally, it should be ≈ 1.0 but here ≈ 0.7, along with a relatively insignificant offset of ≈ 3 tC ha^{-1}. That is, the model over-predicted the landscape charcoal levels by 30 %. Overall, we interpret the agreement between predicted charcoal abundance and variability as good.

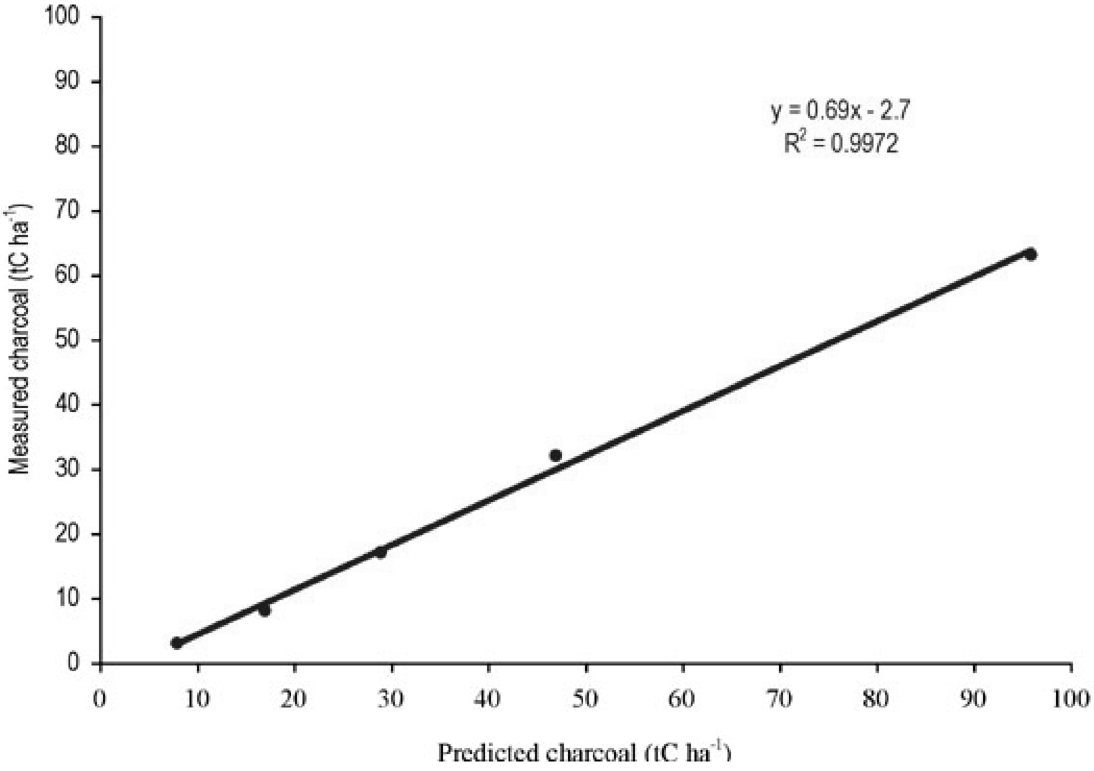

Figure 11: The agreement between predicted and measured charcoal abundance and variability for agricultural landscapes is demonstrated by regression of the 5, 25, 50, 75, 95 percentile values. The linear relationship indicates the variability (distribution) is in excellent agreement, while the slope indicates an over-prediction of ≈ 30 %.

There are two explanations of the over-prediction: the first is that it is a consequence of model structure and inputs while the alternative is that the gradsect is not representative of agricultural landscapes because it was located on the arid edge of current croplands. Both explanations are plausible and will be briefly explored.

The probabilistic model used to generate the predictions has a mechanistically simple structure, see equations (7) and (8). Because, the disagreement between predictions and observations is a consistent factor of ≈ 0.3, it is most likely that this difference is a consequence of the input variables rather than the model structure. The relative importance or influence of the input variables on the final charcoal prediction can be robustly evaluated by performing an absolute rank-order correlation between a sample of the output and a sample of each probabilistic (uncertain) input variable. This procedure was done within the Analytica software package and the relative importance of each variable calculated, see Figure 12. The most influential input variable on predicted charcoal abundance is L, the proportion of the landscape burned, see equation (7). Based on the author’s expert opinion, the value of L used was modelled as a lognormal distribution with a median value of 0.2, see Table A12 in Appendix A. It would be a simple matter to reduce L by ≈ 30 % to an equally plausible median value of 0.15. The same reasoning can be applied to the next two influential variables, the fuel load, and the between-fire interval. However, that is not the point. Rather, it is that the simple modelling used in this report appears adequate to predict landscape level charcoal abundance given correct input variables. It is unlikely that an important mechanistic component was ignored. Consequently, the ≈ 30 % over-prediction casts no significant doubt on the overall validity of the charcoal production modelling.

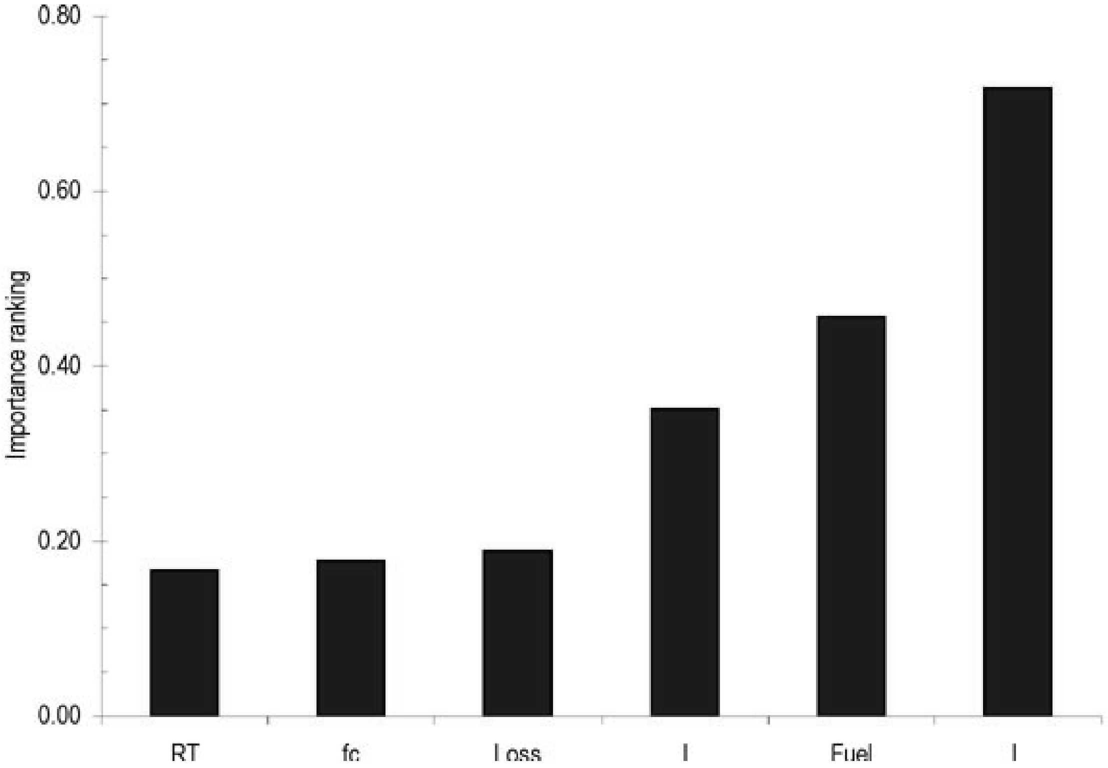

Figure 12: The relative importance of the six input variables in the calculation of charcoal abundance and distribution for agricultural landscapes. They are detailed in equations (7) and (8) and their identity here is as follows: RT (residence time, yr), f_c (carbonised fraction), Loss (fraction removed by water), I (between fire interval, yr), Fuel (loading, tC ha^{-1}), L (fraction of landscape burned).

An alternative explanation for the over-prediction is that the gradsect used for validation is not representative of agricultural landscapes because it was located on the arid edge of current croplands. The reasoning is that samples taken in the core cropping regions will show higher charcoal (and OC) values because the rainfall (and possibly clay levels) will be higher and less variable so that prehistoric burning will have been at the levels captured by the input variables used in equations (7) and (8).

To illustrate the plausibility of this explanation, we examine a supplementary dataset generated within the cropping lands of the Edgeroi 1:100K map sheet (no. 8837) in the Narrabri district of north-eastern NSW. These data, collected by CSIRO as part of a landscape-scaled study, are described by McGarry *et al.* (1989). The sampling strategy used was systematic and therefore unbiased, but it was localized compared with the St George-Duaringa gradsect used above. The data from 71 profiles to 1 m depth were available and analysed as for the St George-Duaringa gradsect.

The first prediction – the ubiquity of charcoal - was supported with all 71 profiles containing charcoal within a range of 1-94 tC ha^{-1}. In aggregate, the profile values had a median value of 25 tC ha^{-1} and were lognormally distributed. The second part of the first prediction – charcoal abundance will always be less than that of OC – was also generally supported. The respective OC and charcoal means, 59 vs. 32 (tC ha^{-1}), were significantly different ($P << 0.001$) and just six of the 71 profiles had higher charcoal than OC densities. Note that the above OC and charcoal mean values are comparable to those for the St George-Duaringa gradsect (54 and 22 tC ha^{-1}).

The second prediction - profile ratios of charcoal to OC will be constant within one (broad) climatic or soil type – was also supported at the level of all profiles aggregate d. A regression forced through the origin gave an overall ratio of charcoal to OC of 0.52 ($P<<0.001$), which translates to charcoal representing 36 % of TOC; a higher overall proportion than was calculated for the St George-Duaringa gradsect (25 %). A positive correlation existed between the clay abundance (for the 0.0-0.3 m of the profile) and the charcoal to OC ratio ($P >> 0.001$). Similarly, a positive correlation was found between the elevation of the profile and the charcoal to OC ratio ($P > 0.05$). Explanations for this correlation are that at low elevations, in the bottom lands, the charcoal is either preferentially lost or that OC production is enhanced and fire frequency diminished under the influence of runon water.

As stated earlier, the support for the first two predictions is of interest because they test the plausible assumptions that underpin our modelling. Testing the third prediction - the median and the distribution of measured profile charcoal densities (tC ha^{-1}) should form a constant fraction of the predicted values in Table 12 - is critical because it tests predictions of both the abundance and variability of charcoal across the landscape. The measured 5, 25, 50, 75, and 95 percentiles of Edgeroi charcoal abundance were regressed against the predicted values (Table 13) to give a very similar result to that for the St George-Duaringa gradsect. The regression has highly significant ($P << 0.001$) with an offset of 5 tC ha^{-1} and a slope of 0.7. That is, the model over-predicted the Edgeroi charcoal levels by 30 % as it did for the St George-Duaringa gradsect.

From this comparison of two different sites, the compelling conclusion is that the modelling of charcoal abundance, and not variability, is at fault. From Figure 12, the most influential variable for adjusting the model predictions is likely to be L, the fraction of the landscape burned. However, we regard the level of agreement between model and field data to be good and sufficient for the purpose of this report.

Tropical grasslands

The predictions were evaluated for the tropical grasslands using another systematic soil survey, the second collected under the direction of Dr Michele Barson of the Bureau of Rural Sciences, Federal Department of Agriculture, Fisheries and Forests of Australia (AFFA). The objective of this survey was the same as that for the agricultural lands, the St George-Duaringa gradsect. The gradsect was aligned with the Stuart Highway, south from Darwin to Wauchope (NT) and systematically sampled at 2-, 5-, and 10-km intervals, with the smallest interval used in the north and the largest in the south. Each profile was excavated to a depth of one metre, with samples collected at the following intervals: 0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.5, and 0.5-1.0.. Laboratory analyses and subsequent processing was as described for the agricultural lands above and all profiles that did not reach 1.0 m, or had missing samples were rejected leaving 223 of the original 320.

Altogether, the gradsect spanned eight degrees of latitude (12 – 20 °S) and the coordinates of the endpoints in the climatic factors of mean annual rainfall (mm) and temperature (°C) ranged from (1560, 27) in the north to (270, 25) in the south. This represents a substantial gradient in rainfall and thus in biomass, productivity, and fire frequency. This region of tropical grasslands has experienced frequent burning, now and in the past.

The first specific prediction - that all profiles will contain charcoal – was supported. Of the 223 profiles, only one profile had a char value of ≈ 0.00; it was at the edge of detection. The most likely explanation is that some (unknown) site soil factor interfered with the charcoal detection method; the adjacent site also had a very low char value. The measured charcoal densities were in the range 0 – 75 tC ha^{-1}, lognormally distributed with a median value of 11 tC ha^{-1}, Figure 13.

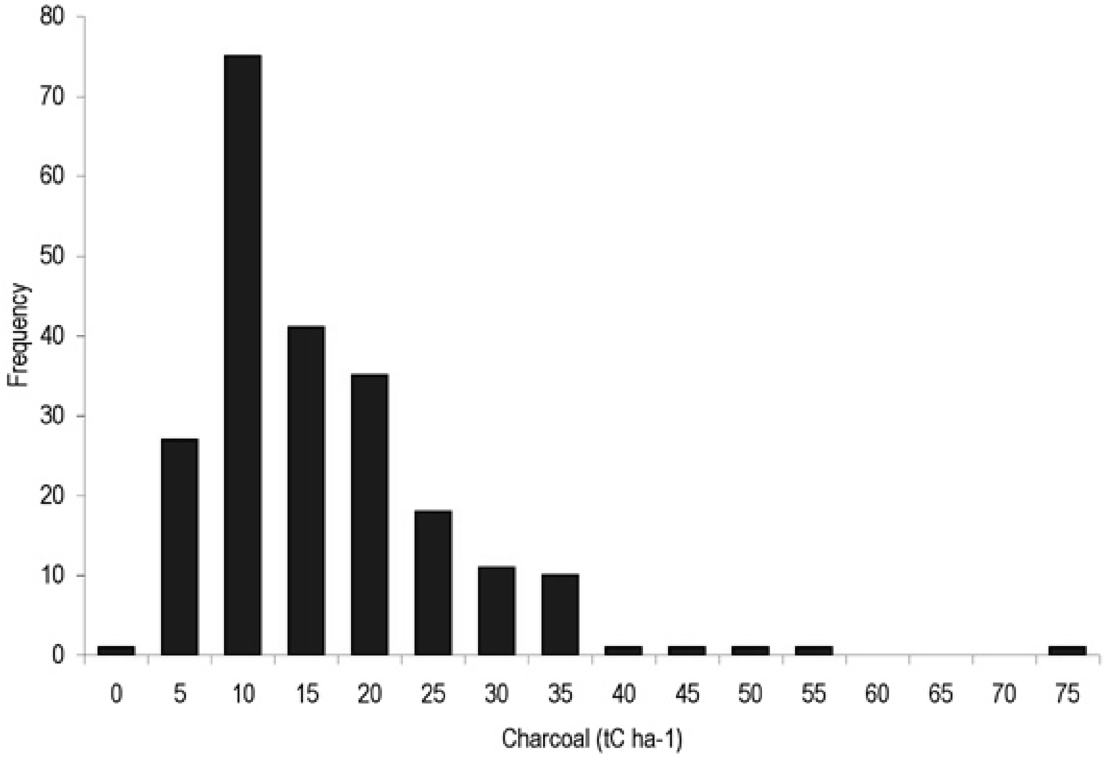

Figure 13: The class/frequency distribution of measured soil charcoal densities from 223 profiles of the Darwin-Wauchope gradsect. The distribution is distinctly lognormal with a median abundance of 11 tC ha^{-1}.

The second part of the first prediction – that charcoal abundance will always be less than that of OC – is also supported. The aggregate mean OC abundance of 35 tC ha^{-1} is significantly different ($P < 0.001$) from that for charcoal, 14 tC ha^{-1}. However, at the individual profile level, 29 of the 223 profiles had values for char abundance exceeding that for OC. Some of these profiles were spatially grouped and all had low to very low OC values. Thus, it is likely that they are inconsistent because of site-related errors in charcoal determination.

The second prediction - profile ratios of charcoal to OC will be constant within one (broad) climatic or soil type – was also supported at the aggregate level. For all 223 profiles, a regression forced through the origin gave an overall ratio of charcoal to OC of 0.3 ($P< 0.001$). That is, charcoal represents 23 % of TOC, a value that is little different from that for the agricultural lands. The variation in the ratio was high with 50 % of values in the range 0.21 – 0.61; an inter-quartile range that was slightly less than that for the agricultural lands above.

Because the Darwin-Wauchope gradsect extended over more than eight degrees of latitude, to 21° S, which is beyond the penetration of the monsoon (≈ 18 ° S, Bowman, 1996), relationships with latitude (as a surrogate for climate) were sought rather than with soil type. Soil nitrogen was negatively correlated ($P< 0.001$) with south latitude, consequently so was OC abundance ($P< 0.001$). There was no direct correlation between charcoal abundance and latitude but it was positively correlated with nitrogen levels ($P< 0.001$), and hence OC, and with soil clay percentage ($P< 0.001$).

The key prediction concerns the overall abundance and variability of soil charcoal; the measured profile values should form a constant fraction of the predicted values in Table 12. The agreement between predicted five percentile values and the measured values is excellent, see Figure 14.

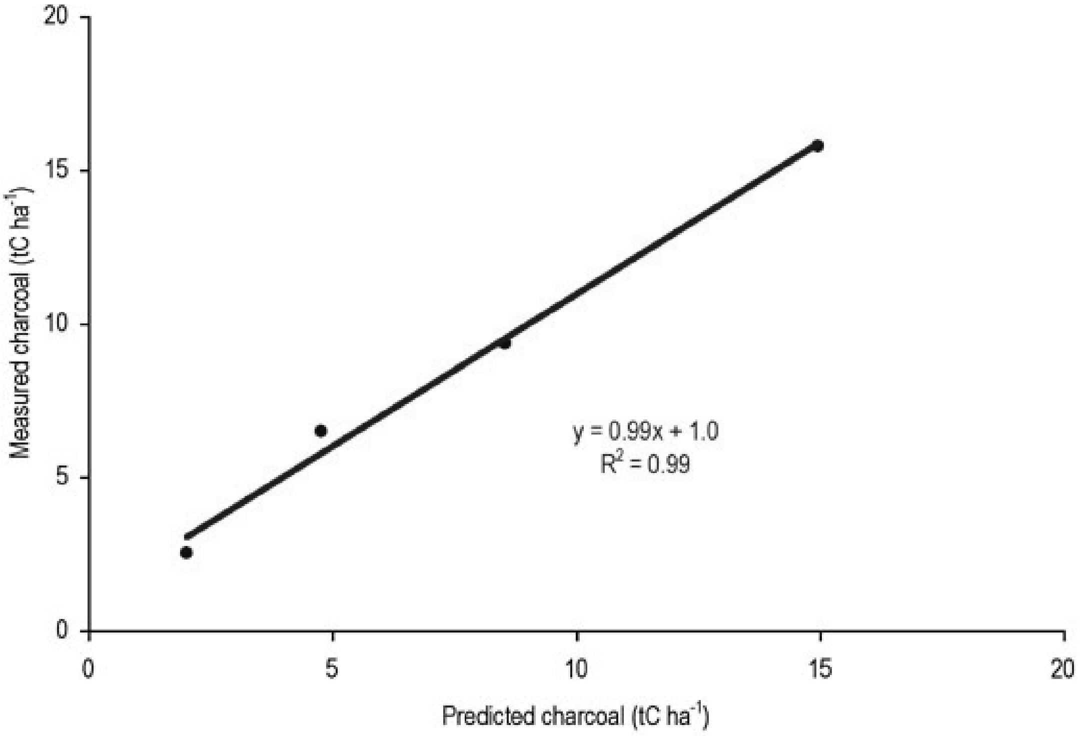

Figure 14: The agreement between predicted and measured charcoal abundance and variability for tropical grasslands is demonstrated by regression of the 5, 25, 50, 75, 95 percentile values. The linear relationship indicates the variability (distribution) is in excellent agreement, while the slope indicates an almost perfect agreement.

The match between predicted and observed is thought provoking. Two possibilities suggest themselves: either the choice of input values was perceptive or it was fortuitous. Choosing between the two explanations is informed by examining the importance or relative influence of the input values on the predicted values as was done for the agricultural lands. The structure of the charcoal production model for the tropical grasslands differs slightly from that used for the agricultural lands, thus the importance ranking in Figure 15 differs from Figure 13.

The most influential variable in the model predictions of charcoal levels in the tropical grasslands is f_c, the fraction carbonised. As explained both in main text and in Appendix A, because of a novel field-estimation technique, we have confidence in the representation of this variable in the model. The next most influential variables are not surprising: total fuel load and the rate of charcoal loss by water. Because of some available data, we have greater confidence in representing the former than the latter because we could find no published data to guide us. What is surprising is the relatively low importance ranking of residence time (RT), which is fortuitous because of all the variables in the model, residence time was entirely based on the expert opinion of the authors.

To summarize: the objective of this last Section was to validate the model calculations of annual charcoal production for the four fire types of the continent. The validation strategy was to predict pool size and variability: specifically by forecasting contemporary soil charcoal levels for the agricultural and tropical grassland, and then testing these predictions against field measurements. For the tropical grasslands, which are the sites of the most extensive annual burning (of resilient landscapes), the agreement was excellent. For the agricultural lands, which are no longer the location of any significant burning, the agreement also was good. The compelling conclusion therefore is that the annual charcoal production rates calculated in a previous Section are very close to the yet unmeasured actual values.

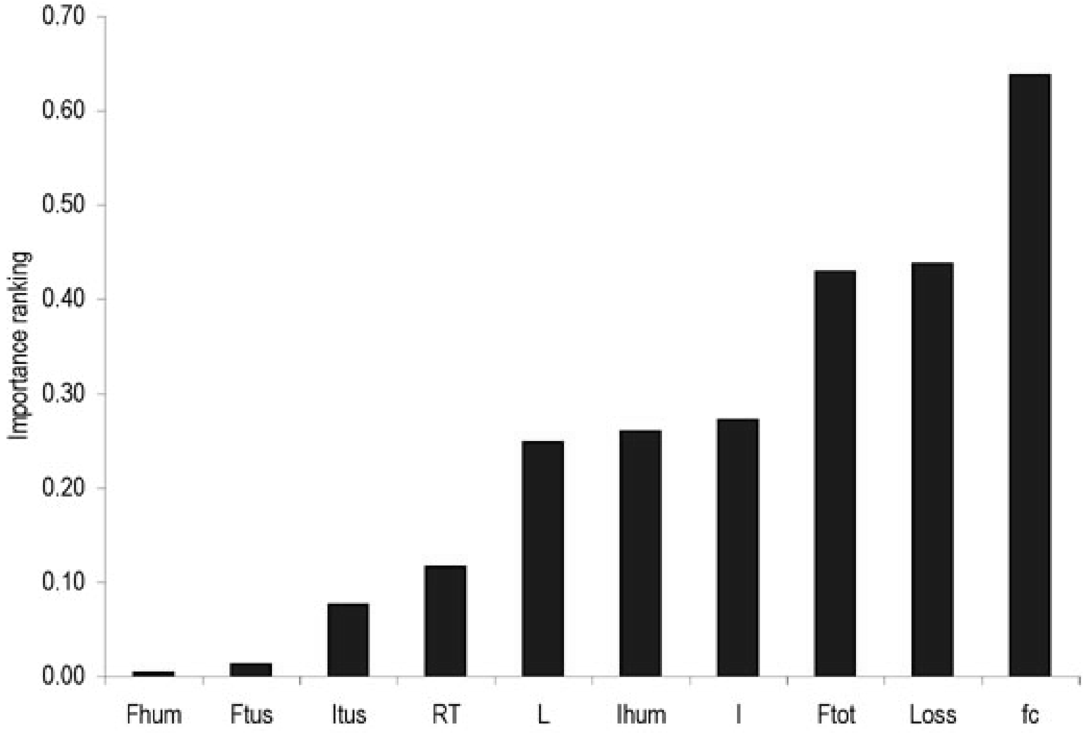

Figure 15: The relative importance of the ten input variables in the calculation of landscape charcoal abundance and distribution for the tropical grasslands. Most of the variables are detailed in equations (7) and (8). A complete listing is as follows: F_{hum} (hummock grass fuel load), F_{tus} (tussock grass fuel load), I_{tus} (tussock grass fire interval, yr), RT (residence time, yr), L (fraction of landscape burned), I_{hum} (hummock grass fire interval, yr), I (0.7 I_{tus} + 0.3 I_{hum}), F_{tot} (0.7 F_{tus} + 0.3 F_{hum}), Loss (fraction removed by water), and f_c (carbonised fraction),

Continental pool size

The final step is to calculate the continental pool size of charcoal based on the estimates of production dynamics that have been successfully validated against field measurement in the previous section. The pool size is the product of the predicted landscape-average charcoal densities (tC ha^{-1}) in Table 13 and the relevant area of landscape. The latter term is the product of annual area burned (A) and the between-fire interval (I).

This calculation can be done with most confidence for the tropical grasslands. For this landscape type, the agreement between prediction and measurement was excellent. From Table 12, the median charcoal pool size (0-1.0 m) was 8 tC ha^{-1}. Taking the mean annual area burned as 40 Mha yr^{-1} and the median between-fire interval as 3 yr (Table A13), the estimated tropical grassland pool size is ≈ 0.96 GtC. Please note that this value is calculated for 120 Mha of grasslands that are notionally burned in the calculation above.

For the agricultural lands, an estimate can be constructed thus. The estimated landscape-average charcoal abundance (tC ha^{-1}) can be adjusted to compensate for the consistent model over-prediction of 30 %, assuming large-scale applicability of this finding. The question then becomes, what is the relevant area of landscape? The agricultural lands of the continent, taken to be the croplands plus improved pasturelands, span a wide range of climatic and soil factors. Weighting these factors, we take 100 Mha of the total 150 Mha of agricultural lands as being relevant to this calculation. From this the estimated charcoal pool size of the agricultural lands is (100 Mha x 29 tC ha^{-1} x 0.7), or 2.03 GtC. Thus, for the two landscape types, agricultural plus tropical grasslands, the total charcoal pool is ≈ 3 GtC.

Policy implications

In the Introduction, we nominated national and international policymakers as one of two audiences for this report. The policymakers specified are those who carry the responsibility for mitigating enhanced greenhouse effect (EGE) Climate Change by minimizing net emissions of greenhouse gases, principally CO_2. Within the last decade, the international community has accepted the overall necessity of, and responsibility for, decarbonizing national economies, where economic activity is taken to include both industrial metabolism and landuse. The objective of decarbonization is to reduce the *net* transfer of carbon (as CO_2) from geospheric (fossil fuels) and biospheric (landuse) pools to that of the atmosphere. To meet this objective, a purely scientific assessment is that the compelling strategy is to simultaneously, but in priority order, (1) reduce emissions and (2) increase sequestration of CO_2.

The scientific community brought the issue of EGE Climate Change to the attention of the international community but its solution is (correctly) political. The political expression of the above (scientifically) compelling strategy is the Kyoto Protocol, an international treaty agreed to in 1997 to reduce greenhouse gas emissions and increase active CO_2 sequestration into biospheric pools via altered land management. The overall objective of the Protocol was a reduction of net emissions to 95 % of the 1990 baseline by the first commitment period of 2008-2012 using a combination of reduced emissions and the creation or enhancement of (biospheric) carbon sinks, as well as the international trading of emissions and sinks. To obtain final agreement on the details of this three-part strategy of emission reductions, sinks, and trading has taken five years and seven periods of negotiation by the Conferences of the Parties (COP 1-7).

Science has been described as the art of the soluble, whereas politics is the art of the possible. In its present form, the Kyoto Protocol (yet to become law at time of writing, early 2003) is obviously the only consensus that was politically acceptable. One assessment by scientists is that the Protocol will have very serious unintended consequences for global biodiversity and the conservation of primary forests. In addition, its currently proposed techniques of verification will be inadequate and that some of its prescribed land management practices are unlikely to sequester carbon (Schulze *et al.*, 2002).

Accepting that the current Kyoto Protocol has significant flaws, it remains the only international agreement to limit the net emissions of greenhouse gases. Somewhat surprisingly, it was agreed that carbon sequestration could account for 80 % of the net reduction in emissions assigned to each participating nation. The only currently acceptable sinks for carbon sequestration are those associated with the land management practices of Afforestation, Reforestation, and Deforestation (ARD), the biospheric sinks of plant biomass and soil carbon (OC).

The charcoal sink of biomass burning is not acceptable as a carbon sink, and in the authors' understanding, it was not proposed as a sink by any nation at any of the Conferences of the Parties (COP 1-7) negotiations. Nonetheless, from a scientific viewpoint, we contend that the charcoal sink has utility and if its merit can be convincingly demonstrated, it may be considered in the future as the Kyoto Protocol evolves. It is unlikely that any changes to the Protocol will occur before the 2008-2012 Commitment Period but change is inevitable given the probable advent of newer CO_2 geo-sequestration technologies, such as deep ocean burial.

The objective of this Section is to substantiate our contention that the charcoal sink has properties that, in comparison with the soil carbon sink currently accepted under the current Kyoto Protocol, make it suitable for consideration. Charcoal and soil carbon are compared nationally, and where possible globally, under the following six headings.

Origin

The formation of both charcoal and soil carbon are natural processes that are also influenced by imposed land management practice. However, not all biomass burning, and thus charcoal production, is the result of land management. While data are few and almost impossible to collect, the widely-held view is that fires in the tropical forests and savannas are entirely the direct result of human action, whereas those in the boreal forests and tundra are the opposite being principally the result of lightning strikes, see for example Glasser and Lulla (2000). Therefore, any national claims of charcoal sink would need ancillary evidence of a history of human ignition. Given opportunity, the charcoal sink could be claimed by the savanna-containing nations of Africa, Asia, South America, and Oceania.

Nature

In the carbon chemistry of biomass burning Section, the analogy was drawn between the chemical nature charcoal and the most recalcitrant form of soil carbon, humus. While both charcoal and humus are very resistant to biodegradation and thus long-lived, the analogy between soil carbon and charcoal is not exact. From the instant of formation, the mixtures of carbon compounds that comprise charcoal are highly inert. In contrast, at the instant of formation following death and decomposition of living tissue, soil carbon is mostly highly labile and readily decomposed by microbes. The recalcitrant humus fraction of soil carbon is generated only as a metabolically resistant fraction that slowly accumulates after repeated cycles of decomposition, and by physical protection by clay complexation (Sollins *et al.*, 1996). Consequently, the humified fraction is usually the oldest fraction of soil carbon (Schlesinger, 1997; Perruchoud *et al.*, 1999). Therefore, all other factors being equal, an equal mass increase in landscape soil carbon and charcoal over a decade does not represent equivalent growth in carbon sinks. The soil carbon sink will be very much more labile than that of charcoal. Thus, in respect of sink lability and thus security, charcoal is superior to soil carbon.

Sink dynamics

Within the Kyoto Protocol, there is implicit recognition that the various (land management) carbon sinks specified represent short-term contributions to the long-term problem of reducing greenhouse gas emissions. Because the underpinning models generate climate simulations to the end of the 21st century, we can take 100 yr (or less) as the maximum time horizon for such biospheric sinks.

To function effectively as a sink over the next 50-100 yr, the starting pool size of soil carbon and charcoal must be a long way from equilibrium so that the rate of increase in pool size is constant and at near maximum. Is this a likely scenario? It is for a soil carbon sink created under Afforestation land management, using land where there have been no trees for the previous 50 yr, but less so for Reforestation. In these two situations, there will be an increase in the quantity and decrease in the quality of dead plant material (above- and below-ground litter) available for decomposition. The general expectation is that together, these two conditions will generate an overall increased level of soil carbon with a (desirable) positive trend in the size of the humified fraction. The generality of this expectation has been specifically challenged by Jackson *et al.* (2002).

The hypothetical situation of claiming a charcoal sink would be very different. This sink could be claimed by a nation only under the condition of biomass burning being part of land management (i.e. lightning fires excluded) on resilient landscapes; that is, where the fuel rapidly regrows. For Australia, such a hypothetical claim could be based the annual biomass burning of the tropical grasslands. These fires, which annually cover about 5 % of the continental area (≈ 40 Mha), burn grassy fuel that regrows during the next Wet Season. Given acceptance of a (direct) human management origin, the principal question then becomes whether the charcoal sink for these tropical grasslands is at steady state; is it in equilibrium with current input, or far from equilibrium such that the char pool size is steadily increasing?

Three interconnected factors shape the answer to this critical question. The first concerns charcoal production dynamics. If production, and thus input to the soil charcoal pool, has exhibited trends on timescales that are significant compared to its estimated residence time, then steady state conditions are unlikely. Given that a median residence time of 4000 yr has been assumed and that the (very poor) record of annual area burned is for the last two decades only, no quantitative demonstration can be made of any trends of a significant length, e.g. 100 yr. Nonetheless, there is expert opinion that resulting from closer settlement and intensified pastoral landuse, the extent and frequency of burning has increased in the last century and particularly in the last 50 yr; e.g. see Preece (2002) and references therein. Therefore, it is unlikely that the charcoal sink of Australia’s tropical grasslands is in equilibrium with current input.

The second factor is the residence time. Based on the expert opinion of one of the authors (JOS), the residence time was judged to be between 3000 to 5000 yr and modelled as a normally distributed variable with a mean of 4000 yr, see earlier. This value is taken to describe the background rate of chemical and biological degradation of charcoal. It was used for modelling the charcoal pool size in both agricultural lands and tropical grasslands even though it was believed the residence time in the latter could be much less, perhaps as short as 500 yr. A shorter residence time was proposed because of comparatively low levels of clay in tropical grassland soils. At high clay levels, ≥ 30 % as in most agricultural soils, charcoal is physically stabilised whereas at lower levels, charcoal can be illuviated from the upper profile and possibly lost via groundwater.

The last factor is the actual fate of soil charcoal. As outlined above, the authors estimated that the residence time of charcoal in soils where it is immobilised by clay particles is 3000 to 5000 yr with the assumption that the ultimate fate is oxidation by chemical or biological agents. By contrast, in clay-poor sandy soils, it is very likely that charcoal is predominantly lost from the upper profile by physical transport, by percolating water. Its fate is then to either accumulate elsewhere or, far more likely, to undergo accelerated oxidation, solution, and then transport in groundwater.

These three factors are connected mechanistically because they are all involved in quantifying sink dynamics, and because of the considerable uncertainty associated with each of them. In the previous two Sections, charcoal pool sizes were predicted based on 5000 yr of biomass burning that were well supported by field measurements. The agreement was excellent for the tropical grasslands even though the residence time used (3000 to 5000 yr) was for oxidation in clay rich (≥ 30 %) soils and almost all profiles of the Darwin-Wauchope gradsect had clay levels of ≤ 30 %.

Two conclusions emerge from this discussion. The first is that it is most unlikely that the charcoal sink of Australia’s tropical grasslands is currently in steady state. The second conclusion is that a critical gap in predictive understanding of charcoal in tropical landscapes is the relative importance of in situ oxidation versus transport. Given resolution of this issue, then a better understanding of the residence time of charcoal in tropical grasslands will follow.

Sequestration rates

Using the model that estimated total annual charcoal production rates, see Table 6, the median annual charcoal production for tropical grasslands was ≈ 0.20 tC ha^{-1} yr^{-1} with an interquartile range of 0.15-0.24 tC ha^{-1} yr^{-1}. This modelled production rate is comparable with the measured rates of 0.04-0.3 tC ha^{-1} yr^{-1} for charcoal production in tropical lowland forests; see Table 5.5 of Schlesinger (1997). What rates of soil carbon formation can be expected?

Changes in soil carbon consequent upon changes in land management are variable being strongly dependent on site factors and historical context (Guo and Gifford, 2002). Reviews of reported rates of short-term soil carbon accretion illustrate this variability (Post and Kwon, 2000). Nonetheless, a value of 3 tC ha^{-1} yr^{-1} (TOC) can be taken as an indicative rate. This rate is 15 times larger than the modelled charcoal production rate from tropical grassland fires.

Schlesinger (1997) acknowledges that short term (< 10 yr) rates of accretion of soil carbon can be high given dramatic changes in land management, such as Afforestation or Reforestation. However, he cautions against optimism by noting that longer term measurements (> 1000 yr) reveal that the high short term accretion rates of labile soil carbon are ultimately translated into overall much lower sequestration rates of recalcitrant soil carbon after steady state conditions are achieved. As an illustration, he notes that the long term rates of sequestration of the recalcitrant humus fraction of soil carbon lie in the range 0.1-1.2 tC ha^{-1} yr^{-1}, with the highest rates occurring under cool, wet conditions, see p. 159 of Schlesinger (1997). Thus, in terms of the sequestration of inert carbon in soils, charcoal production from biomass burning is comparable with the lower (global) rates of humus production. Such low rates of humus production could be expected to typify Australian conditions. Thus, in terms of the sequestration rates of recalcitrant carbon, those for soil carbon approximate those for charcoal.

The objective of sink creation is to reduce the net transfer of carbon from the geospheric to atmospheric pools. With this objective, isn't labile soil carbon equally effective as recalcitrant carbon? Especially, when sinks are regarded as a short-term measure, 30-50 yr, while significant technological changes can be effected to globally increase the carbon efficiency of economic activity. In terms of the chemistry of sequestering carbon, labile soil carbon is equally effective as recalcitrant carbon. In terms of the risks associated with maintaining the sequestered carbon within a landuse system for 30-50 yr, labile soil carbon is most unlikely to be as effective as recalcitrant carbon.

The preceding discussion of relative rates of carbon sequestration is but one aspect of comparing the *potential* for charcoal and soil carbon methods. Equally important is the *actuality* of the current charcoal sink. Considering only the contribution of tropical grassland burning, the estimate of median annual charcoal production is 5.6 MtC yr^{-1}, see Table 6. This is equivalent to ≈ 21 $MtCO_2$ yr^{-1}, or 6 % of Australia's 1990 emission rate; see Table 2 of National Greenhouse Gas Inventory: Analysis of Trends and Greenhouse Indicators, 1990-2000 available at http://www.greenhouse.gov.au/inventory/2000/trends/index.html. Thus, if the charcoal sink was accepted within a hypothetical Kyoto Protocol, Australia would have achieved the target emissions reduction value of 5 % of the 1990 emissions.

Using an indicative sequestration rate from Post and Kwon (2000) of 3 tC ha^{-1} yr^{-1} for soil carbon production under Afforestation, approximately 1.9 Mha of (established) afforested land is required annually to match the carbon sink currently estimated for charcoal. Furthermore, this area would need to be in the higher rainfall areas of the continent, the high value agricultural lands, to achieve soil carbon sequestration rates of 3 tC ha^{-1} yr^{-1}. Such an afforestation effort is possible but only with significant cost.

Sequestration costs

The question considered here is what are the comparative carbon costs of sequestration by soil carbon or by charcoal production. This question is a subset of the larger national policy question of estimating the costs and benefits both in dollar and in carbon terms. A full cost-benefit study is not attempted because both professional (economic) competence and relevant data are limiting. Nonetheless, the question can be addressed in relative rather than absolute terms with the following reasoning.

The absolute carbon costs of land management options are not (yet) known. However, in relative terms, a plausible proposition is that nationally, the carbon costs of land management are greater in the high rainfall, intensively managed lands than in the lower rainfall, extensively managed lands. The carbon benefit is assessed by the actual sequestration rate (tC ha^{-1} yr^{-1}).

In a hypothetical scenario for Australia, four land management options can be compared by the contingency of carbon costs and benefits, each resolved at only two levels, high and low. Afforestation, planting trees where no trees have been for the previous 50 yr, would be the principal sequestration strategy because it is *most likely* to generate higher rates of soil carbon gain than Reforestation, Table 14. However, the recently published findings of Jackson *et al.* (2002) will require a reassessment of this generality.

Table 14: A contingency table of land management options in terms of carbon costs versus carbon benefits.

Carbon costs	HIGH	Afforestation of degraded croplands	Afforestation of high rainfall pasturelands
	LOW	Tropical grassland burning	No option available
		LOW	HIGH
		Carbon benefits	

The first and principal point of Table 14 is that there is no ‘magic bullet’ for carbon sequestration using land management. A low cost, high carbon benefit option just does not exist. The least attractive option is the Afforestation of degraded croplands with high cost and low carbon benefits. Nonetheless, this option is frequently promoted as a solution to the significant and long-lived economic and social problems of some rural areas. The most attractive carbon option, the Afforestation of high rainfall (‘improved’) pasturelands (low cost and high benefit) is economically absurd and thereby socially unacceptable. It would be very difficult for society to accept that the loss of the most valuable agricultural land to a carbon sink was in the national interest. Alternative strategies for reducing net emissions are available but high quality agricultural land is not. The last option is the charcoal sink. While low carbon benefit, it is also (very) low carbon cost and the charcoal carbon is more securely sequestered than that of soil carbon. Therefore, with respect to sequestration costs, charcoal appears superior to soil carbon.

Verification and compliance

For the certification and national accounting of terrestrial sinks, the principal attributes are where, when, and how much. For the case of soil carbon as a component of Afforestation and Reforestation, an independent verification of space and time dimensions of the land management changes can be derived from the national and international archives of satellite images. For a hypothetical charcoal sink, the space and time dimensions of tropical grassland fires are also available from satellite image archives from 1979 onwards. In addition, the critical measurement program for either sink type would be the same, a soil sampling strategy to demonstrate the rate of change of soil carbon or charcoal. Both forms of carbon would require similar levels of sampling intensity and measurement precision, details of which are yet to be finalized by the (yet to be formed) Enforcement and Facilitation Branch of the

Protocol bureaucracy. Currently, for soil carbon, laboratory measurements and standards are more unified than for charcoal. However, this problem is now being addressed by the formation and activity of the International Steering Committee for Black Carbon Reference Materials. Therefore, in terms of ease of verification and compliance, charcoal is equivalent to soil carbon in that they are both similarly difficult. Given the widespread experience of high levels of variability between adjacent sites, many soil scientists doubt that significant changes in soil carbon or charcoal over short periods, such as 5 yr, can ever be demonstrated.

Summary

From the six comparisons discussed above, the following conclusions can be drawn. In terms of the security of the carbon sequestered and of the carbon costs involved, charcoal appears a superior sink to soil carbon. In terms of rates of sequestration of recalcitrant carbon and verification, charcoal and soil carbon are equivalent as sinks. Nevertheless, the most significant point is that the charcoal sink is currently in operation, sequestering carbon at an estimated median rate of 5.6 MtC yr^{-1}, equivalent to ≈ 21 $MtCO_2$ $yr^{-1,}$ or 6 % of Australia’s 1990 baseline CO_2 emission rate.

Conclusions

This report was based on two arguments. The first was this qualitative argument: in a manner analogous to the decomposition of plant biomass and the formation of humus, biomass burning has the potential to generate a sink for atmospheric CO_2 by the production of refractory charcoal. This argument was elaborated by discussion and synthesis of the literature and structured by the question of what is charcoal and how can it be measured?

An analogy was drawn between the chemical nature charcoal and the most recalcitrant form of soil carbon, humus. While both are very resistant to biodegradation and thus long-lived with potential for carbon sinks, the analogy is not exact. From the instant of formation, charcoal is highly inert whereas the recalcitrant humus fraction of soil carbon is generated only as a metabolically resistant fraction that slowly accumulates after repeated cycles of decomposition and by physical protection by clay complexation. Thus, in respect of carbon sink lability and consequently security, newly formed charcoal is superior to newly formed soil carbon.

While laboratory methods for charcoal measurement are not standardised, this problem is now being addressed by the formation and activity of the International Steering Committee for Black Carbon Reference Materials. Nevertheless, char sampled in the field is equivalent to charcoal determined in the laboratory. Whatever fraction of the total char carbon that resides in labile compounds, it is small and insignificant compared with the independent uncertainties associated with identifying charcoal and estimating its production.

The second argument dealt with the quantitative aspects of charcoal and comprised the principal objective of this report: to substantiate the potential of charcoal as a carbon sink by addressing the issues of how much, how long-lived, and where is the sink? These three issues were recast as the following questions: how to quantify the charcoal pool size and dynamics for the continent; what is the production rate of charcoal; and what are the policy implications of our findings?

Because of the paucity of field charcoal measurements, in both number and spatial distribution, the preferred direct strategy of calculating charcoal pool size and then dynamics, could not be used. Instead, an alternate strategy was used beginning with the dynamics and then inferring continental pool size. The dynamics of charcoal was taken to comprise production, redistribution, and residence time. All three components were model-based, and the predictions were tested against available field measurements. The modelling employed, while probabilistic, was simple and transparent.

Biomass burning on the Australian continent was divided into four fire types (Managed, Unmanaged, Grassland, Clearing) and the statistical descriptions of burned area for an 18-yr period were used to calculate charcoal production rates – the dynamics. The median annual charcoal production rates (MtC yr^{-1}) for the four fire types were 0.14, 0.13, 5.6, and 1.9, respectively. The tropical grasslands, which currently experience the most extensive annual burning, are also the largest source of charcoal. The median production of all fire types combined was 8.3 MtC yr^{-1}, equivalent to the sequestration of ≈ 30MtCO$_2$ yr^{-1}, or 8.5 % of Australia's 1990 baseline CO$_2$ emission rate.

To validate the methodology and parameters used, predictions were made of the charcoal distribution in the 0-1 m profile for the tropical grasslands and agricultural lands based on the last 5000 yr of burning. This required modelling of the charcoal production rate, transport by wind and water, and residence time. These predictions of charcoal abundance and variability were tested against two sets of field measurements for the agricultural lands, and one for the tropical grasslands. For the agricultural lands, the predicted median charcoal abundance was 29 tC ha^{-1}, and the agreement with the two sets of field measurements was good but with a consistent model over-prediction of 30 %. For the tropical grasslands, the predicted median charcoal abundance was 8 tC ha^{-1}, and here the agreement was excellent. The calculated charcoal pool sizes for the agricultural and tropical grasslands were 2 GtC and 1 GtC, respectively.

The characteristics of soil carbon and charcoal were compared as operational carbon sinks within a hypothetical Kyoto Protocol. The characteristics were origin, nature, dynamics, sequestration rate and carbon cost, and verification and compliance. In terms of the security of the carbon sequestered and of the carbon costs involved, charcoal appears a superior sink to soil carbon. In terms of rates of sequestration of *recalcitrant* carbon and verification, charcoal and soil carbon are equivalent as sinks. Nevertheless, the most significant point is that the charcoal sink is currently in operation. Considering only the tropical grasslands, the location of the most extensive burning, the charcoal sink is sequestering carbon at an estimated median rate of 5.6 MtC yr^{-1}, equivalent to ≈ 21 MtCO$_2$ yr^{-1} or 6 % of Australia's 1990 baseline CO$_2$ emission rate.

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Appendix A: Char production calculations

Preamble

The objective of this Appendix is to explicitly detail the calculation of charcoal production for each fire type, and to separate this necessary detail from the main text to maintain its readability.

The basic algorithm underpinning all estimates of charcoal production are equations (5) and (6) of the main text, reproduced here for convenience as equation (A1, A2).

$$C_{char} = A\ M\ (1 - \square_{\square}) \qquad \text{(A1)}$$

$$\square_{\square} + \square_{c} + f_{u} = 1.0. \qquad \text{(A2)}$$

Note that ($\square_{\square} + \square_{c}$) defines the fraction of the fuel carbon that is fire affected.

The foundation compilation or derivation of the principal variables (A, M, $\square_{\square}$) is contained in Graetz (2002), to which the reader is referred. The values were derived from an 18-yr time series of State and Territory statistics of variable quality (A), and reasoned from a few published examples (M, $\square_{\square}$). A previously stated assumption is that the 18-yr statistics captured a stationary series of fire occurrence in Australia. From this assumption, we reason that the charcoal production values based on the past are generally applicable to the future.

Appendix A is structured by the objective of calculating the charcoal production for each of four fire types. Each of these four separate Sections addresses the following questions.

1. What is the necessary system description?
2. What modifications to the production equation (A1) are required?
3. What are the appropriate values for the required variables?
4. What are the 5, 25, 50, 75, and 95 percentiles of charcoal production?

The percentiles of charcoal production are transferred as tables to the main text for comment and summary.

Managed forest fires

System description

These are fires prescribed by land management agencies to reduce fuel loadings. From the descriptive title, it is assumed that this category includes a broad range of vegetation types: from tall, closed forests to smaller and sparser open forests and woodlands. The land management agencies most likely to conduct prescribed burning are Forestry (high value forests) and National Parks (open forests, woodlands and heaths). This range of vegetation types will have an equivalent range of intrinsic productivity and thus fuel load.

The fuel layer consists primarily of a dead and decomposing litter layer, and secondly of whatever (live) understorey is present. Because these fires are managed, it is assumed that their intensity is always so low that live overstorey canopy components (leaves, twigs, bark) are *excluded from the fuel*. Typically, the annual contribution from the canopy to the litter fuel layer (bed) consists mostly of fine material (leaves, twigs), and larger sized branches and bark slabs. As this litter layer accumulates over the years, the average composition changes because the fine materials, particularly the leaves, decompose more rapidly leaving behind the more decay-resistant coarse material. Thus, at time of burning when fuel loads are at or approaching some prescribed limit, such as 15 tdm ha^{-1} total, the fuel layer will probably be densely packed and comprise mostly coarse woody material.

Production equation

From the system description above, Managed (and Unmanaged) forest fires are those in which a component of the fuel is exposed to the fire but remains unburned, the third fate mentioned in the main text. For physical reasons, in this and Unmanaged forest fires, the finer fraction of the fuel load is preferentially combusted, leaving the larger coarse woody debris largely unburned. Thus, equation A2 is applicable and equation A1 must be modified to the following to account for this unburned component.

$$C_{char} = A\ M\ (1 - f_v)\ f_c. \qquad \text{(A3)}$$

Here the non-volatised component of the fuel is first calculated, then multiplied by the fraction carbonised (f_c), an additional variable. It should also be noted that in equation A3 above, the charcoal (as black carbon) that forms in the smoke plume is not considered. The emission factor for black carbon is $(0.5 \pm 0.2)\ 10^{-3}$ kg kg^{-1} of fuel burned, equivalent to a trivial 0.1 % of the fuel carbon (Andreae and Merlet, 2001).

Required variables

The areas of Managed forest fires (A, ha yr^{-1}) are modelled as normal distributions for each State and Territory; see Table A4, Graetz (2002). These area distributions are used here after truncation at the minimum recorded value, Table A1. Similarly, the fuel carbon densities (M, tC ha^{-1}) from Table B2 of Graetz (2002) are used after truncation to a minimum value of 2.25 tC ha^{-1} (5.0 tdm ha^{-1}), Table A1.

Table A1: A summary of the values used to model the areas (A, ha yr^{-1}) and (pre-burn) fuel carbon densities (M) for Managed forest fires in each State and Territory. The values for area (A) are in order: mean, standard deviation, truncated lower limit (ha). The values for fuel carbon abundance (M) are in order mean and standard deviation. All M distributions were truncated at 2.25 tC ha^{-1}.

State/Territory	Area (ha yr^{-1})	Fuel carbon abundance (M, tC ha^{-1})
NSW	124000, 46000, 50000	6.3, 1.8
Vic	120000, 57000, 30000	7.2, 1.4
Qld	104000, 38000, 28000	4.5, 1.9
SA	400, 300, 0	4.1, 1.9
Tas	18000, 10000, 5000	5.9, 1.9
WA	271000, 66000, 193000	5.9, 1.8
NT	NA	NA
ACT	500, 300, 0	6.3, 1.7

The fuel fraction volatilised (f_v) for Managed forest fires in each State and Territory was modelled by as a function of pre-burn biomass; see equation B3 of Graetz (2002) who used the symbol ε. With greater experience of its implications, this relationship is revised with a modified (lower) intercept, and slope to accommodate working in carbon rather than biomass densities, thus:

$$f_v = - 0.044M + 0.9. \qquad \text{(A4)}$$

The modelled values are summarised in Table A2.

Table A2: A statistical summary of the modelled fraction of the fuel volatilised (f_v) during Managed forest fires. Median values are in bold.

Percentiles	NSW	Vic	Qld	SA	Tas	WA	NT	ACT
5	0.49	0.48	0.55	0.58	0.44	0.44	NA	0.41
25	0.56	0.54	0.63	0.65	0.55	0.55	NA	0.53
50	**0.62**	**0.58**	**0.69**	**0.70**	**0.63**	**0.63**	NA	**0.61**
75	0.67	0.62	0.73	0.75	0.70	0.70	NA	0.68
95	0.75	0.68	0.78	0.79	0.77	0.77	NA	0.77

It remains to assign a value to the fraction of the (fire-affected) fuel biomass carbonised during exposure to fire, f_c or char fraction. As for most other variables, there is an inadequate volume of reported values with which to unambiguously characterise f_c. Therefore, we are required to transparently reason a plausible value and we begin with this summary of the number of factors involved and their multiplicative interaction.

“The amount and composition of BC and char formed during biomass burning is controlled by a large number of variables related to the quantity, heterogeneity, and condition of combustible material present and the environmental conditions”, (Baldock and Smernik, 2002).

One option for assigning f_c is to accept the value (0.026) prescribed by IPCC in the Greenhouse Gas Inventory Reference Manual (Vol. 3, Footnote 18, 1997), a value that appears to be too low. Our preferred option is to be guided by the published values for Brazilian forests collated as Table XI in Fearnside (2000). We find the 13 values available for the charcoal production *as a proportion of the fuel carbon that was fire-affected (burned)* – the Fearnside values - are lognormally distributed with a median of ≈ 0.05. We argue that these (hard won) field values significantly underestimate the mass of charcoal formed; see Fearnside’s methodology description on page 138. Our argument is that as well as the macroscopic charcoal left on the soil surface; there is an equal mass of microscopic sized particles not measured in the usual field experiments. This argument is based on our laboratory measurements that demonstrate ≥ 60 % of the charcoal in soils is smaller than can be detected by microscopy. In addition, combustion conditions during Managed forest fires are smouldering rather than flaming increasing the probability of charcoal production under reduced oxygen supply. Therefore, we model the Fearnside values as a lognormal distribution with a larger median value (0.08) but a smaller geometric standard deviation (gsdev) of 1.5. Furthermore, the Fearnside values (F_c) are converted to f_c using the expression $(F_c\, f_v)\,(1 - F_c)^{-1}$.

Implementation

The above distributions of A, M, f_v and f_c were implemented as equation A3 within the Analytica software package, and were sampled 10, 000 times to generate probabilistic estimates of the fuel carbon burned and charcoal formed (C_{char}). The results for each State and Territory and for the continent as a whole are presented as Table A3. The median value for annual fuel carbon burned for the continent is 2,483 ktC yr^{-1}, of which forest management in Western Australia contributes 40 %. The median charcoal production for the continent is 143 ktC yr^{-1}, which is equivalent to a sequestration of 524 $ktCO_2$ yr^{-1}. The values for the continent will be repeated in the main text as Table 3.

Table A3: A summary of modelled fuel and charcoal production (both in ktC yr^{-1}) by Managed forest fires. Median values are in bold.

Fuel carbon burned (ktC yr^{-1})								
Percentiles	NSW	Vic	Qld	SA	Tas	WA	NT	ACT	Aus
5	234	195	143	0	25	588	NA	0	1,808
25	358	360	242	1	47	848	NA	1	2,187
50	**476**	**504**	**332**	**1**	**68**	**1,035**	NA	**2**	**2,483**
75	605	660	437	2	95	1,245	NA	3	2,775
95	807	905	600	3	139	1,559	NA	4	3,207
Charcoal formed (ktC yr^{-1})									
5	7	9	3	0	1	13	NA	0	57
25	15	19	7	0	2	31	NA	0	98
50	**25**	**31**	**13**	**0**	**4**	**55**	NA	**0**	**143**
75	41	49	23	0	6	94	NA	0	207
95	82	92	47	0	15	190	NA	0	354

Unmanaged forest fires

System description

These are ‘bushfires’ – unwanted, unmanaged, and probably unmanageable fires in the forest, woodlands, and heaths. It is assumed that the fuel origins and components are the same as described for Managed forest fires; that is, a soil surface bed of dead plant litter plus a live grassy or woody understorey. Depending on the fire intensity, a variable fraction of the canopy (leaves, twigs, small branches) will be combusted if the surface fire is sufficiently intense to be convected into the canopy and a surface plus canopy fire results. See Graetz (2002) for details.

Because very little is known about the pre-burn conditions of this fire type, default assumptions are that the (surface) fuel loading is the same as Managed forest fires in each State and Territory, as is the relationship between fuel load and f_v. The latter assumption differs slightly from Graetz (2002). The assumption that the mass of the canopy consumed is a constant fraction (0.75) of surface fuel consumed, justified in Graetz (2002), is retained.

Production equation

For Unmanaged fires, charcoal will be produced from both surface and canopy fuel loads, where the canopy fuel load is 0.75 that of the surface. Assuming the charring properties of surface and canopy fuels are the same, then the canopy contribution will be an additional 0.75 fraction of the surface contribution. Therefore, the production relation for Managed fires (A3), can be simply modified for Unmanaged fires thus:

$$C_{char} = A\ M\ (1 - f_v)\ f_c\ 1.75. \qquad \text{(A5)}$$

Required variables

The only new variables required for equation A5 above is the distribution modelling of the annual area burned for each State and Territory. Because of the pronounced skew in the distributions, A was modelled by a lognormal distribution for all States and Territories, and truncated to the minimum area recorded in the 18-yr long statistics, see Table A5 in Graetz (2002). The values used are set out as Table A5.

Table A5: A summary of the values used to model the annual area burned (A, ha yr^{-1}) for Unmanaged forest fires in each State and Territory. The values for area (A) are in order: median, geometric standard deviation, truncated lower and upper limits (ha yr^{-1}). Area was modelled by a lognormal distribution.

State/Territory	Area (ha yr^{-1})
NSW	89000, 3.96, 7000, 450000
Vic	25000, 3.12, 5000, 486000
Qld	33000, 1.92, 14000, 197000
SA	100, 4.2, 100, 20000
Tas	14000, 3.17, 1000, 65000
WA	121000, 3.28, 9000, 1225000
NT	NA
ACT	3000, 4.63, 100, 12000

Implementation

As with Managed fires, the above distributions of A, M, f_v and f_c were implemented as equation A5 within the Analytica software package, and were sampled 10, 000 times to generate probabilistic estimates of the fuel carbon burned and charcoal formed (C_{char}). The results for each State and Territory and for the continent as a whole are presented as Table A6. The median value for annual fuel carbon burned for the continent by this type of fire is 1,340 ktC yr^{-1}, of which ≈ 30 % is contributed by Western Australia and ≈ 20 % by NSW. The median charcoal production for the continent is 133 ktC yr^{-1}, which is equivalent to a sequestration of 488 ktCO$_2$ yr^{-1}. The values for the continent will be repeated in the main text as Table 4.

Table A6: A summary of modelled fuel and charcoal production (both in ktC yr^{-1}) by Unmanaged forest fires. Median values are in bold.

Percentiles	NSW	Vic	Qld	SA	Tas	WA	NT	ACT	Aus
Fuel carbon burned (ktC yr^{-1})									
5	45	27	48	0	8	70	NA	1	535
25	128	57	77	0	22	197	NA	3	900
50	**286**	**113**	**114**	**1**	**45**	**427**	NA	**8**	**1,340**
75	610	232	176	2	88	935	NA	17	1,972
95	1,327	660	329	5	186	2,463	NA	37	3,469
Charcoal formed (ktC yr^{-1})									
5	3	2	2	0	1	4	NA	0	38
25	11	6	5	0	2	16	NA	0	78
50	**27**	**13**	**8**	**0**	**4**	**39**	NA	1	**133**
75	62	28	16	0	9	100	NA	2	226
95	176	91	37	0	27	335	NA	6	504

Grassland fires

System description

This fire type is easily the most extensive; being some 40 times larger in area than the sum of Managed and Unmanaged forest fires, and its fuel – the standing live or dead and fallen dead grass stems and leaves - defines this fire type. Because it is so defined, the Grassland fire type will include managed and unmanaged fires, and all States and Territories other than the ACT, report this fire type, see Table A6 of Graetz (2000). However, the NT (46 %), WA (39 %), and Qld (14 %) together contribute 99 % of the mean annual area burnt. Therefore, in the assigning of fuel loadings and burning efficiencies, we have concentrated only on the three largest contributing states, NT, WA and Qld. Further, within these three states, by far the largest proportion of burning occurs north of the Tropic of Capricorn (latitude 23° 27’ S). Grassland fires are a phenomenon of the tropical savannas.

Production equation

Compared with the Managed and Unmanaged forest fires, the charcoal production by Grassland fires is simpler to describe. Because of the finely divided and distributed nature of the grass fuel within the area affected by fire (A), there are only two fates for the fuel carbon; it is either volatilised or carbonised. Thus, for Grassland fires, the production equations, A1 above, applies recast as:

$$C_{char} = A\ M\ f_c. \qquad (A6)$$

Required variables

The annual area burned (A, ha yr^{-1}) is modelled by a lognormal distribution for the non-tropical States where these fires are extreme events or by a normal distribution for the tropical States and Territory where the overwhelming majority of these fires occur. Both distribution types are truncated by the recorded minimum and maximum areas, see Table A7. Not surprisingly given just 18 years of records, A is poorly modelled by lognormal distributions for the non-tropical States. However, it is of no moment because the combined contribution from these States is a trivial 1 % of the total.

Table A7: A summary of the values used to model the annual area burned (A, ha yr^{-1}) for Grassland in each State and Territory. The values for area (A) are in order: median and geometric standard deviation or mean and standard deviation, then the truncated lower and upper limits (ha yr^{-1}). A modelled by a lognormal distribution is denoted by *.

State/Territory	Area (ha yr^{-1})
NSW*	90000, 4.25, 5000, 2500000
Vic*	15000, 2.75, 5000, 205000
Qld	5545000, 1464000, 3800000, 9300000
SA*	125000, 4.67, 3000, 1800000
Tas*	11000, 2.63, 1000, 62000
WA	14862000, 5000000, 6000000, 23000000
NT	17640000, 5321000, 6900000, 27000000
ACT	NA

Only one fuel carbon abundance model is used for all States and Territory. It is based on a mixture of tussock grass and hummock grass (‘spinifex’) fuel, the combined abundance of which is modelled using a lognormal distribution; see Graetz (2002) for details. The only subsequent modification is to truncate the lower end of the distribution at 0.68 tC ha^{-1} (1.5 tdm ha^{-1}). The median value of M is 3.7 tC ha^{-1}, Table A8. The calculations in Graetz (2002) used a fixed value of 0.95 for f_v, thus fixing f_c at 0.05. The most careful field measurement of f_v for Australian savannas by Hurst *et al.* (1994) reported a value of ≈ 0.96, thus f_c becomes 0.04. We suspect that this is an underestimate because of the collection method used; see comments by Kuhlbusch *et al.* (1996), p. 23,652.

An alternative estimate of f_c and its variation between fires based on the chemistry of fuel and char. Silicon is a component of plant tissues, particularly in tropical grasses; occurring as silica (SiO_2) in discrete structural objects called phytoliths, see Figure 2 in the main text. With laboratory measured values of the C/Si for plant (R_{plant}) and char (R_{char}) and assuming that the inert element Si is conserved during the burning process, the ratio of carbon in the char to that in the plant (C_{char}/C_{plant}, the carbonised fraction) is R_{char}/R_{plant}.

The C/Si ratios were investigated for the principal fuel, annual *Sorghum* species. The C/Si ratio in the unburned grass showed a small but systematic geographic variation. The relative proportion of Si, present as SiO_2 in phytoliths, increased with increasing aridity as indicated by increasing latitude. Coastal Sorghum had low silica contents (1 %) and carbon values of 46 %, whereas three degrees south (Katherine district), the silica proportion increased to ≈ 4 % at the expense of carbon whose level fell to 43 %. Seventeen values of R_{plant} and eight values of R_{char} were available. Assuming these values are representative of the entire fuel and char population, the 136 possible combinations of R_{char}/R_{plant}, (C_{char}/C_{plant} or f_c), were calculated. The median value of the lognormally distributed 136 values was 0.04, Figure A1. It is obvious that f_c should be modelled rather than assigned a fixed value as in Graetz (2002). The appropriate model is lognormal with a median value of 0.04 and a geometric standard deviation of 1.8, truncated to 0.14. A percentile summary is given in Table A8. The minimum of this distribution is 0.02. The tail of higher values is included to account for two significant factors. The first is the proportion of burning that occurs early in the Dry Season (April-May) when the grass fuel is less cured and the residual charcoal is likely to be higher. The second factor is the contribution of woody litter to the grass layer from the overstorey.

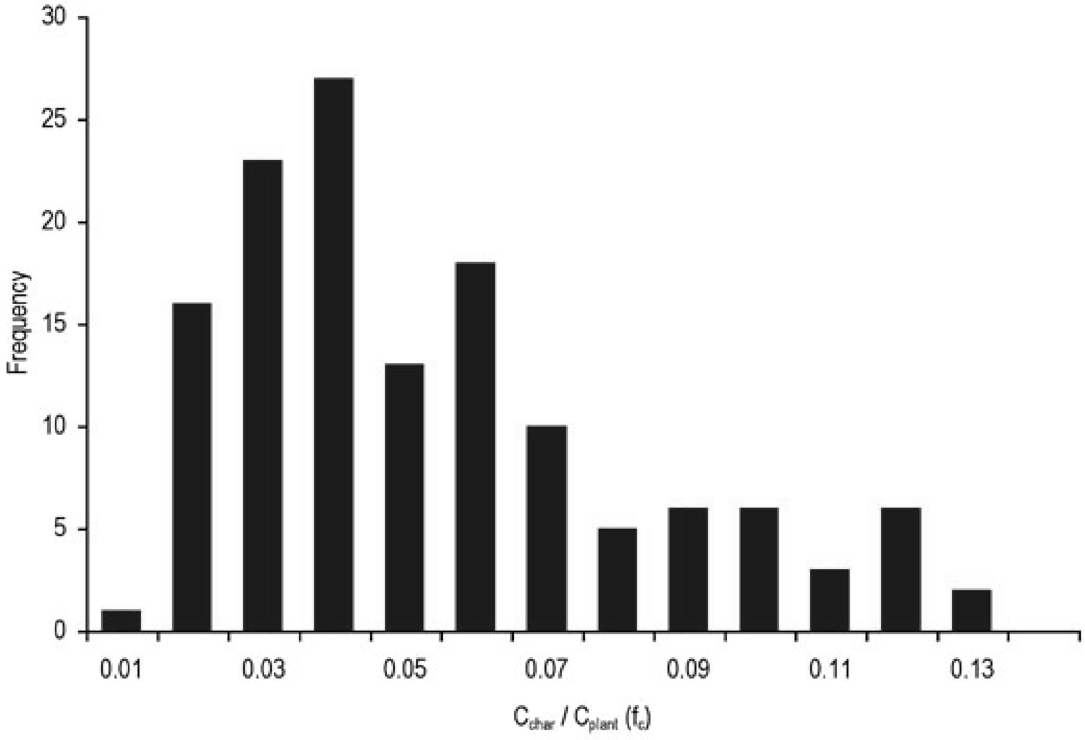

Figure A1: The class-frequency distribution of f_c values derived from the C/Si ratios of fuel and charcoal. The distribution is distinctively lognormal.

Table A8: Statistical summaries of the modelled distribution of fuel carbon abundance (M, tC ha^{-1}) and carbonised fraction (f_c) for Grassland fires. Median values are in bold.

Percentiles	M (tC ha^{-1})	Carbonised fraction (f_c)
5	2.0	0.02
25	2.9	0.03
50	**3.7**	**0.04**
75	4.8	0.06
95	7.0	0.10

Implementation

The distributions of A, M, f_v and f_c were implemented as equation A5 within the Analytica software package, and were sampled 10, 000 times to generate probabilistic estimates of the fuel carbon burned and charcoal formed (C_{char}). The results for each State and Territory and for the continent as a whole are presented as Table A9. The median rate of fuel carbon burned is ≈ 142 MtC yr^{-1}, almost twice current fossil fuel consumption. The median charcoal production rate is 5.6 MtC yr^{-1}, equivalent to the sequestration of ≈ 21 $MtCO_2$ yr^{-1}. The values for the continent will be repeated in the main text as Table 6.

Table A9: A summary of modelled fuel and charcoal production (both in ktC yr^{-1}) by Grassland fires. Median values are in bold.

Fuel carbon burned (ktC yr^{-1})									
Percentiles	NSW	Vic	Qld	SA	Tas	WA	NT	ACT	Aus
5	37	19	10,623	38	8	23,489	28,734	NA	73,484
25	131	37	16,040	157	20	38,439	46,158	NA	107,913
50	**345**	**68**	**21,377**	**434**	**39**	**53,606**	**63,537**	NA	**141,886**
75	927	130	28,651	1,170	77	73,572	86,356	NA	187,347
95	3,508	343	43,786	3,976	174	115,489	134,459	NA	281,182
Charcoal formed (ktC yr^{-1})									
5	1	1	256	1	0	601	718	NA	1,749
25	5	1	519	6	1	1,262	1,507	NA	3,485
50	**14**	**3**	**853**	**17**	**2**	**2,108**	**2,482**	NA	**5,631**
75	39	6	1,355	49	3	3,433	4,104	NA	8,989
95	156	17	2,663	185	9	6,659	8,268	NA	17,467

Clearing fires

System description

As described in the main text, Clearing fires are those fires used to transform landscapes, from forests and woodlands to crops and pastures. Commonly, these fires follow the mechanical felling of woody vegetation. In terms of charcoal production, they are unlike the three previously discussed types because of the fuel amount and arrangement, Graetz (2002). They are manufactured rather than natural fires. These factors are highlighted below. Note that because clearing is overwhelmingly concentrated in Queensland, only one model for the continent is developed.

Production equation

There are only two fates for the fuel carbon; it is either volatilised or carbonised. While this is the same situation as that of Grassland fires, the reasons differ. In Grassland fires, the finely divided and distributed nature of the grass fuel ensured that all of the fuel was combusted. In Clearing fires, the much more coarse fuel elements (tree trunks and branches) are mechanically arranged in ‘windrows’ to maximize the efficiency of combustion (f_v). Thus, for Clearing fires, production equation, A6 above, applies.

Required variables

The annual rates of clearing woody vegetation for crops and pastures over the last 20 years is poorly known; the available statistics are the poorest of all the fire types considered. Nonetheless, it is recognised that annual clearing rates are a trending rather than stationary series. Further, it was judged that such a trending series was plausibly captured by the lognormal distribution described in Table A10. Note that the annual clearing rate is equated to the annual burning rate because the total fuel mass is conserved, even though it is spatially concentrated before burning. The fuel carbon abundance (M) was modelled as per Graetz (2002) with details included in Table A10.

Table A10: A statistical summary of the calculated annual area cleared and burned (A, ha yr^{-1}) and of fuel carbon abundance (M, tC ha^{-1}). The variable A was modelled as a lognormal distribution with a median of 475,000 ha yr^{-1} and a geometric standard deviation of 1.2. The variable M was similarly modelled using a median biomass of 85 tdm ha^{-1} and a geometric standard deviation of 1.5 with coarse woody debris loading of 25 % and then converted to the carbon fraction (0.45). Median values are in bold.

Percentiles	A (kha yr^{-1})	M (tC ha^{-1})
5	352	27
25	420	37
50	**475**	**49**
75	537	63
95	641	94

Assigning a value for f_c for Clearing fires is problematic. For Managed and Unmanaged forest fires with large coarse woody fuel elements, f_c is modelled using a lognormal distribution, Table A3. In Clearing fires, the fuel is concentrated to maximize combustion and thereby minimize charring, Figure A2. In the absence of appropriate measurements, we persist with the modelled f_c described in Table A3.

Figure A2: Mechanically felled woody biomass burning in windrows illustrating the high efficiency of combustion that can be achieved by this technique.

Implementation

The distributions of A, M, and f_c were implemented in a representation of equation A6. Using the Analytica software package, equation A6 was evaluated using a Monte Carlo simulation approach to generate a probabilistic estimate of the charcoal formed (C_{char}). The results are presented as Table A11. These values will be rounded to ktC and re-presented as Table 5 in the main text.

Table A11: A statistical summary of modelled annual charcoal production (tC yr^{-1}) by Clearing fires for the continent. Median values are in bold.

Percentiles	Aus
5	730,290
25	1,259,850
50	**1,858,280**
75	2,767,920
95	4,879,320

Prehistoric fires

As outlined in the main text, we propose that a general pre-historic charcoal production rate is the product of the following terms:

$$D_{prechar} = M\, I^{-1}\, L\, \square_c \qquad \text{(A7)}$$

where

$D_{prechar}$	Pre-historic charcoal deposition (tC ha^{-1} yr^{-1})
M	Carbon abundance (tC ha^{-1}) of the biomass fuel exposed to fire
I	Between-fire interval (yr)
L	Proportion of the landscape burned
$\square_c$	Fraction of the fuel carbon that is carbonised.

In choosing the variables for this equation, we were informed by this remarkable statement: "The overall impression is that fire activity has been relatively constant over the Holocene period with greatest variation during the period of European occupation. The data suggest that burning increased during the early part of European settlement to levels higher than at any other time during the Holocene in all major vegetation types … This period was followed by a reduction in burning to present day levels which are, on average, lower than at any other time during the Holocene" (Kershaw *et al.*, 2002).

Required variables: agriculture

We reason that Aboriginal burning was most common in the woodlands, heaths, and grasslands and never in the closed forests. The fires were primarily for hunting and access and were managed to burn only the understorey grass and litter. Therefore, M was modelled as normal distribution (mean 1.35, stdev 0.68) truncated $\geq$ 0.68 tC ha^{-1}. The between-fire interval (I, yr) at *any one site* was modelled by a normal distribution (5, 1.5) truncated $\geq$ 2.5 yr. The proportion of the landscape burned term (L), meant to capture both the skill of Aboriginal fire management as well as the episodic conflagration, was modelled as a lognormal distribution (0.2, 1.75) truncated to between 0.05-0.90. Because the fuel was largely grass, the carbonised fraction (f_c) was modelled as for tropical grasses using a lognormal distribution (0.04, 1.8) truncated $\leq$ 0.14. These four variables are summarized in Table A12.

Table A12: A statistical summary of the modelled variables used in equation (A7) above for the agricultural lands. Median values are in bold.

Percentiles	M (tC ha^{-1})	I (yr)	L	$\square_c$
5	0.8	3	0.08	0.02
25	1.1	4	0.14	0.03
50	**1.5**	**5**	**0.20**	**0.04**
75	1.9	6	0.29	0.06
95	2.5	8	0.49	0.10

Required variables: tropical grasslands

The landscapes burned in pre-historic times are the same as now, the tropical savannas, and the hummock grasslands (‘spinifex’) of the sandplain deserts. Accordingly, M and f_c are modelled as for the Grassland fires above. The between-fire interval (I, yr) for tussock grasses was modelled by a normal distribution (3, 0.5) truncated ≥ 1 yr and that for hummock grasses was lognormal (10, 1.5). These two intervals were combined with the same weighting (70:30) as is used for M; see Graetz (2002) for details. The proportion of the landscape burned term (L) was modelled as a lognormal distribution (0.3, 1.25) truncated to between 0.01-1.0. The four variables are summarized as Table A13.

Table A13: A statistical summary of the modelled variables used in equation (A7) above for the tropical grasslands. Median values are in bold.

Percentiles	M (tC ha^{-1})	I (yr)	L	$\square_c$
5	2	2	0.21	0.02
25	3	3	0.26	0.03
50	**4**	**3**	**0.30**	**0.04**
75	5	3	0.35	0.06
95	7	4	0.43	0.10