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**Abstract**

The size and space/time patterning of the net carbon dioxide ($CO_2$) flux from contemporary biomass burning is calculated and mapped for the Australian continent. Contemporary is interpreted to be the last two decades.

The principal determinant of the net transfer of carbon (as $CO_2$) from the landscape to the atmospheric pool via the phenomenon of biomass burning is the post-fire response of the fuel material; that is, how rapidly, if at all, it was regenerated by the processes of plant growth. Based on this criterion, a binary stratification of fire and emission types was proposed. By far the largest class in terms of area and emissions, in Australia and globally, are the resilient landscape fires where the fuel recovers to pre-fire levels of carbon storage rapidly, within 0.5 - 5 yr. In contrast is the (smaller) transformed landscape class where the fuel carbon disturbance is effectively irreversible, where the vegetation is converted by clearing and burning from one type to another and the pre-fire carbon storage of the landscapes is permanently diminished.

Applying this stratification within the limits of available fire data, transformed landscape fires, the biomass burning that makes a significant net transfer of carbon from landscape to atmospheric pool, were identified and quantified as Clearing fires. In contrast, resilient landscape fires were identified and quantified as Managed and Unmanaged forest fires, and Grassland fires.

Using transparently edited data of burned area (A) collected by State and territory agencies, fuel type, load (M), and burning efficiency ($\varepsilon$) were reasoned for all fire types based on specific published values and general biological understanding. The uncertainty associated with both burned area and fuel values was captured by probability distributions (pdf) rather than by a single mean value. These probability distributions were then combined to calculate emissions and report them as probability bands; that is, what is known, as well as how well it is known.

The median annual burned area is 37.8 Mha, representing ≈ 5% of the Australian continent. For the 18-year period, 1982 – 2000, the median annual emission rate for continent was 399 $MtCO_2$ $yr^{-1}$. The largest contribution (74%) to this total was from Grassland fires burning on resilient landscapes where the fuel recovery time would be ≤ 1 year. This fire type and the two other resilient landscape fires (together contributing just 5%) make no net carbon contribution to the atmospheric pool on time scales of 1-5 years. However, the second largest contributor at 18%, Clearing fires, is a net transfer of carbon from landscape to atmosphere of ≈ 20 MtC $yr^{-1}$ that approximates 20% of national fossil fuel burning.

The size, geographic and temporal distribution of the (photosynthetic) $CO_2$ uptake of the continent was estimated from the $NDVI_{sum}$ analysis. Based on a calibration of the 18-year record, the median aboveground NPP of the continent was estimated at 1.63 GtC $yr^{-1}$ and consistent and plausible spatial and temporal patterns of $CO_2$ uptake were established for whole continent and the Tropics. In the latter case, the estimated NPP for the Tropics, where most of the biomass burning occurs, is a constant 35% of the continent. The size of this fraction is almost entirely due to areal extent rather than climatic or soil constraints. The median emission from all fire types combined is 109 MtC $yr^{-1}$ (399 $MtCO_2$ $yr^{-1}$). This value represents 7% of estimated continental NPP and is approximately the same size as its interannual variation.

Given future efforts to estimate the net $CO_2$ flux from the continent by inverse modelling techniques, the level and timing of the noise of biomass burning emissions were evaluated. Considering the entire continent for a full year, the emissions from Grassland and Clearing fires are dwarfed by the uptake. Over the year, the grassland fire aggregate is just 5% of the continental uptake flux of 5.97 $GtCO_2$. However, at peak burning month, September, the 82 $MtCO_2$ emitted from fires (noise) is 16% of the median monthly uptake (signal) of 524 $MtCO_2$. In all other months, the contribution is much less. The emissions from clearing fires appear even more insignificant with a median annual 73 $MtCO_2$, they are ≈ 1% of the aggregate annual biogenic flux to the continent. However, if comparisons are focussed on the Tropics, the signal to noise ratio falls. Because the $CO_2$ uptake into the Tropics is just 35% of the entire continent, the relative size of the emissions from Grassland and Clearing fires significantly increases. Over a full year, the emissions from Grassland fires is 14%, and from Clearing fires is 4% of the total uptake of 2804 $MtCO_2$. For the peak burning month of September, the emissions from Grassland fires alone is 52%, and from Clearing fires is 9% of the uptake of 160 $MtCO_2$. This represents significant potential noise for inverse modelling efforts.

Finally, global comparisons were be made of the biomass burning on the Australian continent. Australia contributes ≈ 6% of the biomass burned in and $CO_2$ emitted from Grassland (savanna) fires, and 10% of biomass burned in and $CO_2$ emitted from Extratropical forest fires via Managed and Unmanaged forest fires. Overall, the contribution of biomass burning on the Australian continent to the global whole is ≈ 5%.

Based on the binary classification of fire types used in this essay, the largest location of biomass burned/$CO_2$ emissions globally is the savannas. With the plausible assumption that savanna (Grassland) fires and fuels are globally homologous, then the largest single $CO_2$ emission of ≈ 5 $GtCO_2\ yr^{-1}$ *is not* a net transfer of carbon from landscape to atmospheric pool. Further, if the fires in Tropical and Extratropical forests are predominantly Clearing fires, then this aggregate emission of ≈ 3.1$GtCO_2\ yr^{-1}$ *is* a net transfer of carbon from landscape to atmospheric pool. Thus, only 38% of the total global emission from biomass burning (8.2 $GtCO_2\ yr^{-1}$) is a net carbon transfer from landscape to atmosphere.

## Introduction

The objective of this essay is to calculate and map the size and space/time patterning of the *net* carbon dioxide ($CO_2$) flux from contemporary biomass burning on the Australian continent.

It is anticipated that the data generated here will find two uses. The first will be to inform those interested in understanding the growing concentrations of greenhouse gases ([GHG]) in the global atmosphere. The pyrogenic emissions of $CO_2$, carbon monoxide (CO), and methane ($CH_4$) are appreciable, particularly those of $CO_2$. However, the interpretation and reporting of $CO_2$ emissions is often confusing and misleading. As but one example, Lavorel et al. (2001) noted that global biomass burning "produces some 40% of the world's annual production of $CO_2$". This statement may be correct in one sense but not in the sense that the pyrogenic $CO_2$ emitted makes a *net* contribution equivalent to 40% of the world's annual production of $CO_2$ to the global atmosphere, thereby rivalling that from fossil fuel burning. The net contribution of $CO_2$ from biomass burning to the global atmosphere is much less than "40% of the world's annual production of $CO_2$." The net contribution of biomass burning to the atmospheric [$CO_2$], calculated over the (biologically sensible) annual cycle, is determined by the nature of the (vegetation) fuel consumed. For example, the largest source of pyrogenic $CO_2$ emissions is the tropical savannas where the fuel is either annual or perennial grass, both of which regrow within months of burning. Thus, via photosynthesis, a mass of $CO_2$ equivalent to the emissions is rapidly extracted from the atmospheric back into the biospheric carbon pool. The emissions from biomass burning will appear as short term (months) fluctuations in the overall atmospheric [$CO_2$] but with *no net addition*. However, this is not the case for stand-replacing forest fires where the burned biomass may take decades to centuries to regrow, or where fire is used to convert landcover types, such as forest to cropland, such that the pre-fire carbon pool of the forest becomes permanently transferred to the atmosphere. Thus, a transparent calculation of the net $CO_2$ flux from biomass burning from the Australian continent will illustrate the actual contribution of this phenomenon to the atmospheric pool, and thereby to imputed Enhanced Greenhouse Effect (EGE) global warming and consequent climate change.

The second and foremost application of these data is to support inverse modelling; techniques by which net surface fluxes at continent or smaller scales can be inferred from regional and global patterns of atmospheric concentrations and isotopic composition, (Ciais et al. 2000, Wittenberg et al. 1998). In some situations, this technique has produced some surprising results. As one example, Fan et al. (1998, 1999) showed that part of the northern hemisphere landmass wherefrom the emission rates from fossil fuel burning were known to be high, was actually a large net sink of $CO_2$. This sink was interpreted as the result of extensive, regrowing forests. The important conclusion was that scientifically calculated net flux revealed a $CO_2$ sink in contrast to the politically proscribed calculation based on fossil fuel usage alone. The actual contribution of this landmass to the Enhanced Greenhouse Effect (EGE) phenomenon is the scientifically derived one, not the politically proscribed value. Currently, there is significant uncertainty in separating the relative contributions of various sources and sinks of $CO_2$ to the atmospheric pool, as the above example illustrates (Schimel et al. 2001). Because of this large uncertainty, it could be expected that attempting to encourage nations to reduce their contribution of $CO_2$ to the global atmosphere based on fossil fuel emissions alone and not on their net contribution of emissions minus sinks, will be politically unacceptable. The current laboured negotiations of the Kyoto Protocol supports this expectation and for this and other reasons, the Protocol is unlikely to achieve its goals of significant reduction in GHG emission.

However, it is anticipated that a revised Protocol could be proposed that will attempt to manage the key driving variable of global warming, atmospheric [$CO_2$], by understanding the net sources and sinks, nationally and globally, and distributing reduction efforts accordingly. It is recognized that any such attempt will be limited by current capacity to infer net fluxes with appropriate resolution and certainty. Nevertheless, it can be confidently predicted that inverse modelling techniques will play a major role in this effort.

The Australian continent represents a rewarding test bed for the development of inversion modelling techniques. The land surface is well mapped; estimates of soil and vegetation carbon pool sizes as well as exacting estimates of net primary production (NPP) are in hand (Barrett et al. 2001). However, there remains the issue of noise. Previous attempts at interpreting the global atmospheric [$CO_2$] record have noted irregularities and attributed these to large scale biomass burning (Randerson et al. 1997, Zimov 1999). To remove this noise for the Australian continent, a multi-year summary of the size, timing and geography of the pyrogenic $CO_2$ fluxes and their probable fate is required. This is the foremost objective of this essay.

**Orienting questions**

1. What is the principal determinant of the net transfer of carbon (as $CO_2$) from the landscape to the atmospheric pool via the phenomenon of biomass burning?

2. What stratification of Australian biomass burning separates those which make a significant net transfer of carbon from landscape to atmospheric pools, from those that do not?

3. What are the sizes, geographic and temporal distributions of the $CO_2$ emissions from all fire types?

4. What is the size, geographic and temporal distribution of (photosynthetic) $CO_2$ uptake?

5. Given future efforts to estimate the net $CO_2$ flux from the continent by inverse modelling techniques, where and how strong is the noise of biomass burning?

## Scope

Biomass burning is a pervasive landscape phenomenon both in Australia and globally in all tropical and boreal regions. Thus, it is imperative to clearly state what is included and what is excluded in this essay.

Biomass burning is taken to be the combustion of living or dead plant material of recent origin, where recent is taken to be days to decades to include forest litter but to exclude much older interred plant material such as that transformed into peat. Peats do occur in alpine and tropical areas of the continent but their occurrence is small and restricted and they are not significant fuels in this analysis. Thus, in all cases, it is assumed that there is no contribution to the fuel load from the soil carbon pool. This is in contrast to fires in the boreal forests where peat soils are more common and where because of the mesic conditions, the upper layer of the soil is essentially organic, a 'duff' of mosses and litter, which will burn in intense fires (Amiro et al. 2001).

The principal types of biomass burning considered here are the large area, low fuel load landscape fires, managed or unmanaged, as well as the small area, high fuel load fires of landcover conversion – clearing and burning of woodlands and forests.

The biomass burning types not considered are the (managed) burning of forest slash (very small area, moderate fuel load fires) or the burning of fuel wood. In addition, the burning of agricultural residues, such as crop stubbles, is ignored. Estimates of area burned and fuel load in the National Greenhouse Gas Inventory (NGGI) published by the Australian Greenhouse Office demonstrate that this source of $CO_2$ is small.

In all of the above examples, the $CO_2$ flux is the *direct* outcome of biomass burning. In contrast, there is evidence supporting a substantial $CO_2$ sequestering flux that is an *indirect* consequence of biomass burning. Because of reduction in biomass burning in extensive non-agricultural landscapes, there can arise an increase in the woody component (trees, shrubs) and this slow (decadal) change can result in a significant increase in landscape carbon pools. This succession is essentially a natural phenomenon that can be profoundly influenced by land management.

Estimates of the pyrogenic $CO_2$ and non-$CO_2$ fluxes are annually reported in the NGGI (Australian Greenhouse Office 2002; see http://www.greenhouse.gov.au/). The estimates generated in this essay support an objective that is different from the NGGI; see the first sentences of the Introduction. Thus, the estimates of $CO_2$ fluxes in this essay and in the NGGI should be regarded as complementary and not as alternatives.

**Uncertainty**

The credibility of the emission estimates calculated in this essay will be 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 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.

In the analyses presented below, both types of uncertainty are relevant, model, and variable. Most calculations are based on simple inventory algorithms that are mechanistically sound and widely accepted. Thus, model uncertainty is essentially negligible.

Thus, the principal uncertainty is the *representativeness of the variables used in the model*. For example, the key variable of 'area burned' is often just estimated rather than measured, and 'fuel loads' are only rarely measured for any fire event. Because the object of this study, emissions, is the product of these two variables, their individual uncertainties are propagated.

For scientific purposes, quantitative statements of uncertainty are preferred. Therefore, a probabilistic approach is employed. With this approach, the difficulty that key variables are poorly known can be addressed thus. While it is not possible to know the exact fuel loads of grass fires in the savannas of northern Queensland in late September, 1999, 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 can be transparently reasoned and used, and if required, simply updated given additional information. It follows that because most of the variables in the emission calculation models are represented by statistical distributions, their product, the calculated emission will also be presented as a statistical distribution. In this way, we calculate what we know, as well as how well we know it.

**Conceptual framework**

In this Section, the following questions are addressed:

1. What is the principal determinant of the net transfer of carbon (as $CO_2$) from the landscape to the atmospheric pool via the phenomenon of biomass burning?
2. What stratification of biomass burning separates those which make a significant net transfer of carbon from landscape to atmospheric pools, from those that do not?

To calculate the net $CO_2$ flux from biomass burning, the following conceptual framework was used. Biomass burning is a disturbance to the level of carbon storage of landscapes. On burning, the carbon of the fuel, the live, or dead plant material, is largely transferred to the atmosphere. However, the size of the *net* emission is determined by the post-fire response of the fuel material; that is, how rapidly, if at all, it was regenerated by the processes of plant growth. Based on this criterion, a binary stratification of fire and emission types is made.

The largest class (in terms of area burned) is 'resilient' landscape fires where the fuel recovers to pre-fire levels of carbon storage within 1 - 5 yr. In contrast is the (smaller) 'transformed' landscape class where the fuel carbon disturbance was effectively irreversible and the vegetation was converted by clearing and burning from one type (e.g. woodland) to another (e.g. crop, pasture). In this category, the pre-fire carbon storage of the landscapes was permanently diminished.

For both types of fires, the size of the $CO_2$ emissions are calculated, mapped, and timed. The same is done for the background cycle of $CO_2$ uptake into the continental vegetation. The size and space-time patterns of these two opposing fluxes are then compared.

The last point in this Section concerns style of presentation. The modelling in this essay is very simple and straightforward. However, in order to meet the imperative of transparency, the derivation of input variables is necessarily detailed and thus lengthy. Therefore, to keep the core arguments uncluttered and accessible in the main text, the detailed methodological discussion is consigned to three appendices.

## The phenomenon of biomass burning

*Chemistry and history*

An informative perspective can be gained from the carbon chemistry of biomass burning. Carbon enters and leaves the biosphere via the process of photosynthesis, the forward reaction, and leaves via respiration, the back reaction in this simplified equation.

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

The generic chemical composition of most plant materials, such as carbohydrates, cellulose and lignin, can be simplified as $(CH_2O)_n$. The reverse reaction is respiration (catabolism) where carbon-containing compounds are oxidized to $CO_2$ and $H_2O$. Of the carbon fixed by photosynthesis in land plants (Gross Primary Productivity, GPP), some 45% is respired by the living plant tissue and the residual is the Net Primary Productivity (NPP). This carbon flows into and sustains the biosphere. The variable fraction that remains in various biomass pools is called the Net Ecosystem Production (NEP). Most is respired: ≈ 5-10% is eaten by animals (herbivores, foliovores), with the remaining 45% remaining temporarily as a biomass carbon store that on death is released by consumption (detritivores) or by decomposition/decay (fungi, bacteria).

A difference in rate between photosynthesis and respiration (catabolism, consumption, decomposition) changes the biospheric carbon pool size. In particular, if some $(CH_2O)_n$ compounds have physical or chemical properties that make them resistant to metabolism by decomposing organisms, then they will accumulate. The biopolymer lignin, a component of wood, is one such example, as is the humic fraction of soil organic matter. This latter substance is a mixture of compounds that are highly resistant to decomposition and comprises >60% of total soil carbon. Thus, the largest component of the soil carbon store is essentially a metabolic residual – bacterial and fungal leftovers.

In contrast, the chemistry of biomass burning can be simplified as a unidirectional process, thus:

$$(CH_2O)_n + O_2 \rightarrow \square\square_{\square} + H_2O + C_b \qquad (2)$$

Plant compounds are oxidized (at high temperatures) to $CO_2$ and $H_2O$ and a residual black carbon or char ($C_b$) that is a complex molecular mixture ranging from elemental or graphitic carbon, that is biologically inert, to high molecular weight aromatic ring structures that are also highly refractory and may persist in soils for millennia (Skjemstad et al. 1996).

In one respect, biomass burning is equivalent to the biochemical process of respiration, the reverse of photosynthesis, because it provides an instantaneous decomposition of plant biomass. For the most part, fire and decay are equivalent processes their effects on plant biomass (fuel) differing only in their respective rates of change. Like respiration, biomass burning also provides the opportunity for carbon storage because it *always* sequesters a fraction of the carbon in the fuel as char, a mixture of refractory and inert carbon. The amount of carbon that is sequestered by biomass burning in the long term depends on both the fraction of fuel carbon converted to char generated during the burning event, and its resistance to oxidation by biotic or abiotic agents.

The nature and size of the char sink for the Australian continent is the subject of a separate publication (Graetz and Skjemstad, in preparation).

In contrast to photosynthesis, which is at least 3.5 Gyr old (Nisbet and Sleep 2001), the phenomenon of biomass burning is much, much younger. A prerequisite for fire on land was fuel, the invasion of the land by plants. The first fossil records of burned plant material (fusain) occur in the Devonian period, approximately 380 Myr ago (Robinson 1989, 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 1996). Subsequently, the most successful species of that genus, *Homo sapiens*, has increased the frequency of biomass burning in all occupied biomes, especially the Tropics. Currently, it is estimated that most of the landscape fire on Earth is anthropogenic, and that this proportion is increasing (Dwyer et al. 1998, 2000).

*Combustion Conditions*

At the instant of burning, the carbon content of the plant biomass (fuel) enjoys one of two possible fates; it is either volatilised to gaseous species, principally $CO_2$, CO, $CH_4$ as well as a myriad of other compounds (Andreae and Merlet 2001), or carbonised to the black carbon residues described above. For biomass fires, the predominant fate of the fuel carbon is volatilisation to $CO_2$. Nonetheless, the proportion of the carbon that is volatilised to $CH_4$ and CO, or carbonised is determined by the combustion conditions, a mix of physical conditions and chemical activity that lies between the end points of flaming and smouldering combustion.

Flaming combustion is typified with temperatures of $\geq$ 1000 K with near ambient oxygen concentrations ($\geq$15%) maintained by the convective turbulence of the flames. In contrast, smouldering combustion is characterized by lower temperatures ($\leq$800 K) and lower oxygen concentrations. Given an external source of ignition, that must reach temperatures of approximately 600 K, fuel factors determine which combustion type prevails. Flaming combustion is promoted by low fuel moisture content ($\leq$25%), a preponderance of finely divided fuel elements (e.g. grass stalks, twigs) that are loosely packed (low density). Smouldering combustion is a consequence of the opposite fuel conditions: higher fuel moisture content, coarse fuel elements (e.g. branches and stems) comparatively densely packed. The sequence of these combustion conditions is easy to imagine from the field situation captured in Figure 1. Here the flaming combustion conditions of the fire front consume the finely divided and loosely packed fuel of grass and leaf litter from the tree overstorey. The fire front is transiently hot. Left behind is the coarser woody tree litter of branches and even tree trunks, which if heated to ignition point by the fire front, may slowly smoulder over many days.

Figure 1: The passage of a fire front. Over a distance of 10-15 m, the fuel combustion conditions vary from flaming to smouldering. While it is possible to characterize the flaming and smouldering endpoints, in the crucible of a fire, combustion conditions significantly vary over very short space and time intervals.

Besides the intrinsic fuel characteristics of water content and physical structure, several very influential environmental factors influence combustion conditions. These factors are wind speed, temperature, humidity, and their interactions with fire behaviour and fire intensity are described by Cheney and Sullivan (1997).

The contrasting physical conditions of temperature and oxygen supply for flaming versus smouldering combustion conditions are reflected in a contrasting chemistry of carbon oxidation. Under flaming conditions, the fuel carbon is essentially completely oxidized to $CO_2$. Whereas under smouldering combustion, a larger fraction of the fuel carbon is converted to reduced compounds, such as $CH_4$. In addition, there is also contrast in the volume and chemistry of the aerosols produced with high carbon content particles produced by flaming combustion and fewer generated under smouldering conditions.

*Continental context*

All of the vegetated surfaces of the earth are subject to fire irrespective of the climate in which they are found. Deserts, rainforest, and all other vegetation types burn. It is only the frequency of the occurrence of fire that varies between vegetation types. The Australian continent spans approximately thirty-five degrees of latitude, from tropical Cape York (10° S) to temperate southern Tasmania (45° S). Fire is experienced across the whole continent, including the central arid core, with characteristic intervals ranging from 1-2 yr in the Tropics, 10-50 yr in the arid centre to 25-250 yr in the temperate south. These intervals are broad and reflect current land use and climate. Archaeological and historical evidence indicates that while the frequency of fire has changed over the millennia driven by changes in climate and culture, it has always been present (Kershaw et al. 2002). Today, satellite observations show that it is uncommon for the continent to be without fire of sufficient size to be detectable from space. For the Australian continent, fire is ubiquitous.

In historic time, such as the last 100 yr, there is qualitative and anecdotal evidence of changing fire regimes because of changing land management practices. In the northwest of the continent, fire frequency has apparently increased and as a result, the density of woody plants on the affected landscapes is declining. However, in the northeast of the continent, fire frequency has declined with a concomitant increase in woody plant density. While there is no doubt that changes in woody plant density will result in landscape emission or sequestration of $CO_2$, the available quantitative evidence is inadequate. Therefore, the $CO_2$ flux from *changing* rather than *stationary fire regimes* is not considered.

**$CO_2$ emission model**

The $CO_2$ emitted from burned landscapes is the product of the following terms:

$$E = A \times M \times \varepsilon \times \phi \qquad (3)$$

where

- E Mass of $CO_2$ emitted ($tCO_2$)
- A Burnt area (ha)
- M Fuel mass density (as dry matter, tDM $ha^{-1}$)
- $\varepsilon$ Burning efficiency, the fuel fraction that is volatilised (0 –1, dimensionless)
- $\phi$ Emission factor, the mass ratio of $CO_2$ produced/fuel consumed (1.6 t $t^{-1}$)

For each fire type, only the three variables A, M and $\varepsilon$ must be determined. The emission factor ($\phi$) is regarded as a constant for this exercise with a value of 1.6 t $t^{-1}$ and is derived from the several values provided in Table 1 of Andreae and Merlet (2001). Essentially, this assumes that the predominant burning condition in all fire types is flaming combustion. With the emission factor set at 1.6 t $t^{-1}$ and setting the fuel carbon fraction as a constant 0.45, approximately 97% of the fuel carbon volatilised is converted to $CO_2$.

Two variables in Equation (3) require additional comment. The first is that the burned area ( A) is taken to be that area of landscape actually burned, and not just the total area of a fire footprint within which there is some fraction of vegetation that remained unburned. Secondly, the burning efficiency term ($\varepsilon$) determines the (small) proportion of the fuel carbon that is carbonised but this faction is not considered further in this essay.

*Probabilistic usage*

As discussed in the Uncertainty Section above, a core strategy of this essay is to include explicitly the uncertainty associated with the variables in the emission model, Equation (3) above. The principal consequence of this strategy is that the estimates of the $CO_2$ emissions will also be explicitly probabilistic. It is implemented in two steps beginning with the three fire types occurring on resilient landscapes as defined above. First, the multi-year burned area values (A) for all types are processed and summarised by statistical distributions in Appendix A. Similarly, the fuel loads (M) and burning efficiency values ($\varepsilon$) are generated in Appendix B. For the distinct case of biomass burning associated with transformed landscapes, all three variables are derived in Appendix C.

The second step involves converting the statistical summaries for each fire type of the variables A and M into probability distribution functions (pdf) for *annual area burned* and for fuel loading, and substituting into Equation (3) above. Using the techniques of Monte Carlo simulation, and with the assumption that there is no significant correlation between the three variables, a pdf of annual $CO_2$ emissions is calculated. This step was implemented using 10, 000 iterations within the Analytica software package (Lumina Decision Systems, USA). For brevity, the (continuous) emissions pdf output was summarized in the text only as percentiles describing the *annual $CO_2$ emissions*. The interquartile range, which holds 50% of the observations, is particularly informative. Nonetheless, if required, all intermediate pdf are available from the author.

The above strategy of probabilistic calculation of emissions is based on the following assumptions.

1. The time series of burned area for the various fire types are all stationary series. This demonstrably true for all but transformed landscape fires, and this is explicitly noted and accommodated in its treatment in Appendix C.

2. The three variables represented as pdf ($A, M, \varepsilon$) are uncorrelated. Because of the nature of the ignition source, any correlation between A and M is likely to be insignificantly small, and there are no adequate and independent measures of M to quantify the level of correlation.

3. For Managed and Unmanaged fire types, the burning efficiency ($\varepsilon$) is specified as dependent on fuel load (M). Nonetheless, the very small range over which $\varepsilon$ varies in the emission calculation, the effect of this correlation is trivial compared with the variation in M and A.

Restating the strategy outlined above, to calculate the *net* annual $CO_2$ emissions, fires must first be stratified by the permanence of their impact on the fuel carbon store and this follows in the next Section.

**$CO_2$ emissions from resilient landscapes**

The principal fuel type identifies three types of fires in this category. They are Managed forest fires, Unmanaged forest fires, and Grassland fires, all of which are described in more detail in Appendix A.

In terms of area burned, almost all of the biomass burning across the continent involves resilient fuel carbon stores; i.e. the fuel carbon recovers to pre-fire levels of carbon storage within 1-5 yr. This is to be expected of the grassland fires where the annual or perennial grasses can essentially regrow to pre-fire biomass levels in one growing season. The prescribed burning of forests (Managed forest fires) where the fuel is almost all accumulated litter is a similar situation except that here fuel loads recover more slowly taking several years rather than just one year, with the rate being determined by the intrinsic productivity (NPP) of the site. The impact of unmanaged fires, bushfires, on landscape carbon stores is also transient with fuel loads recovering usually in ≤5 years (Morrison et al. 1996).

Even though bushfires usually burn with high intensity and consume most of the fuel (litter) layer and part or all the canopy (leaves and twigs), they never burn all the standing live stems. Apart from standing dead stems, the live stems only rarely burn even though (depending on species tolerance) a proportion may be killed. Perhaps 85% of the carbon stored in a burned forest or woodland remains after the fire, and depending on species, the carbon pool rapidly refills. This generally true for species of the genus Eucalyptus but less applicable to other species of the genus *Acacia* and *Callitris* but the latter are relatively insignificant in the overall carbon pool size of the continent (Gill 1997).

*It can be concluded that with resilient fuel carbon stores, it is highly probable that the net $CO_2$ flux from this type of biomass burning will be effectively zero for a moving average of ≤ 3 years.*

*Managed forest fire emissions*

Using the area, fuel loading and burning efficiency values derived in Appendices A and B, a pdf of annual $CO_2$ emissions was generated for each State and Territory using Equation (3) and the Monte Carlo simulation techniques described above. Statistical summaries of these $CO_2$ emissions pdf for Managed forest fires (prescribed burning) are set out in Table 1. The following abbreviations for States and Territories will be used consistently hereafter: New South Wales (NSW), Victoria (Vic), Queensland (Qld), South Australia (SA), Tasmania (Tas), Western Australia (WA), Northern Territory (NT), and Australian Capital Territory (ACT).

Over the 18-year period, the annual emission rates for all States and Territories for this fire type were assessed to be stationary series that could be modelled with normal distributions.

The median emission rate for the continent from this type of biomass burning is ≈ 13 $MtCO_2\ yr^{-1}$, with the Western Australia being the largest contributor (40%), followed by Victoria, New South Wales, and Queensland. To provide some perspective of these median emissions, that for the continent equates to ≈ 3.5 $MtC\ yr^{-1}$, or 4% of the current national fossil fuel usage of ≈ 80 $MtC\ yr^{-1}$.

Table 1: A summary of the annual $CO_2$ emissions ($MtCO_2\ yr^{-1}$) from Managed forest fires (prescribed burning). The emission rates are normally distributed for all States and Territories. The median values are highlighted

| Percentiles | NSW | Vic | Qld | SA | Tas | WA | NT | ACT | Australia |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 0.8 | 0.8 | 0.4 | 0 | 0.1 | 2.3 | NA | 0 | 8.3 |
| 25 | 1.7 | 1.9 | 0.9 | 0 | 0.2 | 3.8 | NA | 0 | 10.8 |
| **50** | **2.5** | **2.8** | **1.5** | **0** | **0.3** | **5.2** | **NA** | **0** | **12.8** |
| 75 | 3.4 | 3.8 | 2.2 | 0 | 0.5 | 6.7 | NA | 0 | 14.9 |
| 95 | 4.9 | 5.5 | 3.3 | 0 | 0.8 | 9.2 | NA | 0 | 18.2 |
| Interquartile range (IR) | 2 | 2 | 1 | 0 | 0 | 3 | NA | 0 | 4 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| IR/Median | 0.67 | 0.70 | 0.81 | 1.20 | 0.91 | 0.55 | NA | 0.90 | 0.32 |

The interquartile range bounds 50% of the simulated annual missions. The variation about the median value, as indicated by the ratio of the interquartile range to the median, is high for most of the principal contributing States, with Western Australia being the exception. As will become evident when considering emissions from other fire types, those from Managed forest fires are (relatively) small and invariant.

*Unmanaged forest fires*

Using the area, fuel loading and burning efficiency values derived in Appendices A and B, a pdf of annual $CO_2$ emissions was generated for each State and Territory using Equation (3) and the Monte Carlo simulation techniques described above. Statistical summaries of these $CO_2$ emissions pdf for Unmanaged forest fires (bushfires) are set out in Table 2.

Table 2: A summary of the annual $CO_2$ emissions ($MtCO_2$ $yr^{-1}$) from Unmanaged forest fires (bushfires). The emission rates are log-normally distributed for all States and Territories. Median values are highlighted.

| Percentiles | NSW | Vic | Qld | SA | Tas | WA | NT | ACT | Australia |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 0.1 | 0.1 | 0.2 | 0 | 0.0 | 0.4 | NA | 0 | 3.0 |
| 25 | 0.5 | 0.4 | 0.4 | 0 | 0.2 | 1.3 | NA | 0 | 5.6 |
| **50** | **1.4** | **1.0** | **0.7** | **0** | **0.3** | **2.8** | **NA** | **0** | **8.9** |
| 75 | 3.8 | 2.4 | 1.2 | 0 | 0.7 | 6.1 | NA | 0.1 | 14.8 |
| 95 | 14.9 | 8.2 | 2.5 | 0.1 | 1.5 | 17.7 | NA | 0.4 | 34.1 |

Over the 18-year period, the annual emission rates for all States and Territories for this fire type were visually assessed to be stationary series that could be modelled with either lognormal or normal distributions.

The median emission rate for the continent from bushfires is ≈ 9 $MtCO_2$ $yr^{-1}$, with the Western Australia being the largest contributor (32%), followed by New South Wales and Victoria. Using the fossil fuel perspective, the median emission rate for the continent is ≈ 2.4 MtC $yr^{-1}$, which is just 3% of the current national fossil fuel consumption rate. Variability in annual emission rates is high and varies between States

For strong social and economic reasons, bushfires hold a special place in the national consciousness. In terms of $CO_2$ emissions, because they are the smallest contributor of the three resilient landscape fire types, they are essentially insignificant.

*Grassland fires*

Using the area, fuel loading and burning efficiency values derived in Appendices A and B, a pdf of annual $CO_2$ emissions was generated for each State and Territory using Equation (3) and the Monte Carlo simulation techniques described above. Statistical summaries of these $CO_2$ emissions pdf for Grassland fires are set out in Table 3.

Within the constraint of very poor original data, over the 18-year period, the annual emission rates for all States and Territories for this fire type were assessed to be a stationary series with extreme values that could be modelled with either normal or lognormal distributions.

The median emission rate for the continent from Grassland fires is ≈ 294 $MtCO_2\ yr^{-1}$, with the Northern Territory and Western Australia the largest contributors (80%), followed by Queensland, then the remaining States and Territory being insignificant contributors. The fossil fuel perspective reveals that the median emission rate for the continent is ≈ 80 $MtC\ yr^{-1}$, which is equivalent to the current national fossil fuel consumption rate. The interannual variability as indicated by the interquartile range is low at ≈ 115 $MtCO_2\ yr^{-1}$, or 39% of the median value.

Table 3: A summary of the annual $CO_2$ emissions ($MtCO_2\ yr^{-1}$) from Grassland fires. The distributions of emission rates are normal or lognormal. Median values are highlighted.

| Percentiles | NSW | Vic | Qld | SA | Tas | WA | NT | ACT | Australia |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 0.1 | 0 | 19 | 0.1 | 0 | 40 | 55 | NA | 178 |
| 25 | 0.2 | 0.1 | 31 | 0.3 | 0 | 76 | 92 | NA | 241 |
| **50** | **0.6** | **0.1** | **42** | **0.8** | **0.1** | **107** | **125** | **NA** | **294** |
| 75 | 1.7 | 0.3 | 56 | 2.3 | 0.1 | 147 | 169 | NA | 356 |
| 95 | 6.8 | 0.8 | 83 | 11.0 | 0.4 | 229 | 259 | NA | 469 |

## $CO_2$ emissions from transformed landscapes

In contrast to the resilient landscapes described in the previous Section, the emissions summarized here are part of an agricultural landcover conversion – from woodlands to grasslands – that is effectively permanent. This process, which involves an initial mechanical clearing of the woody biomass followed by its burning, permanently diminishes the carbon pool size of these landscapes. Via the process of burning, the fuel carbon is permanently transferred to the atmospheric pool. There is no compensating regrowth of the biomass that was burned because the vegetation was transformed – converted from one type to another – resulting in an accompanying reduction in the landscape carbon pool size as well as its potential to sequester carbon. This latter factor will be noted later.

Estimated emissions from Clearing fires are both topical and contentious. They are contentious because in spite of their large emissions, they are currently the most poorly documented of all fire types considered in this essay. For reasons outlined in Appendix C, one set of continent-wide distributions for area, fuel load, and burning efficiency have been derived and they are summarized along with the emissions in Table 4.

Table 4: A statistical summary of the calculated annual $CO_2$ and C emissions, from Clearing fires. Median values are highlighted.

| Percentiles | Area ($Kha\ yr^{-1}$) | Total aboveground biomass ($tDM\ ha^{-1}$) | Emissions ($MtCO_2\ yr^{-1}$) | Emissions ($MtC\ yr^{-1}$) |
|---|---|---|---|---|
| 5 | 350 | 50 | 35 | 9.5 |
| 25 | 420 | 80 | 54 | 15 |
| **50** | **480** | **110** | **73** | **20** |

| | | | | |
|---|---|---|---|---|
| 75 | 540 | 140 | 98 | 27 |
| 95 | 640 | 210 | 151 | 41 |

The most contentious values in Table 4 are those for area. For the 18-year period considered, it is believed that area is both highly variable from year to year, and trending in decline. To capture this variability and trend, the area series were simulated by a lognormal distribution and fitted by expert opinion.

For the 18-year period, the estimated median annual emission from Clearing fires - the biomass burning that is coupled to land clearing - was ≈ 73 Mt$CO_2$ (≈20 MtC). The average fossil fuel consumption – all fuels for the continent - during this period was ≈75 MtC $yr^{-1}$. Therefore, the contribution from Clearing fires – from landcover conversion – was an additional 26% of that from fossil fuels and unlike the perspective comparison used for the fires on resilient landscapes, this emission was *a net contribution*. It should be noted that the total $CO_2$ emissions from the clearing process would be perhaps twice that from burning alone when the contributions from the subsequent decomposition of belowground biomass and the oxidation of soil carbon are added (Barrett et al. 2001).

**Emissions summary**

For the convenience of the reader, the calculated annual emissions from the four fire types and for the entire continent are summarised as kt$CO_2$ in Table5 and ktC in Table 6.

For the 18-year period, the simulated median annual emission rate for continent was 399 Mt$CO_2$ $yr^{-1}$. The largest contribution (74%) to this total was from Grassland fires burning on resilient landscapes where the fuel recovery time would be ≤ 1 year. *This fire type and the two other resilient landscape fires (together contributing just 5%) make no net carbon contribution to the atmospheric pool on time scales of 1-5 years*. The second largest contributor at 18%, Clearing fires, is a net transfer of carbon from landscape to atmosphere that is currently about 20% of national fossil fuel burning.

Table 5: A statistical summary of the calculated annual $CO_2$ emissions (Mt$CO_2$ $yr^{-1}$) for each fire type, and for the entire continent. The median values have been highlighted.

| Percentiles | Managed forest | Unmanaged forest | Grassland | Clearing | Continent |
|---|---|---|---|---|---|
| 5 | 8.3 | 3.0 | 178 | 35 | 267 |
| 25 | 10.8 | 5.6 | 241 | 54 | 342 |
| **50** | **12.8** | **8.9** | **294** | **73** | **399** |
| 75 | 14.9 | 14.8 | 356 | 98 | 467 |
| 95 | 18.2 | 34.1 | 469 | 151 | 589 |

By comparing the total biomass, burning emissions (399 Mt$CO_2$ $yr^{-1}$) with contemporary national fossil fuel consumption provides one informative perspective. Another equally informative perspective is obtained by asking this question: What are the global atmospheric consequences of the Australian emissions?

This question can be simply answered as follows. In the global atmosphere, 1 part per million by volume (ppmv) of $CO_2$ has the equivalent mass of 2.121 GtC. The total area of the Australian continent is 7.7 x $10^6$ $km^2$ while that of the globe is 510 x $10^6$ $km^2$. Therefore, the fraction of the global airmass above the Australian continent is 0.015. From this, we can calculate that in the hypothetical situation of no circulation of the airmass over the continent, the total emissions of 399 $MtCO_2$ $yr^{-1}$ would result in an increase in [$CO_2$] of just 3.4 ppmv in a year. At first glance, this result appears insignificant but it should be further considered in relation to the timing and duration of the emissions in relation to the biospheric uptake flux, which is discussed below.

In the sections that follow, the NPP of the continent is derived from satellite data. The median NPP is calculated to be 1.6 GtC $yr^{-1}$. Therefore, the total biomass burning emissions of 108.8 MtC $yr^{-1}$, Table 6, represents 7% of continental NPP. To provide one point of view on the size of this value, the coefficient of variation (CoV) in continental NPP of the 18 individual years was ≈ 8%. That is, the NPP cost of all biomass burning is approximately the same size as the interannual variation.

Table 6 also summarises biomass consumed. The median annual mass consumed is ≈ 242 MtDM. From Andreae and Merlet (2001), the estimated global equivalent is 5130 MtDM; therefore, the Australian contribution is ≈ 5%.

Table 6: A statistical summary of the calculated annual emissions (MtC $yr^{-1}$) for each fire type, and for the entire continent. The biomass consumed aggregated to continental level (MtDM $yr^{-1}$) is included in parentheses. Median values have been highlighted.

| Percentiles | Managed forest | Unmanaged forest | Grassland | Clearing | Continent |
|---|---|---|---|---|---|
| 5 | 2 | 1 | 48 | 10 | 73<br>(162) |
| 25 | 3 | 2 | 66 | 15 | 93<br>(207) |
| **50** | **4** | **2** | **80** | **20** | **109**<br>**(242)** |
| 75 | 4 | 4 | 97 | 27 | 127<br>(283) |
| 95 | 5 | 9 | 128 | 41 | 161<br>(357) |
| Interquartile range | 1 | 3 | 31 | 12 | 34<br>(76) |

## Patterns of emissions

### *In space*

The objective of this and the following Section are to illustrate and generalize the spatial and temporal patterns of biomass burning for the entire continent. To simplify the task, only Grassland and Clearing fires are considered. In aggregate, these two fire types contribute ≈ 95% of the total emissions, Tables 5 and 6.

A continental map of burned area for the calendar year 2000 is used to illustrate and typify the spatial patterning of $CO_2$ emissions from biomass burning, Figure 2. The individual burned areas were mapped by machine using SPOT VEGETATION image data as a part of the Global Burnt Area initiative (http://www.grid.unep.ch/activities/earlywarning/preview/ims/gba). The individual burned areas are colour coded indicating the month in which they occurred – see later. From Figure 2, it is apparent that for the year 2000 the concentration of burned area is in the Tropics and concentrated along the northern coastline and hinterland. Almost all of these burned areas were tussock Grassland fires close to the coast, or in the hummock ('spinifex') grasslands of the arid interior. Managed and Unmanaged forest fires in the south of the continent are not easily detected using daily images, such as that used here, partly because of the inherent coarse resolution (≈ 1 $km^2$) but mostly because Managed forest fires, in particular, have only a small impact on the overstorey canopy.

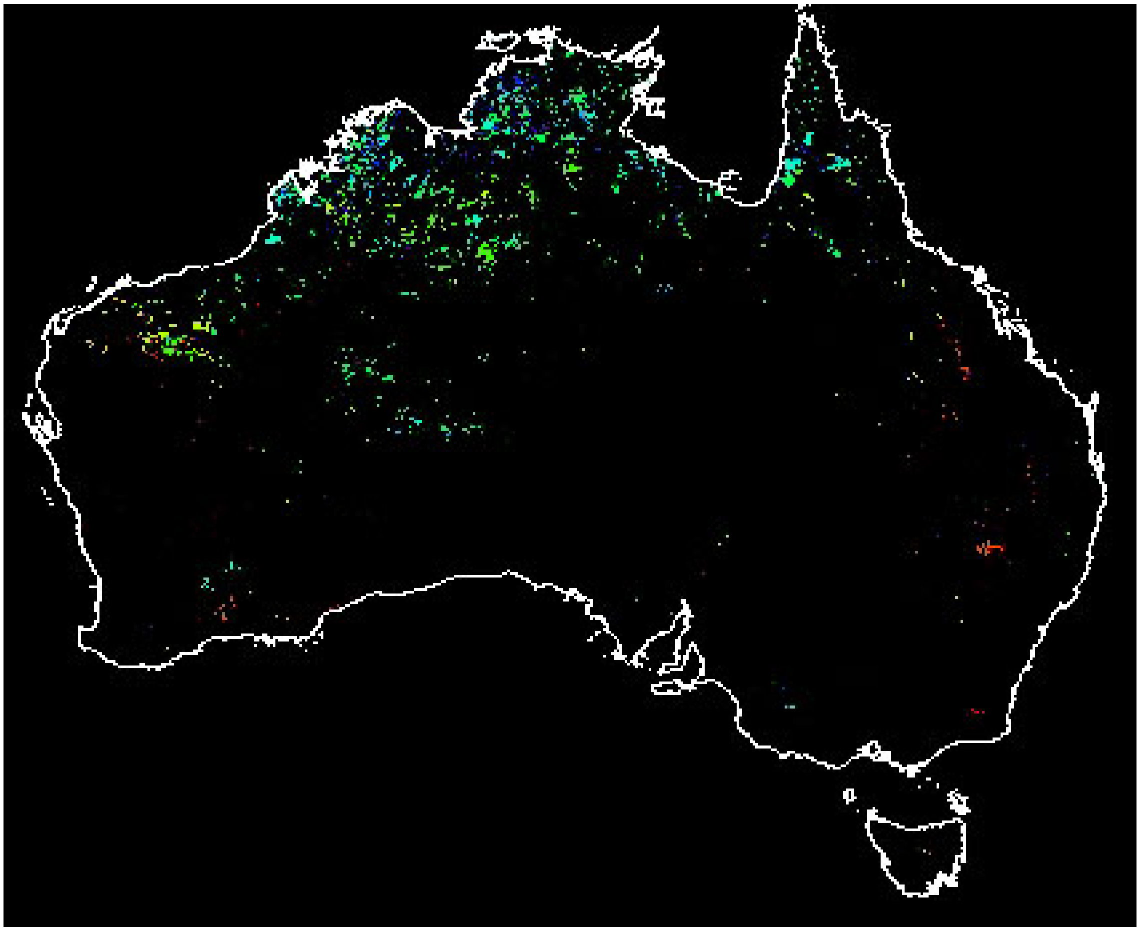

Figure 2: The continental distribution of burned area for the calendar year 2000. These areas were mapped by machine using daily coarse resolution (≈1 $km^2$) SPOT VEGETATION satellite data. The burned areas are concentrated in the Tropics along the northern coastline and hinterland. They are almost all Grassland fires. Managed and Unmanaged fires are not easily detected with this type of satellite data.

In Figure 2, the individual burned areas are colour coded by the month in which they burned. The colour coding is a rainbow but the year is not the calendar year. The carbon metabolism of the continent is best captured by the year that runs from April to March. This year, often called the (agricultural) statistical year includes both the winter greening response of the Extratropics and the summer greening response of the Tropics. The colour coding is a rainbow so that the first months (April, May, June) are violet-blue, and the last months (January, February, March) are orange-red.

Using this colour coding, a few burned areas in Figure 2 appear to be Unmanaged forest fires, such as in southwestern WA or Grassland fires in the summer months in inland NSW and QLD. To accurately monitor the location and area of all fire types discussed in this essay, a systematic multi-stage sampling strategy would be required that employs both coarse and fine resolution data using different frequencies of observation. The presence of quite small fires – hotspots - can be detected using images in the thermal wavebands and this would help identify and then quantify Managed and Clearing fires. In particular, Clearing fires are likely to be detected by such hotspots but only rarely as burned areas because the fuel was (mechanically) gathered into windrows. In the absence of such data, the continental distribution of Clearing fires is inferred and heavily generalised from the detected patterns of clearing, Figure 3.

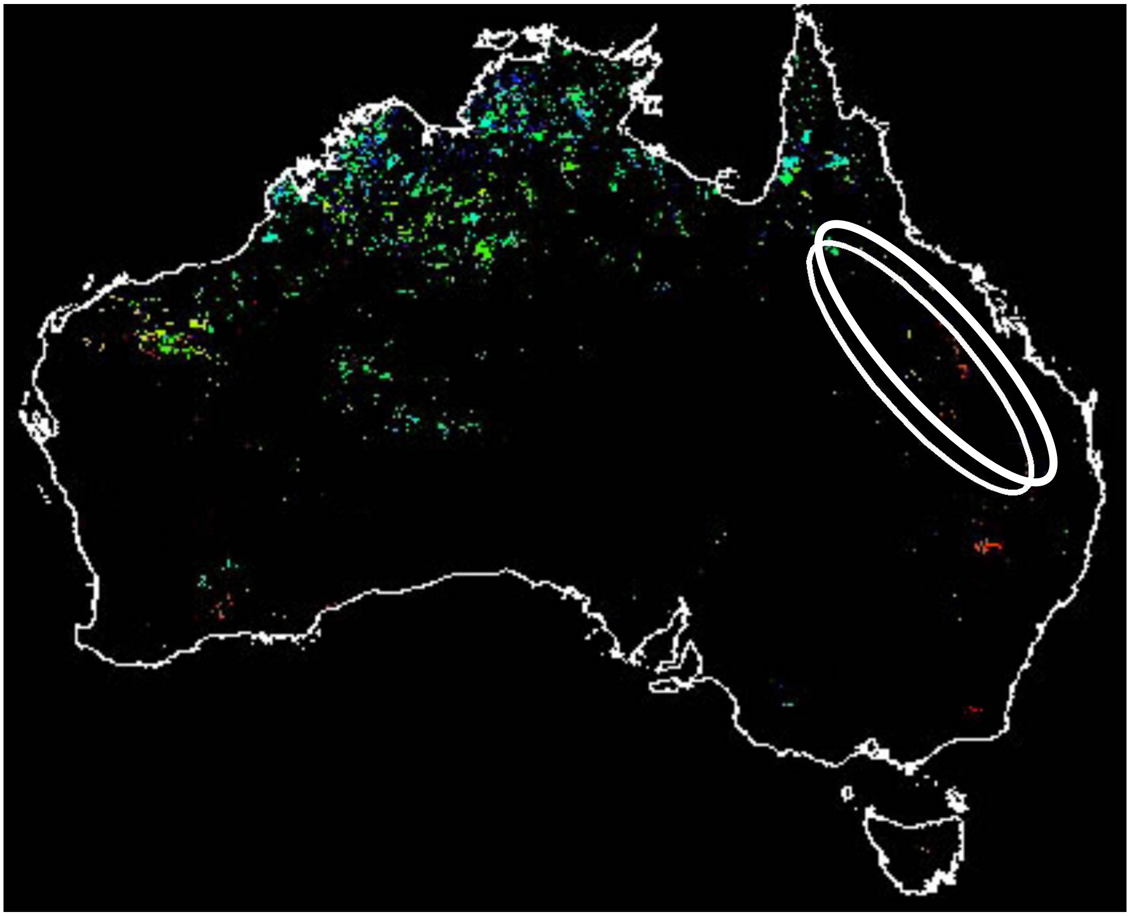

Figure 3: The base image is the same as Figure 2. The location of the majority of current Clearing fires is inferred from the patterns of vegetation clearing, also detected using satellite data.

*In time*

To generalize the temporal pattern of biomass burning, the reasonable assumption is made that pattern of burning activity for the year 2000 and captured in Figure 2, is typical. From Figure 2, a simple and plausible temporal pattern of biomass burning is extracted, Figure 4. The area burned begins to increase from April, the start of the Dry Season, and peaks in September when approximately 30% of burning occurs. Thereafter, there is steep decline towards December when the first rains of the Wet Season can occur. Approximately 90% of the total burning has occurred by November. There is a small increase in burning in January and February, the hot dry months in southern Australia where from their orange-red colour coding, these (most likely Unmanaged) fires can be identified, see Figure 2.

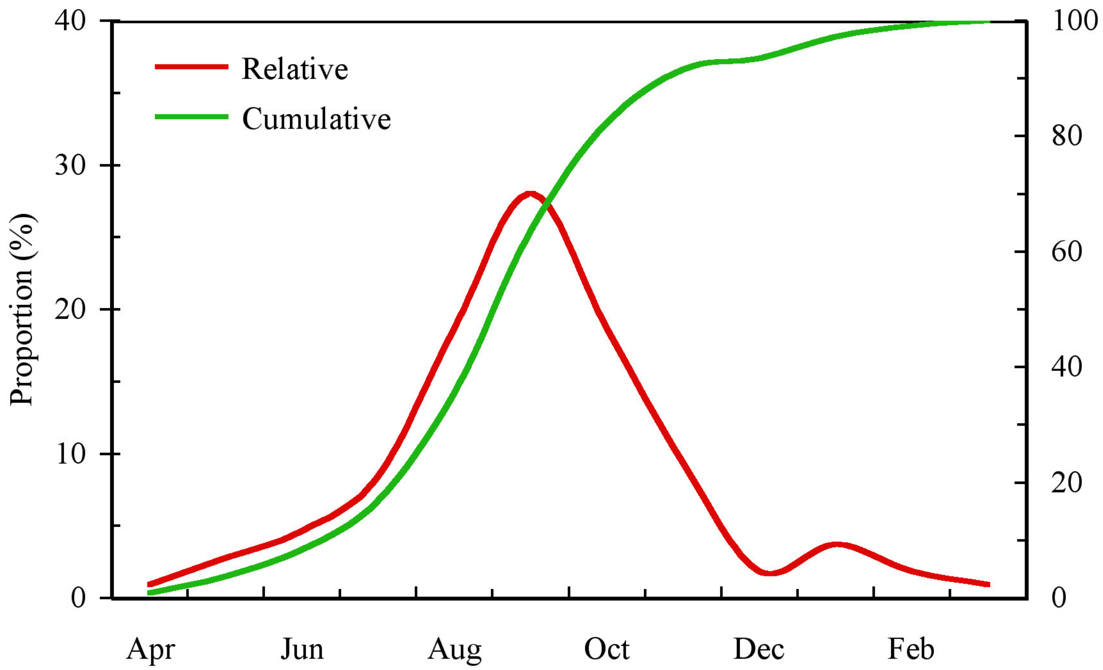


Figure 4: The relative and cumulative distribution of burned area – almost entirely Grassland fires - throughout a typical year based on the data used to construct Figure 2

**$CO_2$ uptake**

This Section addresses this question: What is the size, geographic and temporal distribution of (photosynthetic) $CO_2$ uptake?

To evaluate the consequences of the calculated and mapped $CO_2$ emissions, there is now a requirement to generate equivalent spatial and temporal mapping for $CO_2$ uptake. That is, essentially, the space-time patterning of Net Primary Productivity (NPP) for the continent.

The approach used is based on a long time series of satellite observations of the continent. The satellite sensor was the Advanced Very High Resolution Radiometer (AVHRR) that was flown on a series of spacecraft from August 1981 to present. From the visible and near-infrared channels of this sensor, an index of vegetation greenness, the Normalized Difference Vegetation Index (NDVI), is derived. It is not an overstatement that the availability of the NDVI time series derived from the AVHRR sensor has revolutionised the understanding of the carbon metabolism of the global land surface with a pioneering effort by Tucker et al. (1986).

A geocoded, high quality NDVI time series for the Australian continent is available from 1981 to the present, an extension of that reported by Lovell and Graetz (2001). These data were used to generate temporal and spatial patterns of continental NPP using the following argument. Because the NDVI is a measure of 'greenness', which is in turn a measure of the abundance and (photosynthetic) vigour of the vegetation, it is proposed that its sum over a year ($NDVI_{sum}$) is directly proportional to aboveground NPP for that year. Strictly speaking, $NDVI_{sum}$ captures Gross Primary Productivity (GPP) but since GPP, less autotrophic respiration (the cost of living for plants), is NPP, and autotrophic respiration will be site specific, then what is captured by

$NDVI_{sum}$ is NPP. This is a plausible hypothesis that has successfully been used by others, such as Box et al. (1989). It is further substantiated below.

*$CO_2$ uptake in space*

Given that NPP for the Australian continent is primarily determined by (limited) soil water availability, it could be expected that a map of $NDVI_{sum}$ would resemble a map of soil water availability. Using the Annual Mean Moisture Index (AMMI) variable from the BIOCLIM datasets (Center for Resource and Environment Studies, CRES, Australian National University), the resemblance with $NDVI_{sum}$ is very close, Figure 5. The two images are coloured with a linear rainbow stretch so that the black-violet colours are the lowest AMMI and $NDVI_{sum}$ values, with red as the highest.

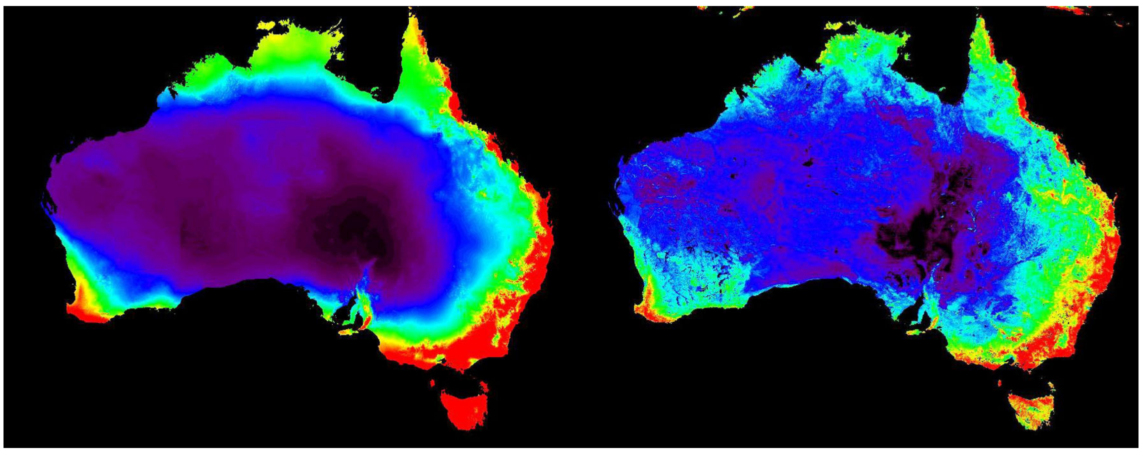

Figure 5: A comparison of the continental distribution of Annual Mean Moisture Index (AMMI), LHS, and $NDVI_{sum}$, RHS. The agreement is very close. Most obvious variations can be explained by landscape factors, such as soil and vegetation type (Barkley Tableland, East Kimberley, Nullarbor Plain), or clearing (WA wheatbelt, south and east coast hinterland), or by persistent cloud contamination (south central Tasmania).

The first point to be made is that the overall pattern closely resembles a map of mean annual rainfall. The central and western arid core of the continent shown in AMMI is faithfully by $NDVI_{sum}$. The high rainfall (and AMMI) areas restricted to the southern and eastern tropical coastlines are closely paralleled by the $NDVI_{sum}$ image. The most obvious, but not very significant variations between $NDVI_{sum}$ and AMMI can be explained by vegetation type, such as the Nullarbor Plain, or persistent cloud contamination in central Tasmania. The second point is that in the $NDVI_{sum}$ image, there is a strong suggestion that areas of high NPP (red) are restricted to perennial woody vegetation. Where this vegetation type was cleared for crops and pastures, these latter replacement vegetation types have significantly lower NPP as measured by the $NDVI_{sum}$ technique. That is, it appears that clearing will not only permanently reduce the landscape carbon pools; it also permanently diminishes the potential of that landscape to take up carbon. There is sound physiological support for this tentative interpretation of the detail within $NDVI_{sum}$ image. Unfortunately because of its coarse spatial resolution (0.05°), the interpretation cannot immediately be tested.

*Converting $NDVI_{sum}$ to NPP*

Aboveground NPP is equated to $NDVI_{sum}$ with the following assumptions:

1. There is a linear relationship between NPP and $NDVI_{sum}$ with no offset;

2. This relationship applies to all vegetation types;

3. The slope of this relationship is the same for monthly and annual time intervals.

The assumptions are plausible and not critical to the general illustrative purpose for which the resultant calculations will be used. The widely used CASA model employs almost identical assumptions (Malmstrom et al. 1997).

By extracting the $NDVI_{sum}$ values for forests and croplands, a calibration of this variable was made. Equating the 99 percentile of $NDVI_{sum}$ to 5.0 tC $ha^{-1}$ $yr^{-1}$ (≈11 tDM $ha^{-1}$ $yr^{-1}$) and the 1 percentile at 0.5 tC $ha^{-1}$ $yr^{-1}$, gives highly plausible values for the annual aboveground NPP of crops, woodlands and high value forests. Using this linear calibration, the maximum NPP values for the continent over the period 1982-3 to 1999-00 are approximately 5.5 tC $ha^{-1}$ $yr^{-1}$ with the mean values at 2.0 tC $ha^{-1}$ $yr^{-1}$. As would be expected, a class-frequency distribution of NPP for the entire continent is highly skewed, Figure 6. The mode of the distribution is approximately 1.5 tC $ha^{-1}$ $yr^{-1}$ and 90% of the continent has NPP values ≤ 3.5 tC $ha^{-1}$ $yr^{-1}$. An interesting consequence of this calibration is that the continental aggregate aboveground NPP is 1.63 GtC $yr^{-1}$ (5.98 $GtCO_2$ $yr^{-1}$). This value is somewhat higher than the current estimates of ≈1 GtC $yr^{-1}$ available from mechanistic models.

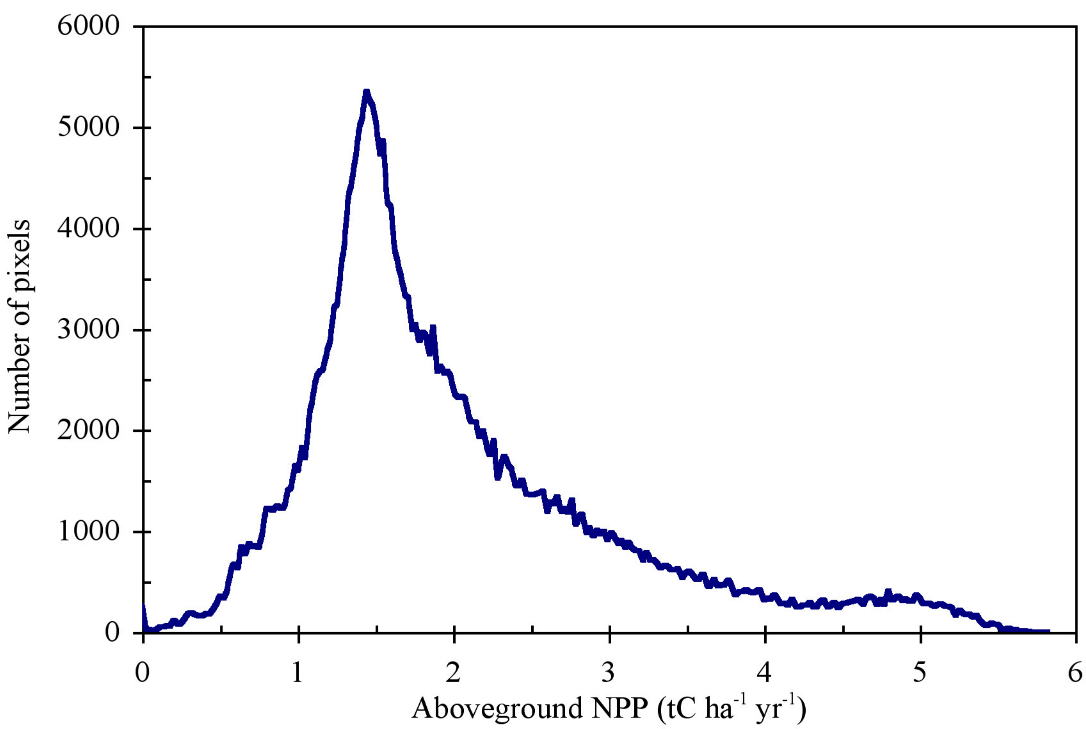


Figure 6: A class frequency distribution of aboveground NPP for the continent as derived from calibrating $NDVI_{sum}$. The mode of this distribution is ≈ 1.5 tC $ha^{-1}$ $yr^{-1}$ and 90% of the continent has NPP values ≤ 3.5 tC $ha^{-1}$ $yr^{-1}$. The continental aggregate NPP is 1.63 GtC $yr^{-1}$.

*$CO_2$ uptake in time*

Having converted $NDVI_{sum}$ values to aboveground NPP, the 18 years of satellite data, 1982/1983 – 1999/2000 are used to characterize the time course of photosynthetic $CO_2$ uptake for the continent. Three individual years of the 1982/1983 –1990/2000 period illustrate the extremes of carbon uptake, Figure 7. The typical rate of continental $CO_2$ uptake, measured in MtC per 10-day epochs, throughout the year is that for the 1987-8 year. There is a very broad peak during the period April-September, the winter rainfall period in southern Australia. This is followed by a depression in uptake rate that bottoms in December, and is then followed by a slow increase through to March. The simplest interpretation of this general shape present in the traces of the three years is that is reflects the winter and summer rainfall regimes. The NPP for the 1987-8 year was 1.62 GtC.

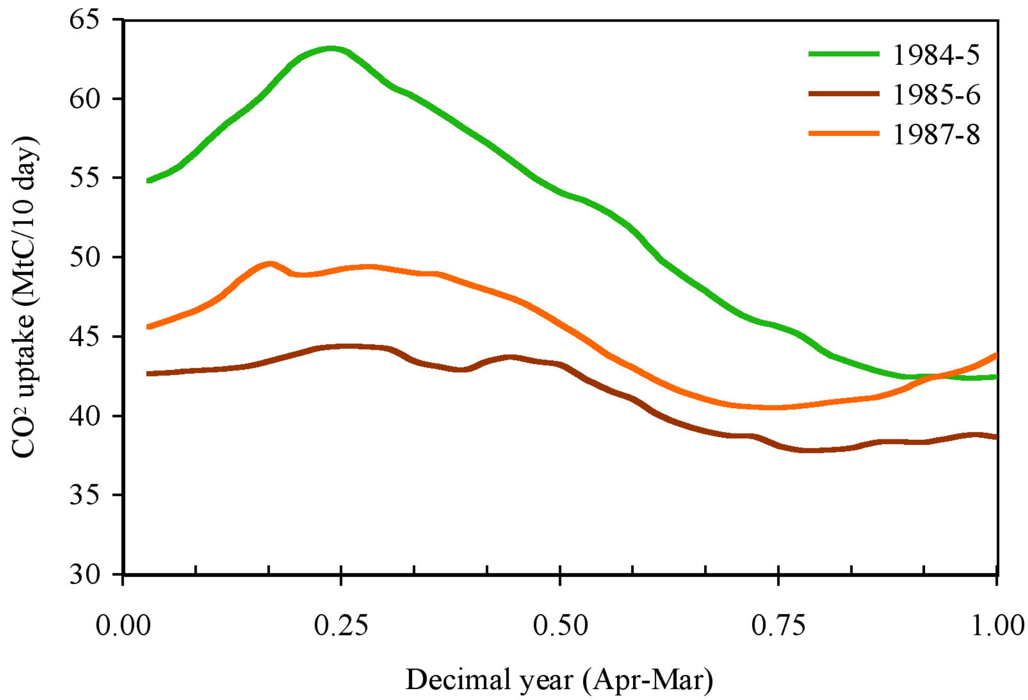


Figure 7: A comparison of the $CO_2$ uptake rates (MtC 10-day period$^{-1}$) for three separate years. The year 1987-8 was close the median of all 18 years in the time series. The year 1984-5 had the highest overall aboveground NPP in contrast to 1985-6, which had the lowest of the series.

The 1984-5 and 1985-6 trajectories reflect wet and dry years respectively. During the 1984-5 year, the continent exhibited high levels of greenness (NDVI) from May-June through until February and the calculated NPP for this year was 1.89 GtC. The trace for the drought year 1985-6 captures a continent with very low levels of 'greenness' throughout the winter rainfall months *and* during the following summer. The aggregate NPP for this year was just 1.49 GtC.

Figure 7 is scaled to highlight the differences in the behaviour of the continent during the six months of winter, April-September, and its contrast with the six summer rainfall months, October-March. However, in aggregate the overall difference is small. Typically, the continental aggregate carbon flux in these summer rainfall months is ≈ 10 % less than the six months of winter. Of all 18 years in the time series, the largest variation occurs in the months of May-July.

To separate the influences of rainfall season, winter vs. summer, and geography, Tropics versus Extratropics, the continent was stratified along the Tropic of Capricorn and the separate NPP values calculated. The total aboveground NPP for the Tropics was ≈ 35% of the continental total. The principal factor is a smaller land area than the Extratropics, and when this is compensated for, it leaves a small margin of just 2% that is the consequence of climatic and soil fertility influences on plant productivity. However, the best summary of the primary productivity of the Australian continent is captured in Figure 5. Some 70% - the core of the continent - is arid or semiarid. Australia is the most arid, permanently occupied, continent on Earth.

**Uptake and emissions**

This Section addresses the last of the orienting questions: Given future efforts to estimate the net $CO_2$ flux from the continent by inverse modelling techniques, where and how strong is the noise of biomass burning?

To address this question, both $CO_2$ emissions and uptake are plotted for a median year, Figure 8. The carbon uptake fluxes of Figure 7 are converted to $CO_2$ on monthly time steps, for both continent and Tropics. Superimposed are the median $CO_2$ emissions from Grassland fires (294 $MtCO_2$ $yr^{-1}$, Table 3) distributed throughout the year as per Figure 4.

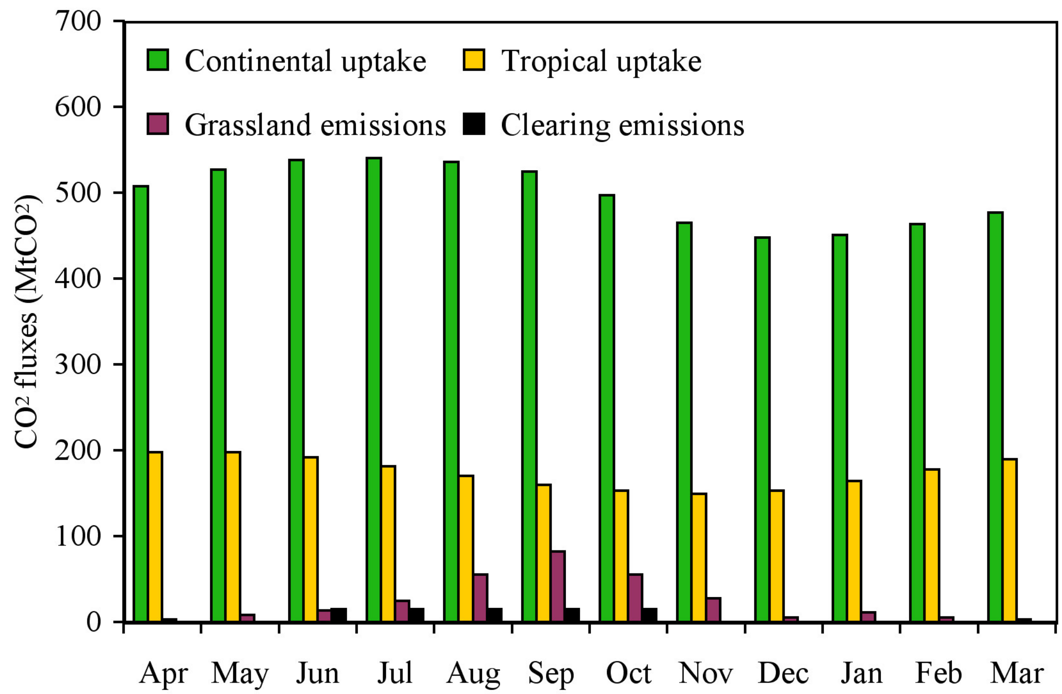


Figure 8: A comparison of $CO_2$ uptake for the continent and the Tropics with the emissions from Grassland and Clearing fires distributed throughout a median year. Compared with overall continental uptake, the emissions are relatively small, particularly those from Clearing fires. When compared with the uptake to the Tropics only, the relative importance of emissions is considerably increased. During the peak emission month of September, the proportions relative to the uptake flux are 52% for Grassland fires, and 10% for Clearing fires.

Considering the entire continent for a full year, the emissions from the two fire types are dwarfed by the uptake. Over the year, the grassland fire aggregate is just 5% of the continental uptake flux of 5.97 $GtCO_2$. However, at peak burning month, September, the 82 $MtCO_2$ emitted from fires (noise) is 16% of the median monthly uptake (signal) of 524 $MtCO_2$. In all other months, the contribution is much less. The emissions from clearing fires appear even more insignificant with a median annual 73 $MtCO_2$, Table 5, they are ≈ 1% of the aggregate annual biogenic flux. Thus, in comparison with the $CO_2$ uptake by the whole continent, the biomass burning emissions that originate mostly in the Tropics, appear to contribute limited noise.

However, if comparisons are focussed to just the Tropics, the above conclusion is reversed. Because the $CO_2$ uptake into the Tropics is just 35% of the entire continent, the relative size of the emissions from the two fire types significantly increases. Over a full year, the emissions from Grassland fires is 14%, and from Clearing fires is 4% of the uptake of 2804 $MtCO_2$. For the peak burning month of September, the emissions from Grassland fires is 52%, and from Clearing fires is 9% of the uptake of 160 $MtCO_2$. This represents significant noise.

**Global comparisons**

As calculated in this essay, the median annual burned area is 37.8 Mha, representing ≈ 5% of the Australian continent.

The median annual emission from all fire types combined is 108.8 MtC (399 $MtCO_2$). This value represents 7% of estimated continental NPP and is approximately the same size as its interannual variation.

It is not possible to find credible estimates of equivalent global values for comparison. The measurement of global burned area has just begun and the estimates of fuel loading are very uncertain. Nonetheless, estimates of the biomass consumed and the consequent emissions are regularly generated based on the best available data.

A recent estimation by Andreae and Merlet (2001) is selected to provide perspective to the Australian values, Table 7. The comparison is a simple one. Australia contributes ≈ 6% of the biomass burned in and $CO_2$ emitted from Grassland (savanna) fires and 10% of biomass burned in and $CO_2$ emitted from Extratropical forest fires (Managed and Unmanaged forest fires). Because there are no (equatorial) tropical forests, overall the contribution of biomass burning on the Australian continent to the global whole is just 5%.

Revisiting the binary classification of fire types used in this essay, we can interpret the global values, Table 7. The largest location of biomass burned/$CO_2$ emissions is the savannas. Based on the argument that savanna (Grassland) fires and fuels are globally homologous, the largest single $CO_2$ emission in Table 7 (> 5 $GtCO_2$ $yr^{-1}$) is *not* a net transfer of carbon from landscape to atmospheric pool. If the fires in Tropical and Extratropical forests are predominantly Clearing fires, then their aggregate emissions (3.1 $GtCO_2$ $yr^{-1}$) represent a net transfer of carbon from landscape to atmospheric pool. Based on this interpretation of Table 7, only 38% of the total global emissions from biomass burning (8.2 $GtCO_2$ $yr^{-1}$) are net carbon transfers from landscape to atmosphere.

Table 7: A comparison of global and Australian values for biomass burned and $CO_2$ emitted. The units are Gt. The global data are from Andreae and Merlet (2001).

| | Grassland | Tropical forest | Extratropical forest | Total |
|---|---|---|---|---|
| | Global | | | |
| Biomass | 3.2 | 1.3 | 0.6 | 5.1 |
| $CO_2$ | 5.1 | 2.1 | 1.0 | 8.2 |
| | Australia | | | |
| Biomass | 0.18 | - | 0.06 | 0.24 |
| $CO_2$ | 0.29 | - | 0.11 | 0.4 |

**Summary**

The structure of this essay was determined by the five questions posed in the Orienting questions Section above. These questions were addressed in sequence.

The first question sought the principal determinant of the net transfer of carbon (as $CO_2$) from the landscape to the atmospheric pool via the phenomenon of biomass burning. Biomass burning is a disturbance to the level of carbon storage of landscapes. The carbon of the fuel, the live or dead plant material is on burning, largely transferred to the atmosphere. However, the size of the *net* emission is determined by the post-fire response of the fuel material; that is, how rapidly, if at all, it was regenerated by the processes of plant growth. Based on this criterion, a binary stratification of fire and emission types was proposed. By far the largest class in terms of area and emissions, in Australia and globally, are the resilient landscape fires where the fuel recovers to pre-fire levels of carbon storage rapidly, within 0.5 - 5 yr. In contrast is the (smaller) transformed landscape class where the fuel carbon disturbance is effectively irreversible and the vegetation is converted by clearing and burning from one type (e.g. woodland) to another (e.g. crop, pasture). Here, the pre-fire carbon storage of the landscapes is permanently diminished.

The second question dealt with the application of the above stratification to Australian conditions. Within the constraints of the available data, transformed landscape fires, the biomass burning that make a significant net transfer of carbon from landscape to atmospheric pool, were identified and quantified as Clearing fires. In contrast, resilient landscape fires were identified and quantified as Managed and Unmanaged forest fires, and Grassland fires.

Using transparently edited data of burned area (A) collected by State and territory agencies, fuel type, load (M), and burning efficiency ($\varepsilon$) were reasoned for all fire types based on specific published values and general biological understanding. The uncertainty associated with both burned area and fuel values was captured by probability distributions (pdf) rather than by a single mean value. These probability distributions were then combined to calculate emissions and report them as probability bands; that is, what is known, as well as how well it is known.

The median annual burned area is 37.8 Mha, representing ≈ 5% of the Australian continent. For the 18-year period, 1982 – 2000, the median annual emission rate for continent was 399 $MtCO_2$ $yr^{-1}$. The largest contribution (74%) to this total was from Grassland fires burning on resilient landscapes where the fuel recovery time would be ≤ 1 year. This fire type and the two other resilient landscape fires (together contributing just 5%) make no net carbon contribution to the atmospheric pool on time scales of 1-5 years. However, the second largest contributor at 18%, Clearing fires, is a net transfer of carbon from landscape to atmosphere of 73 $MtCO_2$ $yr^{-1}$ (≈20 MtC $yr^{-1}$), which approximates 20 % of national fossil fuel burning.

The size, geographic and temporal distribution of the (photosynthetic) $CO_2$ uptake of the continent was estimated from the $NDVI_{sum}$ analysis. Based on a calibration of the 18-year record, the median aboveground NPP of the continent was estimated at 1.63 GtC $yr^{-1}$ and consistent and plausible spatial and temporal patterns of $CO_2$ uptake were established for whole continent and the Tropics. In the latter case, the estimated NPP for the Tropics, where most of the biomass burning occurs, is a constant 35% of the continent. The size of this fraction is almost entirely due to areal extent rather than climatic or soil constraints. The median emission from all fire types combined is 109 MtC $yr^{-1}$ (399 $MtCO_2$ $yr^{-1}$). This value represents 7% of estimated continental NPP and is approximately the same size as its interannual variation.

Given future efforts to estimate the net $CO_2$ flux from the continent by inverse modelling techniques, the level and timing of the noise of biomass burning emissions were evaluated. Considering the entire continent for a full year, the emissions from Grassland and Clearing fires are dwarfed by the uptake. Over the year, the grassland fire aggregate is just 5% of the continental uptake flux of 5.97 $GtCO_2$. However, at peak burning month, September, the 82 $MtCO_2$ emitted from fires (noise) is 16% of the median monthly uptake (signal) of 524 $MtCO_2$. In all other months, the contribution is much less. The emissions from clearing fires appear even more insignificant with a median annual 73 $MtCO_2$, they are ≈ 1% of the aggregate annual biogenic flux. However, if comparisons are focussed to just the Tropics, the signal to noise ratio falls. Because the $CO_2$ uptake into the Tropics is just 35% of the entire continent, the relative size of the emissions from Grassland and Clearing fires significantly increases. Over a full year, the emissions from Grassland fires is 14%, and from Clearing fires is 4% of the uptake of 2804 $MtCO_2$. For the peak burning month of September, the emissions from Grassland fires alone is 52%, and from Clearing fires is 9% of the uptake of 160 $MtCO_2$. This represents significant potential noise for inverse modelling efforts.

Finally, based on Andreae and Merlet (2001), global comparisons can be made of biomass burning on the Australian continent. Australia contributes ≈ 6% of the biomass burned in and $CO_2$ emitted from Grassland (savanna) fires, and 10% of biomass burned in and $CO_2$ emitted from Extratropical forest fires, i.e. Managed and Unmanaged forest fires. The overall the contribution of biomass burning on the Australian continent to the global whole is just 5%.

Based on the binary classification of fire types used in this essay, the largest location of biomass burned/$CO_2$ emissions globally is the savannas. Because savanna (Grassland) fires and fuels are globally homologous, then the largest single $CO_2$ emission of ≈ 5 $GtCO_2$ $yr^{-1}$ is *not* a net transfer of carbon from landscape to atmospheric pool. Further, if the fires in Tropical and Extratropical forests are predominantly Clearing fires, then this aggregate emission of ≈ 3.1 $GtCO_2$ $yr^{-1}$

represents a net transfer of carbon from landscape to atmospheric pool. Thus, only 38% of the total global emissions from biomass burning (8.2 $GtCO_2$ $yr^{-1}$) are a net carbon transfer from landscape to atmosphere.

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## Appendix A: Resilient landscapes - burned area census

### Preamble

The calculation of annual $CO_2$ emissions from biomass burning presented in the main text is critically dependant upon the annual census of burned area (A). These data, their source, quality, and processing are discussed in this Appendix.

### Nature

Two datasets of annual burned area are used. The first and principal set is that collected by the eight State and Territory agencies for the period 1982-2000. The measurement of fire-affected (burned area) area is the responsibility of the eight State and Territory land management agencies. Agencies responsible for the management of forests, national parks, and rangelands record the incidence, location, and area of landscapes affected by managed and unmanaged fires (bushfires, wildfires). These data are primary collected for within-agency purposes and are not part of a systematic national accounting process. Thus, it can be expected that depending upon the relative importance of fire to the individual land management agency, so also will vary the data quality for burned area. For some types of fires within some States or Territories, burned areas are now systematically measured from satellite data, as is done in WA, NT and Qld. Otherwise, the area burned is measured by other techniques or estimated by expert opinion. Setting aside these differences, it is *assumed that these datasets are a systematic census of burned area, consistently made*. These same informal and uncoordinated efforts for recording burned area currently support the emissions calculations within the NGGI.

The second dataset is smaller but of great value. The only formal coordinated effort to systematically measure spatial and temporal patterns of the development of burned area for the entire continent known to the author is a recent initiative by Environment Australia. As part of its portfolio responsibilities for the State of the Environment reporting, this federal agency commissioned a two-year measurement program for the entire continent conducted by the Department of Lands (WA). This state agency has nationally unrivalled experience in the systematic detection and mapping of burned area using daily satellite data as part of bushfire management, especially in the tropical parts of the state: see Firewatch, http://data.wa.gov.au/home.nsf. The initiative ran for two years, April 1999-March 2000 and was reported by Craig et al. (2000).

### Collation

The retrieval of the burned area values from the eight State and Territory agencies, and the exacting synthesis into a national summary was done by Dr. C.P. Meyer of CSIRO Atmospheric Research. The objective was the production of the relevant statistic (area burned, A) to calculate the non-$CO_2$ emissions component of the NGGI. The location or geocoding of burned areas is not consistently available over the period, and thus cannot be used.

The burned area data were collated by Meyer into three fire categories: Prescribed, Bushfire and Savanna. The Prescribed category comprises the managed fires; those fires intentionally lit for fuel reduction purposes, Table A1. The Bushfire category, Table A2, comprises the unmanaged fires, presumably mostly in forested or woodland landscapes. Savanna fires comprise both managed and unmanaged fires in the understorey of open woodlands and grasslands, Table A3.

Meyer has retrieved and collated these data for the 18-year period, 1982-1983 to 1999-2000. Note that the year used is the financial year, June to July. This is understandable given that the financial year is the common interval of government. It is also unfortunate because as will be demonstrated, the largest area of biomass burning is in the tropical savannas – Grassland fires – and here the fire year extends throughout the Dry Season, April – November. Thus, the financial year-based accounting of burned areas that bisects the burning season is likely to add additional accounting errors.

The State and Territory dataset, Tables A1, 2, 3, hereafter the Meyer data set, are the basis of processing reported in this Appendix. Because of the large size of these and subsequent Tables, they are all collected at the end of this Appendix.

**Assumptions**

Because of their central significance of the Meyer dataset to the objective of this essay, the following are the explicit assumptions made in their processing and use.

*Census*

The values are in fact a census; a *comprehensive* tabulation of the continental fire history with no fires excluded.

*Accuracy*

That whatever the assessment method used - expert estimation or actual measurement - the values *consistently* reflect reality.

*Fuel*

The three fire categories created by Meyer represent distinct classes of fuel conditions, i.e. of fuel type and mass (loading). This assumption underpins the assigning of fuel loads developed in Appendix B.

**Assessment**

Perusal of the base datasets, Tables A1, 2, 3, reveals inadequacies that can be reduced and thereby improve their overall utility. This assessment is not a criticism of the efforts of Meyer. Rather it reflects different objectives for the use of these data.

The Prescribed data set, Table A1, has data gaps (SA, Qld) and apparently arbitrary values (SA, ACT). This is expected given that these two have only plantation forests of exotic species and thus prescribed burning is restricted. Note that the values of the majority of States and Territories (NSW, Tas, WA, Vic, Qld, NT) appear plausible. The values for the Prescribed category are important because nationally they are the second largest sources of burned area, and thus potentially of $CO_2$ emissions.

A similar assessment can be made for the Bushfire category, Table A2. The data for most States and Territories are plausible, given an expectancy of episodic large values, with suspiciously arbitrary values for ACT and puzzling ones for SA.

By far the largest source of burned area is the Savanna category. The data for the extratropical States and Territory are adequate. Unfortunately, that for the tropical States and Territories (WA, Qld, NT), which are the largest source of national burning, is either gapped or suspiciously arbitrary (NT). Because this category is important, this and the other two databases are reconstructed for use in emissions calculations.

**Data reconstruction**

The base datasets discussed above were transformed in four stages. The first step was renaming the three categories to reflect both fuel conditions and fire intensity, and thereby the likely burning efficiency of that fuel. The new indicative name for the original Prescribed category is Managed forest fire; for Bushfire it is Unmanaged forest fire; and for Savanna, it is Grassland fire. The reasoning supporting these names is provided in Appendix B.

The second step involved the removal of all suspicious values and the calculation of the statistical variables required to describe the distribution of any fire type for any States and Territories over the 18 years, with data gaps ignored. The permitted distributions were either normal (gaussian) or lognormal, the latter to describe the highly skewed distributions of the Unmanaged forest burned areas. The lognormal distributions were not objectively fitted because the small number of observations. Instead, they were iteratively fitted using the author's expert judgment. The purpose of selecting and fitting a distribution for each fire type by States and Territory time series is to characterize it for later use, and for the interpolation of missing values.

Next, the missing values were replaced by techniques that added minimal but consistent bias. As expected, there are significant correlations between individual States and Territories but they are insufficiently numerous or robust to allow the values for one State or Territory to predict those in another. Instead, based on the distribution type, random numbers lying between ± one standard deviation were generated and inserted. This technique, which is biased against extreme values, appeared the only acceptable way to fill in the substantial gaps for the (normally distributed) Grassland series for Qld, NT, and WA.

Finally, the final reporting of values was addressed. The Meyer base data has burned area values rounded to the nearest hectare (ha). This is quite unrealistic given the mix of measurement and estimating techniques used States and Territory agencies in generating the values. Therefore, as a final step, all the values were rounded to the nearest 100 ha (1 $km^2$). Even with this rounding, the intrinsic accuracy of the data remains overstated by perhaps an order of magnitude. The new reconstructed burned area datasets used in emission calculations are tables A4, 5, 6, and a continental summary of areas as Table A.7.

**Trend**

Given the overall quality of the base dataset, the occurrence of extreme values in the Unmanaged forest and Grassland fire datasets, and the few years of available records, no sustained attempt was made to establish any time trends in burned area for any fire type.

*Therefore, it is assumed that the burned area sequence for the three fire types for all States and Territories is a stationary series and the 18 years of records can be represented by summary statistics.*

**Summary**

Datasets of burned area collected by various state agencies were edited in a transparent and consistent manner. The result is an 18-year time series of burned area for three fire types for each of the eight States and Territories:

Fire types (3) x States and Territories (8) x Year (18)

The median annual burned area for the continent was 37.8 Mha $yr^{-1}$, representing ≈ 5% of the continental area. This total area burned reflects the overwhelming contribution from Grassland fires of 36.5 Mha, or 97% of the total. Thus, in terms of burned area, the contribution of Managed and Unmanaged fires is trivial.

The data in tables A.4 – A.6 are used along with the fuel loading and burning efficiency values from Appendix B to calculate the annual $CO_2$ emissions for the continent.

Table A1: The Prescribed burned area dataset (ha) as collated by Meyer from the eight State and Territory agencies for the 18-year period. It is likely that the actual accuracy of these values is exaggerated by the number of significant figures used.

| Year | NSW | Tas | WA | SA | Vic | Qld | NT | ACT | Australia |
|---|---|---|---|---|---|---|---|---|---|
| 1982/83 | 64,708 | 16,722 | 272,986 | | 167,136 | 119,000 | 0 | 700 | 641,252 |
| 1983/84 | 100,834 | 32,042 | 252,851 | | 62,345 | 96,020 | 0 | 700 | 544,792 |
| 1984/85 | 72,392 | 26,183 | 282,056 | | 106,370 | 164,000 | 0 | 700 | 651,701 |
| 1985/86 | 160,917 | 41,811 | 268,954 | | 96,200 | 141,000 | 0 | 700 | 709,582 |
| 1986/87 | 116,531 | 30,476 | 208,569 | | 210,792 | 165,000 | 0 | 700 | 741,921 |
| 1987/88 | 124,847 | 22,423 | 227,281 | | 200,000 | 151,000 | 0 | 700 | 734,978 |
| 1988/89 | 89,777 | 5,356 | 234,514 | | 34,171 | 28,000 | 0 | 700 | 405,994 |
| 1989/90 | 158,675 | 22,239 | 277,364 | 1,000 | 105,500 | | 0 | 700 | 564,978 |
| 1990/91 | 171,077 | 19,442 | 365,164 | 1,000 | 205,000 | | 0 | 700 | 762,383 |
| 1991/92 | 61,777 | 5,101 | 309,350 | 1,000 | 100,000 | | 0 | 700 | 477,928 |
| 1992/93 | 93,971 | 11,317 | 270,682 | 12 | 100,000 | | 0 | 300 | 476,280 |
| 1993/94 | 205,469 | 6,532 | 248,330 | 140 | 180,000 | 102,820 | 0 | 300 | 640,771 |
| 1994/95 | 131,629 | 6,700 | 260,846 | 142 | 141,000 | 101,039 | 0 | 20 | 659,417 |
| 1995/96 | 169,377 | 9,058 | 363,209 | 297 | 131,000 | 61,067 | 0 | 200 | 734,208 |
| 1996/97 | 159,999 | 11,245 | 449,201 | 173 | 131,000 | 103,650 | 0 | 200 | 855,468 |
| 1997/98 | 173,585 | 20,737 | 205,497 | | 30,268 | 95,314 | 0 | 100 | 525,501 |
| 1998/99 | 119,940 | 18,565 | 192,911 | | 104,586 | 67,131 | 0 | 100 | 503,233 |
| 1999/00 | 49,865 | | 194,969 | | 40,024 | 80,974 | 0 | 300 | 366,132 |

Table A2: The Bushfire burned area dataset (ha) as collated by Meyer from the eight State and Territory agencies for the 18-year period. It is likely that the actual accuracy of these values is exaggerated by the number of significant figures used.

| Year | NSW | Tas | WA | SA | Vic | Qld | NT | ACT | Australia |
|---|---|---|---|---|---|---|---|---|---|
| 1982/83 | 326,400 | 62,385 | 11,513 | 19,981 | 20,648 | 197,000 | 0 | 12,000 | 649,927 |
| 1983/84 | 8,454 | 20,283 | 9,164 | 125 | 486,030 | | 0 | 3,000 | 527,162 |
| 1984/85 | 242,000 | 2,230 | 59,524 | 3,718 | 240,037 | 19,000 | 0 | 3,000 | 569,509 |
| 1985/86 | 35,400 | 873 | 72,654 | 106 | 14,778 | 15,000 | 0 | 3,000 | 141,811 |
| 1986/87 | 249,801 | 5,079 | 235,678 | 101 | 24,958 | 44,000 | 0 | 3,000 | 562,617 |
| 1987/88 | 158,954 | 30,861 | 76,543 | 293 | 32,352 | 14,000 | 0 | 3,000 | 316,003 |
| 1988/89 | 79,452 | 8,833 | 78,431 | 138 | 30,744 | 33,000 | 0 | 3,000 | 233,598 |
| 1989/90 | 99,340 | 14,529 | 247,147 | 300 | 26,297 | 73,930 | 0 | 3,000 | 464,543 |
| 1990/91 | 251,252 | 9,675 | 1,221,102 | 101 | 51,943 | 28,945 | 0 | 3,000 | 1,566,018 |
| 1991/92 | 449,800 | 15,466 | 279,320 | 102 | 4,815 | 37,925 | 0 | 3,000 | 790,428 |
| 1992/93 | 10,000 | 5,623 | 144,200 | 1 | 4,815 | 39,855 | 0 | 200 | 204,694 |
| 1993/94 | 123,604 | 12,735 | 199,200 | 21 | 16,000 | 22,525 | 0 | 200 | 374,285 |
| 1994/95 | 23,716 | 52,572 | 101,692 | 7 | 19,000 | 90,256 | 0 | 180 | 287,423 |
| 1995/96 | 32,764 | 51,607 | 400,899 | 7 | 14,169 | 20,844 | 0 | 500 | 520,789 |
| 1996/97 | 30,242 | 47,623 | 168,192 | 145 | 25,612 | 47,761 | 0 | 200 | 319,775 |
| 1997/98 | 341,861 | 31,085 | 268,762 | | 57,475 | 37,679 | 0 | 100 | 736,962 |
| 1998/99 | 18,796 | 5,407 | 45,029 | | 60,680 | | 0 | 300 | 131,723 |
| 1999/00 | 7,293 | 10,755 | 74,334 | | 22,648 | 24,746 | 0 | 100 | 129,121 |

Table A3: The Savanna burned area dataset (ha) as collated by Meyer from the eight State and Territory agencies for the 18-year period. It is likely that the actual accuracy of these values is exaggerated by the number of significant figures used.

| Year | NSW | Tas | WA | SA | Vic | Qld | NT | ACT | Australia |
|---|---|---|---|---|---|---|---|---|---|
| 1982/83 | 121,000 | 21,796 | | 175,229 | 99,166 | | 13,428,400 | 0 | 13,845,591 |
| 1983/84 | 12,500 | 19,589 | | 13,129 | 10,979 | | 11,708,400 | 0 | 11,764,597 |
| 1984/85 | 2,478,000 | 11,305 | | 177,130 | 205,054 | | 14,268,400 | 0 | 17,139,889 |
| 1985/86 | 93,148 | 61,582 | | 178,029 | 11,170 | | | 0 | 343,929 |
| 1986/87 | 207,878 | 32,068 | | 350,179 | 37,830 | | | 0 | 627,955 |
| 1987/88 | 51,048 | 11,193 | | 1,769,006 | 72,550 | | | 0 | 1,903,797 |
| 1988/89 | 40,657 | 14,803 | | 71,462 | 44,330 | | | 0 | 171,252 |
| 1989/90 | 195,073 | 15,785 | | 62,264 | 14,210 | | | 0 | 287,332 |
| 1990/91 | 517,168 | 5,301 | | 789,808 | | | | 0 | 1,312,277 |
| 1991/92 | 50,600 | 3,761 | | 217,188 | 5,880 | | | 0 | 277,429 |
| 1992/93 | 21,772 | 4,343 | 7,790,000 | 7,557 | 11,500 | | | 0 | 7,835,172 |
| 1993/94 | 382,398 | 7,574 | 14,990,000 | 207,875 | 17,900 | | 18,700,000 | 0 | 34,305,747 |
| 1994/95 | 89,112 | 28,134 | 14,790,000 | 88,338 | 17,502 | | 22,900,000 | 0 | 37,913,086 |
| 1995/96 | 90,480 | 18,662 | 19,382,000 | 3,707 | 7,564 | 7,500,000 | 25,000,000 | 0 | 52,002,413 |
| 1996/97 | 131,068 | 2,585 | 13,658,703 | | 15,131 | 3,802,000 | 17,773,000 | 0 | 35,382,487 |
| 1997/98 | | 5,017 | 22,248,007 | | 7,965 | 4,619,892 | 20,123,786 | 0 | 47,004,667 |
| 1998/99 | 16,380 | 1,428 | 6,249,527 | | 18,979 | 4,991,912 | 18,494,009 | 0 | 29,772,235 |
| 1999/00 | 5,528 | 7,425 | 23,016,105 | 441,168 | 8,958 | 9,296,201 | 27,210,118 | 0 | 59,985,503 |

Table A4: The Managed forest fire burned area dataset (ha) reconstructed from the original Meyer Prescribed fire dataset. Descriptive statistics are attached. The low Skew values indicate that the distributions of annual burned areas are normally distributed.

| Year | NSW | Tas | WA | SA | Vic | Qld | NT | ACT | Australia |
|---|---|---|---|---|---|---|---|---|---|
| 1982/83 | 64,700 | 16,700 | 273,000 | 100 | 167,100 | 119,000 | 0 | 700 | 641,300 |
| 1983/84 | 100,800 | 32,000 | 252,900 | 300 | 62,300 | 96,000 | 0 | 700 | 544,800 |
| 1984/85 | 72,400 | 26,200 | 282,100 | 700 | 106,400 | 164,000 | 0 | 700 | 651,700 |
| 1985/86 | 160,900 | 41,800 | 269,000 | 300 | 96,200 | 141,000 | 0 | 700 | 709,600 |
| 1986/87 | 116,500 | 30,500 | 208,600 | 500 | 210,800 | 165,000 | 0 | 700 | 741,900 |
| 1987/88 | 124,800 | 22,400 | 227,300 | 300 | 200,000 | 151,000 | 0 | 700 | 735,000 |
| 1988/89 | 89,800 | 5,400 | 234,500 | 0 | 34,200 | 28,000 | 0 | 700 | 406,000 |
| 1989/90 | 158,700 | 22,200 | 277,400 | 1,000 | 105,500 | 82,300 | 0 | 700 | 565,000 |
| 1990/91 | 171,100 | 19,400 | 365,200 | 1,000 | 205,000 | 57,400 | 0 | 700 | 762,400 |
| 1991/92 | 61,800 | 5,100 | 309,400 | 1,000 | 100,000 | 115,700 | 0 | 700 | 477,900 |
| 1992/93 | 94,000 | 11,300 | 270,700 | 0 | 100,000 | 137,800 | 0 | 300 | 476,300 |
| 1993/94 | 205,500 | 6,500 | 248,300 | 100 | 180,000 | 102,800 | 0 | 300 | 640,800 |
| 1994/95 | 131,600 | 6,700 | 260,800 | 100 | 141,000 | 101,000 | 0 | 0 | 659,400 |
| 1995/96 | 169,400 | 9,100 | 363,200 | 300 | 131,000 | 61,100 | 0 | 200 | 734,200 |
| 1996/97 | 160,000 | 11,200 | 449,200 | 200 | 131,000 | 103,700 | 0 | 200 | 855,500 |
| 1997/98 | 173,600 | 20,700 | 205,500 | 200 | 30,300 | 95,300 | 0 | 100 | 525,500 |
| 1998/99 | 119,900 | 18,600 | 192,900 | 300 | 104,600 | 67,100 | 0 | 100 | 503,900 |
| 1999/00 | 49,900 | 11,000 | 195,000 | 800 | 40,000 | 81,000 | 0 | 300 | 378,000 |
| Mean | 123,600 | 17,600 | 271,400 | 400 | 119,200 | 103,800 | | 500 | 611,600 |
| Max | 205,500 | 41,800 | 449,200 | 1,000 | 210,800 | 165,000 | 0 | 700 | 855,500 |
| Min | 49,900 | 5,100 | 192,900 | 0 | 30,300 | 28,000 | 0 | 0 | 378,000 |
| Median | 122,350 | 17,650 | 264,900 | 300 | 105,950 | 101,900 | 0 | 700 | 641,050 |
| Stdev | 45,700 | 10,400 | 66,400 | 300 | 57,100 | 38,100 | 0 | 300 | 133,600 |
| CoV | 0.37 | 0.59 | 0.24 | 0.75 | 0.48 | 0.37 | | 0.60 | 0.22 |
| Skew | -0.02 | 0.73 | 1.28 | 0.80 | 0.09 | -0.05 | | -0.48 | -0.10 |

Table A5: The Unmanaged forest fire burned area dataset (ha) reconstructed from the original Meyer Bushfire fire dataset. Descriptive statistics are attached. With the exception of New South Wales and Tasmania, the high Skew values indicate the distributions of annual burned area are lognormal.

| Year | NSW | Tas | WA | SA | Vic | Qld | NT | ACT | Australia |
|---|---|---|---|---|---|---|---|---|---|
| 1982/83 | 326,400 | 62,400 | 11,500 | 20,000 | 20,600 | 197,000 | - | 12,000 | 649,900 |
| 1983/84 | 8,500 | 20,300 | 9,200 | 100 | 486,000 | 32,900 | - | 3,000 | 527,200 |
| 1984/85 | 242,000 | 2,200 | 59,500 | 3,700 | 240,000 | 19,000 | - | 3,000 | 569,500 |
| 1985/86 | 35,400 | 900 | 72,700 | 100 | 14,800 | 15,000 | - | 3,000 | 141,800 |
| 1986/87 | 249,800 | 5,100 | 235,700 | 100 | 25,000 | 44,000 | - | 3,000 | 562,600 |
| 1987/88 | 159,000 | 30,900 | 76,500 | 300 | 32,400 | 14,000 | - | 3,000 | 316,000 |
| 1988/89 | 79,500 | 8,800 | 78,400 | 100 | 30,700 | 33,000 | - | 3,000 | 233,600 |
| 1989/90 | 99,300 | 14,500 | 247,100 | 300 | 26,300 | 73,900 | - | 3,000 | 464,500 |
| 1990/91 | 251,300 | 9,700 | 1,221,100 | 100 | 51,900 | 28,900 | - | 3,000 | 1,566,000 |
| 1991/92 | 449,800 | 15,500 | 279,300 | 100 | 4,800 | 37,900 | - | 3,000 | 790,400 |
| 1992/93 | 10,000 | 5,600 | 144,200 | 300 | 4,800 | 39,900 | - | 200 | 204,700 |
| 1993/94 | 123,600 | 12,700 | 199,200 | - | 16,000 | 22,500 | - | 200 | 374,300 |
| 1994/95 | 23,700 | 52,600 | 101,700 | 300 | 19,000 | 90,300 | - | 200 | 287,400 |
| 1995/96 | 32,800 | 51,600 | 400,900 | 100 | 14,200 | 20,800 | - | 500 | 520,800 |
| 1996/97 | 30,200 | 47,600 | 168,200 | 100 | 25,600 | 47,800 | - | 200 | 319,800 |
| 1997/98 | 341,900 | 31,100 | 268,800 | 200 | 57,500 | 37,700 | - | 100 | 737,000 |
| 1998/99 | 18,800 | 5,400 | 45,000 | 100 | 60,700 | 29,600 | - | 300 | 131,700 |
| 1999/00 | 7,300 | 10,800 | 74,300 | 100 | 22,600 | 24,700 | - | 100 | 129,100 |
| Mean | 138300 | 21500 | 205200 | 1500 | 64100 | 44900 | - | 2300 | 473700 |
| Max | 449800 | 62400 | 1221100 | 20000 | 486000 | 197000 | - | 12000 | 1566000 |
| Min | 7300 | 900 | 9200 | 0 | 4800 | 14000 | - | 100 | 129100 |
| Median | 89400 | 13600 | 122950 | 100 | 25300 | 32950 | - | 3000 | 419400 |
| Stdev | 138,600 | 19,700 | 275,300 | 4,700 | 117,700 | 42,700 | - | 2,800 | 341,700 |
| CoV | 1.0 | 0.9 | 1.3 | 3.2 | 1.8 | 1.0 | - | 1.2 | 0.7 |
| Skew | 0.9 | 1.0 | 3.2 | 4.0 | 3.2 | 3.0 | - | 2.6 | 2.0 |

Table A6: The Grassland fire burned area dataset (ha) reconstructed from the original Meyer Savanna fire dataset. Descriptive statistics are attached. Based on the Skew values, normal or lognormal distributions were fitted to the annual burned area values.

| Year | NSW | Tas | WA | SA | Vic | Qld | NT | ACT | Australia |
|---|---|---|---|---|---|---|---|---|---|
| 1982/83 | 121,000 | 21,800 | 15,120,100 | 175,200 | 99,200 | 5,650,200 | 13,428,400 | - | 34,615,900 |
| 1983/84 | 12,500 | 19,600 | 20,698,100 | 13,100 | 11,000 | 6,182,400 | 11,708,400 | - | 38,645,000 |
| 1984/85 | 2,478,000 | 11,300 | 12,423,700 | 177,100 | 205,100 | 4,104,000 | 14,268,400 | - | 33,667,600 |
| 1985/86 | 93,100 | 61,600 | 14,884,300 | 178,000 | 11,200 | 4,284,100 | 19,299,500 | - | 38,811,900 |
| 1986/87 | 207,900 | 32,100 | 6,656,800 | 350,200 | 37,800 | 4,901,600 | 23,150,800 | - | 35,337,200 |
| 1987/88 | 51,000 | 11,200 | 9,244,800 | 1,769,000 | 72,600 | 6,653,200 | 12,118,000 | - | 29,919,800 |
| 1988/89 | 40,700 | 14,800 | 14,581,600 | 71,500 | 44,300 | 7,519,400 | 6,888,900 | - | 29,161,100 |
| 1989/90 | 195,100 | 15,800 | 17,826,100 | 62,300 | 14,200 | 4,514,900 | 13,462,600 | - | 36,090,900 |
| 1990/91 | 517,200 | 5,300 | 18,056,600 | 789,800 | 5,500 | 4,170,500 | 22,734,200 | - | 46,279,100 |
| 1991/92 | 50,600 | 3,800 | 15,892,800 | 217,200 | 5,900 | 5,372,700 | 14,741,100 | - | 36,284,000 |
| 1992/93 | 21,800 | 4,300 | 7,790,000 | 7,600 | 11,500 | 6,457,300 | 15,507,900 | - | 29,800,500 |
| 1993/94 | 382,400 | 7,600 | 14,990,000 | 207,900 | 17,900 | 4,752,300 | 18,700,000 | - | 39,058,000 |
| 1994/95 | 89,100 | 28,100 | 14,790,000 | 88,300 | 17,500 | 5,042,800 | 22,900,000 | - | 42,955,900 |
| 1995/96 | 90,500 | 18,700 | 19,382,000 | 3,700 | 7,600 | 7,500,000 | 25,000,000 | - | 52,002,400 |
| 1996/97 | 131,100 | 2,600 | 13,658,700 | 88,900 | 15,100 | 3,802,000 | 17,773,000 | - | 35,471,400 |
| 1997/98 | 71,700 | 5,000 | 22,248,000 | 75,700 | 8,000 | 4,619,900 | 20,123,800 | - | 47,152,000 |
| 1998/99 | 16,400 | 1,400 | 6,249,500 | 89,100 | 19,000 | 4,991,900 | 18,494,000 | - | 29,861,400 |
| 1999/00 | 5,500 | 7,400 | 23,016,100 | 441,200 | 9,000 | 9,296,200 | 27,210,100 | - | 59,985,500 |
| Mean | 254,200 | 15,100 | 14,861,600 | 267,000 | 34,000 | 5,545,300 | 17,639,400 | - | 38,616,600 |
| Max | 2,478,000 | 61,600 | 23,016,100 | 1,769,000 | 205,100 | 9,296,200 | 27,210,100 | - | 59,985,500 |
| Min | 5,500 | 1,400 | 6,249,500 | 3,700 | 5,500 | 3,802,000 | 6,888,900 | - | 29,161,100 |
| Median | 89,800 | 11,250 | 14,937,150 | 132,150 | 14,650 | 5,017,350 | 18,133,500 | - | 36,187,450 |
| Stdev | 571,000 | 14,600 | 5,007,100 | 420,800 | 49,600 | 1,463,500 | 5,320,900 | - | 8,327,200 |
| CoV | 2.2 | 1.0 | 0.3 | 1.6 | 1.5 | 0.3 | 0.3 | - | 0.2 |
| Skew | 3.9 | 2.1 | -0.2 | 3.1 | 2.8 | 1.1 | 0.0 | - | 1.2 |

Table A7: A summary of the three fire types for all States and Territories. Descriptive statistics are attached.

| Year | Managed forest | Unmanaged forest | Grassland | Total |
|---|---|---|---|---|
| 1982/83 | 641,300 | 649,900 | 26,125,600 | 27,416,800 |
| 1983/84 | 544,800 | 527,200 | 33,973,600 | 35,045,600 |
| 1984/85 | 651,700 | 569,500 | 32,635,200 | 33,856,400 |
| 1985/86 | 709,600 | 141,800 | 34,743,000 | 35,594,400 |
| 1986/87 | 741,900 | 562,600 | 37,577,800 | 38,882,300 |
| 1987/88 | 735,000 | 316,000 | 43,295,300 | 44,346,300 |
| 1988/89 | 406,000 | 233,600 | 34,406,800 | 35,046,400 |
| 1989/90 | 565,000 | 464,500 | 39,979,900 | 41,009,400 |
| 1990/91 | 762,400 | 1,566,000 | 38,280,300 | 40,608,700 |
| 1991/92 | 477,900 | 790,400 | 35,497,500 | 36,765,800 |
| 1992/93 | 476,300 | 204,700 | 30,370,900 | 31,051,900 |
| 1993/94 | 640,800 | 374,300 | 38,615,100 | 39,630,200 |
| 1994/95 | 659,400 | 287,400 | 44,686,700 | 45,633,500 |
| 1995/96 | 734,200 | 520,800 | 52,002,400 | 53,257,400 |
| 1996/97 | 855,500 | 319,800 | 35,463,300 | 36,638,600 |
| 1997/98 | 525,500 | 737,000 | 47,159,400 | 48,421,900 |
| 1998/99 | 503,900 | 131,700 | 29,862,800 | 30,498,400 |
| 1999/00 | 378,000 | 129,100 | 59,985,500 | 60,492,600 |
| Mean | 611,600 | 473,700 | 38,592,300 | 39,677,600 |
| Max | 855,500 | 1,566,000 | 59,985,500 | 60,492,600 |
| Min | 378,000 | 129,100 | 26,125,600 | 27,416,800 |
| Median | 641,050 | 419,400 | 36,537,650 | 37,824,050 |
| Stdev | 133,600 | 341,700 | 8,334,700 | 8,313,200 |
| CoV | 0.22 | 0.72 | 0.22 | 0.21 |
| Skew | -0.1 | 2.0 | 1.1 | 1.0 |

## Appendix B: Resilient landscapes - fuel loading and burning efficiency

**Context:**

In the calculation of the $CO_2$ emissions from biomass burning ( $E$ ), the required variables are the area burned ( $A$, ha), the dry mass density of fuel, or fuel loading ( $M$, tDM ha$^{-1}$), and the burning efficiency of that fuel ( $\varepsilon$): see Equation (3) in main text.

Fuel loading is defined as the plant biomass available for combustion. The biomass components (leaves, sticks, twigs, bark) will vary along with their condition (woody/non-woody, living/dead, wet/dry) according to the fire type and prevailing environmental conditions. Obviously, fuel loading is determined only by total amount. However, the other two fuel attributes, composition and condition, influence its burning efficiency so are relevant to the overall emissions calculations. The fuel loading (tDM ha$^{-1}$) for any location and time is the net balance between the biomass supply and the loss from natural decay or fire, and the dynamics of this net balance greatly varies between the three fire types.

In Appendix A, the base (and only) available data for burned area was edited to fill the following three-dimensional matrix

Fire types (3) x States and Territories (8) x Year (18)

The objective of Appendix B is to transparently assign values of fuel loading ( $M$ ) and burning efficiency ( $\varepsilon$) to each of the fire situations in the above matrix, a potential maximum of 432. Our starting point is that there are no systematic measurements of the above two required variables available for any of the fires.

**Strategy**

One of the goals of this essay is the estimation of the $CO_2$ emissions in probabilistic terms, i.e. in the form of a probability distribution function (pdf). This task is made easier by the recognition in Appendix A that no significant time trend in burned area could be confidently assigned. That is, all of the time series of burned area (A) are stationary. *In addition, the time series for all fire types for all eight States and Territories could be described with normal or lognormal distributions.* This reduces the size of the potential matrix from 432 to 24.

To progress further, the assumption is made that from the three fire types within the eight States and Territories, appropriate fuel type, loading ( $M$ ) and burning efficiency ( $\varepsilon$), both defined as part of Equation (3) in the main text, can be reasoned from existing understanding and the few relevant published data.

Given that even with the defining attributes of fire type and location (to the level of States and Territories), the uncertainty in assigning a fuel loading will still be high. For example, compare the case of a Managed forest fire in Western Australia with an Unmanaged forest fire in Queensland. It is highly probable that fuel loads and types will be significantly different. Even so, *we can progress with the assertion that while the actual fuel loadings are not known at time of burning, the upper and lower bounds of fuel load and the shape of its distribution can be more* *confidently prescribed*. Thus, to assign a fuel loading for all occurrences of a particular fire type in all States and Territories, probability distribution functions (pdf) will be derived and used.

One imperative becomes obvious from perusal of the values for mean annual burned area in Table A7. The value for Grassland fires (≈ 39 Mha) is almost 40 times larger than the mean annual totals of Managed and Unmanaged forest fires combined (≈ 1.1 Mha). Thus, unless the fuel loading for the two forest fire types is significantly larger than that for the Grasslands fires - such as by a factor of 20 – and they are not, then the priority concern must be for the fuel loading of the Grassland fires. Regardless of the social and economic impacts of Unmanaged forest fires (i.e. ‘bushfires’), in terms of the biomass burning emissions, the Grassland fires of the tropical savannas are by far the largest source. Therefore, the veracity and transparency of the values for fuel loading and burning efficiency for this fire type require some focus.

**Managed forest fires**

*Background*

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. This assumption is supported by the nature of the two State and Territory land management agencies most likely to conduct prescribed burning. They 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. Assigning fuel loading for each state will require the estimation of the contribution to the total burned area of Managed fires by the various vegetation types.

*Fuel type*

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.

*Fire type*

Given the origins of this fire type, it is assumed they are all of low-medium intensity. Therefore, the overstorey is never part of the fuel, and burning efficiency will be lower than that for the Unmanaged fire type, Figure B1.

Figure B.1: Typical burning characteristics of a managed fuel reduction fire in open woodland. The fuel loading is high but the fire is of low intensity because the fuel moisture content is high and there is little or no wind. The fine fuel components (grass, litter) are almost completely burned while the more coarse woody litter (branches) appear unaffected.

*Fuel loading*

The following reasoning concerning the dynamics of litter fuel loads is common to all fire types, but most relevant to Managed and Unmanaged forest fires.

Fuel loading is primarily determined by the intrinsic productivity of the site, i.e. by the net primary productivity (NPP) of both understorey and overstorey. The overstorey litter contribution (accession rate) increases with age and equals the NPP at maturity. Thus, the timescale of fuel accumulation is decadal and therefore interannual variability in climate factors has relatively little effect. However, on landscape scales and because of topographic, soil and microclimatic variations, the spatial variability in fuel load and composition is high relative to non-forest (grassland) conditions. In addition, there is a variability imposed by management in determining at what point along the fuel accumulation trajectory the prescribed burning is undertaken.

Now, setting aside the (minor) live understorey component, the rate of increase in the biomass of a litter layers can be described by a simple first-order decay function, thus.

$$M_t = M_{max} (1 - e^{-kt}) \qquad (B1)$$

Where $M_t$ is the biomass at time t, $M_{max}$ is the maximum (equilibrium) value for that site and $k$ is the decay constant, the proportion of the litter that decomposes per year ($yr^{-1}$).

Alternatively, the equation can be usefully rewritten to

$$Mt = (L / k^{-1}) (1 - e^{-kt}) \qquad (B2)$$

where L is the litter accession rate (tDM $ha^{-1}$ $yr^{-1}$) that is assumed constant, and L = $k$ x $M_{max.}$ (Walker 1981). Fuel load accumulation is thus determined by the accession rate (L) and the natural decomposition rate ($k$) to asymptote at tens of tonnes of dry matter after 10-30 years post-disturbance. This simple model assumes that the litter accession rate (L) is constant, and that in setting the decay constant ($k$), its dependence on litter type (grass versus twigs) and climate conditions can be meaningfully combined.

Given that the litter accession rate (L, defined above) is related to the NPP of the site, and using decay constant values from the literature, it is possible to estimate a plausible range fuel loads that could be expected. However, one significant factor remains: these are managed fires prescribed to reduce fuel loads from a higher to a lower level. Fires are repeated to effect this fuel reduction with return intervals from five or more years.

Given the natural and social systems context outlined above, the following three-step strategy is employed to estimate fuel loads at the time of burning for each State and Territory. First, calculate an equilibrium fuel load, litter mass ($M_{max}$) for a variety of forest and woodland types. Then using vegetation maps, combine the values for each vegetation type into an appropriate overall value for each State and Territory. Finally, prescribe the fuel load probabilities for each State and Territory to plausibly account for natural landscape variability and that imposed by management.

Table B1 contains the results of the first step. It was assumed that the sixteen structural vegetation types (T4 – S1) include all those subject to prescribed burning within all States and Territories. For each of these types, an annual litter fall (L) was calculated with the assumption that each type was of mature age. The annual litter fall rates were stratified by the cover class and the height of the canopy. I estimated the four linear equations from the graphed data presented in Walker (1981) for leaf fall and assumed that for mature canopies, there would be a 50% additional fall of woody components (branch, bark).

To calculate the equilibrium fuel load, decay constants ($k$, defined above) were assigned to the four canopy classes, Table B1. The declining sequence of cover classes was taken as a surrogate of increasing aridity and the $k$ values were diminished in sympathy. These $k$ values are overall values for all fuel components. The values calculated in Table B1 are generally with published values and are considered adequate to the objective.

Table B1: The calculation of maximum litter fuel load for the structural vegetation types that comprise the forests, woodlands and heaths likely to be subject prescribed burning. The structural nomenclature follows the Atlas of Australian Resources (1990).

| | | | | | |
|---|---|---|---|---|---|
| | Annual litter fall (L, tDM $ha^{-1}$ $yr^{-1}$) | | | | |
| Foliage cover class and percentage | T | M | L | S | |
| 4 (85) | | 13 | 10 | 9 | |
| 3 (50) | 11 | 8 | 6 | 5 | |
| 2 (20) | 4 | 3 | 2 | 2 | |
| 1 (5) | | 1 | 1 | 1 | |
| | Maximum litter biomass ($M_{max}$, tDM $ha^{-1}$) | | | | |
| | T | M | L | S | *k* |
| 4 (85) | | 36 | 27 | 26 | 0.35 |
| 3 (50) | 32 | 23 | 17 | 16 | 0.33 |
| 2 (20) | 14 | 10 | 8 | 7 | 0.30 |
| 1 (5) | | 3 | 2 | 2 | 0.27 |

To calculate the equilibrium fuel loading ($M_{max}$) for the managed fires in each State and Territory, the values for each vegetation type (T3, M4, etc. in Table B1) were combined to give a representative value for each State and Territory, Table B2. The proportional combinations reported in this Table were based on the author's expert opinion guided by vegetation maps, and by comments collected from the various agencies by Chatto (1999).

Table B2: A summary of the fuel loadings for managed forest fires for each State and Territory. For each State and Territory, the maximum fuel load is calculated by estimating the proportional contribution of the vegetation types (from Table B1). The maximum fuel load is then discounted by a management factor (see text) to an actual fuel load. This value is then assumed the mean of a normally distributed fuel load, the dispersion of which is assigned by the coefficient of variance (CoV) that is in turn inversely scaled by the mean.

| State or Territory | Maximum fuel load (tDM $ha^{-1}$) | Management factor | Actual fuel load (tDM $ha^{-1}$) | CoV |
|---|---|---|---|---|
| NSW | 18 | 0.75 | 14 | 0.29 |
| Vic | 20 | 0.80 | 16 | 0.19 |
| Qld | 13 | 0.75 | 10 | 0.43 |
| SA | 10 | 0.90 | 9 | 0.47 |
| Tas | 15 | 0.85 | 13 | 0.32 |
| WA | 19 | 0.70 | 13 | 0.30 |
| NT | NA | NA | NA | NA |
| ACT | 16 | 0.85 | 14 | 0.27 |

The last step is the prescription of the fuel load probabilities for each State or Territory that accounts for variation imposed by management, and by inherent landscape variation. The variability imposed by management was captured as a factor discounting the maximum fuel load, Table B2. This factor is an assessment of the relative effectiveness of prescribed programs between States and Territories.

To illustrate: for an agency that assiduously manages its prescribed burning, the fuel loads would be kept below the maximum value by a factor of 0.7. In contrast, where an agency is less assiduous in prescribed burning, fuel loads will be closer to the maximum and enjoy a management coefficient of 0.9. Because the time series of Managed forest fires is normally distributed, the coefficient of variation (CoV) is taken as a measure of managerial perseverance, see Table A4. The state of WA had the lowest CoV and was assigned a management factor value of 0.75 whereas SA had the highest CoV and was assigned the value of 0.90. Values for the remaining States and Territories were lineally interpolated from the two extreme values and a discounted or 'actual' fuel load calculated, Table B2.

The natural or inherent landscape variation in actual fuel load was captured by choosing a distribution type and then a measure of spread. All published fuel values report mean and variance values as if the measured value were normally distributed, which is to be expected. The variation about the mean was assigned based on the proposition that CoV is inversely related to mean fuel loading. At low fuel loadings, the spatial distribution will be discontinuous or 'gappy'. For high fuel loads, the converse applies with the fuel load tending to be more evenly distributed. A linear relationship was assumed between a CoV of 0.65 for a fuel load of 5 tDM $ha^{-1}$ and a CoV of 0.1 for a high fuel loading of 20 tDM $ha^{-1}$. The CoV values for the actual fuel loads for each State and Territory were interpolated accordingly, Table B2.

*Burning efficiency*

This is the fraction of the fuel load that is volatilised. In the field, its value may range from near 1.0 to values as low as perhaps 0.30. Both fuel and environmental factors influence burning efficiency. Efficiency is high for fine fuel element size (leaves, twigs) and low for coarsely sized elements (bark slabs, branches). Fuel packing – the physical arrangement of the elements - is a multiplicative factor. Diffusely packed fuel elements are much more likely to be completely volatilised than densely packed elements. The environmental factors of fuel moisture content and wind speed are also influential and their effects are predictable.

Managed forest fires take place within only a very small subset of possible combinations of fuel and environmental conditions. The objective of these burns is to reduce fuel loads while minimizing the impact of the fire on the overstorey stems and canopy. Thus, they are conducted under prescribed conditions of (relatively) high fuel moisture and low wind speeds to maintain a manageable low intensity fire, see Figure B1. Low intensity fires have a low rate of spread and therefore a long dwell time compared with high intensity fires. These attributes encourage a high burning efficiency by initiating smouldering combustion of the more coarsely sized fuel components (bark, branches) that will be major components of high (and therefore old) fuel loads.

With these factors in mind, burning efficiency is assigned based on fuel load. The argument being that because all the fuel and environment factors will be kept quasi-constant by prescription, the principal determinant of burning efficiency will be fuel load because the higher the load, the larger the proportions of coarse sized elements, and thus the lower the burning efficiency. The following relationship was used:

$$\varepsilon = -0.02M + 1.0 \qquad \text{(B3)}$$

This relationship gives values of 0.90 for the low fuel loading of 5.0 tDM ha$^{-1}$ and 0.50 for the high fuel load of 25 tDM ha$^{-1}$.

*Summary*

Based on the reasoning set out above, the fuel loads for Managed forest fires for all States and Territories is summarised in Table B3, for burning efficiencies in Table B4, and for the mass of fuel volatilised in Table B5. While Table B5 is the product of B3 and B4, some truncation was necessary during calculation and the consequences are here made explicit.

Table B3: A statistical summary of assessed (pre-burn) fuel loads (tDM ha$^{-1}$) for Managed forest fires.

| Percentiles | NSW | Vic | Qld | SA | Tas | WA | NT | ACT |
|---|---|---|---|---|---|---|---|---|
| 5 | 7 | 11 | 3 | 2 | 6 | 7 | NA | 8 |
| 25 | 11 | 14 | 7 | 6 | 10 | 10 | NA | 11 |
| **50** | **14** | **16** | **10** | **9** | **13** | **13** | **NA** | **14** |
| 75 | 17 | 18 | 13 | 12 | 16 | 16 | NA | 17 |
| 95 | 21 | 21 | 17 | 16 | 20 | 19 | NA | 20 |

Table B4: A statistical summary of calculated burning efficiencies for Managed forest fires.

| Percentiles | NSW | Vic | Qld | SA | Tas | WA | NT | ACT |
|---|---|---|---|---|---|---|---|---|
| 5 | 0.89 | 0.89 | 0.92 | 0.92 | 0.90 | 0.90 | NA | 0.89 |
| 25 | 0.93 | 0.92 | 0.95 | 0.96 | 0.93 | 0.94 | NA | 0.93 |
| **50** | **0.95** | **0.94** | **0.97** | **0.98** | **0.96** | **0.96** | **NA** | **0.95** |
| 75 | 0.97 | 0.96 | 0.99 | 0.99 | 0.98 | 0.98 | NA | 0.97 |
| 95 | 0.99 | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 | NA | 0.99 |

Table B5: A statistical summary of calculated fuel combusted (tDM ha$^{-1}$) for Managed forest fires.

| Percentiles | NSW | Vic | Qld | SA | Tas | WA | NT | ACT |
|---|---|---|---|---|---|---|---|---|
| 5 | 7 | 10 | 3 | 3 | 6 | 6 | NA | 7 |
| 25 | 11 | 13 | 7 | 6 | 10 | 10 | NA | 11 |
| **50** | **13** | **15** | **10** | **9** | **12** | **12** | **NA** | **13** |
| 75 | 16 | 17 | 13 | 12 | 15 | 15 | NA | 16 |
| 95 | 20 | 20 | 17 | 15 | 19 | 19 | NA | 19 |

## Unmanaged forest fires

*Background*

These are 'bushfires' – unwanted, unmanaged, and probably unmanageable fires in the forest, woodlands, and heaths. This is the only description available with which to infer fuel loads and burning efficiency.

*Fuel type*

Beginning with common characteristics, we note 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.

In contrast however, is the potential contribution of the overstorey canopy to the fuel load. 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. This fire condition is to be distinguished from that where the surface (litter) fire only scorches the canopy, i.e. kills but not combusts the fire elements of the canopy. The key variable is the fire intensity and the enhancing factors of this are conditions of moderate to high fuel levels of low moisture content accompanied by high winds, Figure B2.

Figure B2: Typical fuel consumption characteristics of an intense Unmanaged fire in a woodland. All the ground fuel was consumed and as well, some of the fine canopy elements, the leaves, twigs and fibrous bark. The canopy leaves that were not consumed were scorched killed and have now fallen as litter. In spite of the lifeless nature of this image, taken within days of the fire, the fire killed none of the trees. Regrowth of the grassy understorey and the overstorey began with the next rainfall – a resilient landscape.

*Fuel loading*

Assigning fuel loads to this fire type is difficult. The fire type is essentially defined by being unwanted. The source of ignition is most likely arson and the antecedent and current weather conditions are those that will encourage a high intensity fire. *Thus, the incidence of these fires may be largely independent of fuel load*. Therefore, a default position is taken by assuming that the (surface) fuel loading for this fire type is that assigned for the managed forest fire type, Table B3.

Assuming all Unmanaged forest fires are 'bushfires', then the surface fuel load will be supplemented by a contribution, however small, from the canopy. The next assumption in that given the necessary predisposing conditions of low fuel moisture and high winds, the mass of canopy elements that is combusted is related to the mass of the surface fuel load that is consumed.

Measurements of the above relationship are globally few and appear non-existent for Australian vegetation. Stocks (1997) had compiled one small set of for Canadian boreal forests that indicate the relationship between surface and canopy fuel combustion is linear with a slope of approximately 1.0 but with an appreciative negative constant term. That is, given a certain start-up level of surface fuel combustion (≈ 6 tDM $ha^{-1}$), thereafter any increase in surface fuel *consumption* is matched by an equal (0.9) contribution from the canopy. Now, assuming that coniferous forest canopies are intrinsically more combustible than the broad leaf eucalypt forests (needles versus leaves), the proposed relationship for Australian conditions (where $M \geq 5.0$ tDM $ha^{-1}$) is:

$$M_{canopy} = 0.75 \text{ x } (M_{combusted} - 5.0) \qquad \text{(B4)}$$

Note that before the canopy conditions can be added, the mass of surface fuel actually consumed ($M_{combusted}$) must first be calculated, and that requires the assigning of a burning efficiency appropriate to bushfire conditions.

*Burning efficiency*

By definition, high intensity fires equate to high levels of fuel combustion. This condition is maximized by fine fuel components that have low moisture content and are diffusely packed. However, even intense fires rarely result in complete combustion of the fuel load. Because the dwell time is short, the coarsest fuel fractions (branches, stems) are charred but often remain unburned. Under these fire conditions, burning efficiencies will still be determined by the absolute fuel load, as per the Managed forest fire, (B3) but with a differing sensitivity. The relationship proposed is as below truncated to <1.0.

$$\varepsilon = - 0.01M + 1.1 \qquad \text{(B5)}$$

*Summary*

Based on the reasoning set out above, the burning efficiencies for Unmanaged forest fires for all States and Territories is summarised in Table B6, the mass of fuel volatilised in Table B7, and the mass of canopy elements consumed in Table B8. While Table B7 is the product of B3 and B6, some truncation was necessary during calculation and the consequences are here made explicit. Note that it is assumed that the pre-fire fuel loading for Unmanaged fires was the same as for Managed fires, i.e. as summarized in Table B3.

Table B6: A statistical summary of calculated burning efficiencies for Unmanaged forest fires.

| Percentiles | NSW | Vic | Qld | SA | Tas | WA | NT | ACT |
|---|---|---|---|---|---|---|---|---|
| 5 | 0.89 | 0.89 | 0.92 | 0.92 | 0.92 | 0.90 | NA | 0.89 |
| 25 | 0.93 | 0.92 | 0.95 | 0.96 | 0.96 | 0.94 | NA | 0.93 |
| **50** | **0.95** | **0.94** | **0.97** | **0.98** | **0.98** | **0.96** | **NA** | **0.95** |
| 75 | 0.97 | 0.96 | 0.99 | 0.99 | 0.99 | 0.98 | NA | 0.97 |
| 95 | 0.99 | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 | NA | 0.99 |

Table B7: A statistical summary of calculated surface fuel combusted (tDM $ha^{-1}$) in Unmanaged forest fires.

| Percentiles | NSW | Vic | Qld | SA | Tas | WA | NT | ACT |
|---|---|---|---|---|---|---|---|---|
| 5 | 7 | 10 | 3 | 2 | 2 | 6 | NA | 7 |
| 25 | 11 | 13 | 7 | 6 | 6 | 10 | NA | 11 |
| **50** | **13** | **15** | **10** | **9** | **9** | **12** | **NA** | **13** |
| 75 | 16 | 17 | 12 | 11 | 11 | 15 | NA | 16 |
| 95 | 20 | 20 | 16 | 15 | 15 | 19 | NA | 19 |

Table B8: A statistical summary of calculated canopy fuel combusted (tDM $ha^{-1}$) in Unmanaged forest fires.

| Percentiles | NSW | Vic | Qld | SA | Tas | WA | NT | ACT |
|---|---|---|---|---|---|---|---|---|
| 5 | 2 | 4 | 1 | 0 | 0 | 1 | NA | 2 |
| 25 | 4 | 6 | 2 | 2 | 2 | 4 | NA | 4 |
| **50** | **6** | **8** | **4** | **3** | **3** | **6** | **NA** | **6** |
| 75 | 8 | 9 | 6 | 5 | 5 | 8 | NA | 8 |
| 95 | 11 | 11 | 9 | 8 | 8 | 10 | NA | 11 |

## Grassland fires

*Background*

This fire type is easily the most extensive; being some 40 times larger in area than the sum of Managed and Unmanaged forest fires, Table A7. 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, Table A6. However, the proportional distribution of burned area for this fire type is far from even, Table A6. The NT (45.7%), WA (38.5%), and Qld (14.4%) together contribute 98.6% of the mean annual area burned, with the remaining four states combined contributing just 1.4%. Therefore, in the reasoning of fuel loadings and burning efficiencies, it is reasonable to concentrate only on the three largest contributing states, NT, WA and Qld. Further, it is a reasonable generalisation that within these three states, by far the largest proportion of burning occurs north of the Tropic of Capricorn. Grassland fires are essentially a phenomenon of the tropical savannas.

*Fuel type*

In contrast to the two fire types discussed earlier, the primary fuel for these fires is grass. A secondary fuel component is leafy and woody litter from the sparse overstorey tree canopy that because of its low decomposition rate will accumulate more so than unburned grass. There is also a small contribution to the fuel load from live woody shrubs. These secondary fuel components have different combustion efficiencies compared with a grass canopy that is comparatively finely structured and diffusely packed. Fire intensities can be high and therefore, burning efficiencies are high. Because, this fire type is defined by fuel, it includes both managed and unmanaged fires. The predominant source of ignition is deliberate so that *the carbon consequences of these fires are an aspect of the land management*.

For the purpose of calculating $CO_2$ emissions, a binary fuel type classification – tussock, hummock- is adequate. The tussock grass fuel category includes a range of species. However, two attributes separate this class from the hummock grass fuel. The first is their general morphology is implied by their name. Each individual tussock has at some stage had the shape of an inverted cone with a small volume of fuel occupying a large volume of space. The second attribute is that this fuel type includes some fraction of litter form the overstorey canopy. The relative mass of tussock grass and the litter fuel with vary depending on the tree canopy cover and the time of the year. Williams et al. (1998) report the increase in fuel load from tree litter as the Dry Season progressed. The increase in fuel load at this site (Kapalga, NT) was approximately 50%, as interpreted from their Figure 3, but the tree cover at this coastal site is higher than the vast inland areas of savanna, Figure B3.

Figure B3: The structure of a typical coastal savanna in the early dry season. The understorey of tussock grasses (3-5 tDM $ha^{-1}$) that present an array of finely divided, loosely packed fuel. The overstorey canopy (10-20% cover) contributes litter as the Dry season progresses.

In contrast to the tussock fuel, that is the understorey on the tropical (mostly eucalypt) savannas, the hummock or 'spinifex' grasslands are almost without any woody component. Overstorey trees are rare and the few woody shrubs that occur in these grasslands have little biomass. Even though the botanical composition of these grasslands varies at species level of the genus *Triodia*, individual plants all have much the same unique morphology – the hummock shape and the discrete spatial patterning, Figure B4.

Figure B4: Fire in hummock grassland. In the foreground, there are a few unburned hummocks showing typical pincushion shape and discrete spatial patterning. The background fire indicates typical intensities and smoke colour because most species contain significant levels of flammable resins. Because this site was on skeletal stony soils rather than the more usual sandplain, the woody canopy cover shown here is much higher than is common.

*Fire type*

The source of ignition for fires in both fuel types is predominantly from land management activities. The probability of ignition by lightning (during dry thunderstorms in the late Dry Season) is higher in the Tropics than anywhere else on the continent. Even so, it is generally believed that lightning accounts for ≈ 10% of ignitions in the tussock grasslands and ≈30% in the hummock grasslands. Because the lightning ignitions tend to occur late in the Dry Season, the resulting fires are often of very high intensity and may burn very large areas (Allen and Southgate 2002), Figure B4.

The tussock savanna grasslands are almost all under pastoral use. To achieve different or multiple objectives, pastoralists strategically burn part or all of their grasslands early in the Dry Season (April, May) when the fuel is barely cured, i.e.: still green with high moisture content. Because of the tussock structure with its diffuse packing of fine fuel, it is possible to burn quite moist fuel. Under these conditions, the burning efficiency is lowered and even though it is of no concern in this essay, *the emission factor for the trace gases is significantly increased under these conditions* (Saarnak 2001). As the Dry Season progresses, fuel moisture declines and fire weather becomes more severe, the intensity of fires becomes higher (Gill et al. 1996, 2000).

Williams et al. (1998) report a three-fold increase in fire intensity between early and late Dry Season fires.

*Fuel loading*

Based on the fuel type descriptions above, the factors affecting the fuel load can be prioritised and an estimate of fuel loading for each type derived. For the tussock grass fuels the factors are, in order of decreasing contribution, annual productivity, canopy litter input, and the accumulation of these two components over the interval between fires. Even though fires can be of such intensity that complete tree canopy leaf scorch occurs, crown fires are rare and the living canopy does not contribute to the fuel load. Within any one year, the (Wet Season) productivity of both grass and overstorey will be driven by rainfall and constrained by (the generally low level of) available plant nutrients. Because the burned tussock grasslands extend over an appreciable latitudinal zone, so also will the local productivity of the grasses and the overstorey tree canopy. The canopy litter component of the fuel is taken as zero at the beginning of the Dry Season (April) increasing as the Dry Season progresses (July-October) see later. As for the litter accumulation models, the ground fuel accumulation can be modelled as before:

$$M = (L / k)\,(1 - e^{-kt}) \qquad \text{(B6)}$$

With finely divided fuel, abundant termites, and livestock in a tropical climate, the 'decay' rate ($k$) will be high. In a decay analogue, eucalypt leaves in a wet temperate environment, the $k$ value is $\approx 0.85\ yr^{-1}$; see Table 4 of Walker (1981). This value was used in the equation above with the return fire interval (t) set at 3 yr.

Two interacting processes are at work. In the higher rainfall savannas, the annual productivity will be high and the return fire interval will be short (1-2 year). In the lower rainfall savannas, the base productivity will be lower but the return fire interval is likely to be longer (2-4 year), thereby resulting in approximately equivalent fuel loads.

What is more significant than the carryover is the input of canopy litter. This is only applicable to late Dry Season fires, here taken to be from July onwards. Interpreting the data contained in Craig et al. (2000), the author estimates the proportions of the total area burned by early Dry Season fires (June and before) for both tussock and hummock fuels to be ≈ 45%. Therefore, for 55% of the area burned, a higher fuel loading (33%) is assigned to represent the overstorey canopy litter input.

To assign a representative fuel loading (biomass at time of burning) for the tussock grassland, the following reasoning was used. The annual production of new grass biomass was set at three tDM $ha^{-1}\ yr^{-1}$. This base value will be increased by an additional 33% with the litter fall from the overstorey canopy over 55% of the area that is not affected by early Dry Season fires. This additional litter loading (3.0 x 0.33 x 0.55) is $\approx 0.5$ tDM $ha^{-1}\ yr^{-1}$, thereby giving an end of Dry Season fuel load of 3.5 tDM $ha^{-1}$.

If of the entire tussock grass area, approximately 40% is burned each year, this gives a mean interval between fires of 2.5 yr. Substituting L = 3.5, $k$ = 0.80 and t = 2.5 in (B6) above the accumulated carryover fuel load is 4.0 tDM $ha^{-1}$.

Given the significant spatial and temporal variability in the three dominant landscape factors, that determine grass growth in the tussock grasslands (rainfall, soil type, water redistribution), it is unrealistic to assign a single value for biomass at time of burning. As with all the other calculated fuel loads, a distribution is chosen to capture the median value within a realistic range. For the tussock grasslands, a lognormal distribution was chosen because the positive skew captures the less frequent large values as well as a sharp truncation at low fuel values, below which fires will not propagate. The median value of the distribution was 4.0 tDM $ha^{-1}$ with a geometric standard deviation of 1.6. The range of fuel loads within this distribution is described in Table B9**.**

In contrast to the tussock grasslands, the assigning of fuel loads to the hummock grasslands (which account for 30% of the area of all Grassland fires) is uncomplicated. It is a simpler task because the individual plants are slow-growing perennials in spatially discrete patterning. Post-fire, individual plants regrow from seed or suckers and it is many years before the size and patterning of the individual hummocks is such that a fire can propagate. The time between fires is a function of cumulative rainfall (Allan and Southgate 2002) and thus can vary between 10 – 20 years given non-limiting ignition. However, because the vast spinifex covered landscapes are the most remote and sparsely occupied, ignition can be such that fuel build-up can reach unusually high levels, especially with wet years. When fires occur in those high fuel conditions, they are persistent and burn very large areas; see Figure 7.2 in Allan and Southgate (2002). Based on published values, the hummock grassland fuel load was designated as a lognormal distribution having a median value of 5.0 tDM $ha^{-1}$ and geometric standard deviation of 2.5 tDM $ha^{-1}$. The range of fuel loads within this distribution is set out in Table B9.

Based on the expert opinion of state agency officers collected in Chatto (1999) and the national fire census conducted by Craig et al. (2000), it is assumed that throughout the 18 year record tussock-fuelled fires account for 70% of the area burned with hummock grasslands contributing the remainder. Therefore, a composite fuel loading was computed as (0.70 x tussock + 0.30 x hummock). The range of fuel loads for this composite is set out in Table B9.

*Burning efficiency*

The nature of the fuels (moisture content, packing) and of the fire weather (temperature, humidity, windspeed) ensures that fire intensity and therefore burning efficiency, will be high for early and late burns, for both tussock and hummock grass fuels. Taking the measurements of Williams et al. (1998) to be universally applicable to tussock grassland fires, we have burning efficiencies for the early Dry Season fires of 90% increasing to 95% in late Dry Season fires; based on Figure 7 in Williams et al. (1998). For simplicity, a fixed value of 95% is selected for all tussock fires.

No equivalent measurements for the hummock grasslands could be found. Nonetheless, aerial inspections of burned areas suggest that the same burning efficiency (95%) is appropriate for these fires.

*Summary*

Based on the reasoning set out above, the component and composite (pre-burn) fuel loading for Grassland fires *in all States and Territories* is summarised in Table B9. As argued earlier, these fuel values strictly apply only to the tropical parts of the NT, WA, and Qld but because the other States contribute less than 2% of the total burned area of Grassland fires, any misrepresentation will be small. Further, unlike the previous two fire types discussed, a fixed burning efficiency (0.95) was employed.

Table B9: A statistical summary of calculated (pre-burn) fuel loadings (tDM $ha^{-1}$) for Grassland fires. The combined loading comprises 70% tussock plus 30% hummock fuel loads.

| Percentiles | Tussock (tDM $ha^{-1}$) | Hummock (tDM $ha^{-1}$) | Combined |
|---|---|---|---|
| 5 | 2 | 3 | 3 |
| 25 | 3 | 4 | 4 |
| **50** | **4** | **6** | **5** |
| 75 | 5 | 8 | 6 |
| 95 | 9 | 13 | 9 |

## Appendix C: Transformed landscapes – burned area, fuel loading and burning efficiency

### Clearing and biomass burning

*Background*

The biomass burning discussed in this Section is that which permanently diminishes the biomass carbon pool of landscapes. That is, the landscape carbon storage and storing capacity is not resilient to the impact of fire. Via the process of burning, the fuel (biomass carbon) is permanently transferred to the atmospheric pool. There is no compensating regrowth of the biomass that was burned because the vegetation was transformed – converted from one type to another – resulting in an accompanying reduction in the landscape carbon pool size and in its potential to sequester carbon – see main text.

Globally, the two principal expressions of this phenomenon are stand-replacing wildfires and deforestation or clearing. Stand-replacing fires – those so intense that they kill and consume all the trees – are extremely rare events in Australian forests and woodlands. Such intense forest and woodland fires do occur but they are episodic rather than common, and localized rather than extensive. In such fires, a proportion of mature trees may be killed but it is only a very much smaller fraction of these killed trees – usually only termite piped mature individuals – that are consumed. Fire tolerance of trees is a function of age – the juveniles and the aged are the most susceptible – and species, with most Eucalyptus species showing a remarkable tolerance to fire (Gill 1997) compared with intolerant rainforest species or gymnosperms, the dominant trees of the of the Northern Hemisphere boreal forests. Therefore, stand-replacing fires as a significant source of $CO_2$ are not considered further.

On the Australian continent, 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 burned to transform this landscape into those more financially productive, such as crops or pastures. The clearing and burning of woody vegetation began about two centuries ago and has progressively but slowly increased driven by enlarging export markets of grain and wool. For technological and economic reasons, the rate of clearing and burning has dramatically increased since circa 1950 with as large an area being cleared in the last 50 years as was cleared in the previous 150 years. At the beginning of the $20^{th}$ century, clearing was concentrated in the southern, winter rainfall areas of the continent. From mid-century onwards, clearing (and burning) is now largely located in the tropical woodlands of Queensland.

In this Appendix, the three required variables of burned area (A), fuel loading (M) and burning efficiency ($\varepsilon$) are derived for the period 1980 – 2000, which is equivalent to the length of record available for the fire types on resilient landscapes.

*Annual burned area*

Until relatively recently, the annual rate of clearing of woody vegetation was not annually surveyed by State and Territory agencies. The record of clearing could only be inferred from published increases in the crops and pasture areas.

Two recent surveys of clearing rates and location based on satellite data provide the base data for burned area (A). The first used satellite observations at two times, 1982 and 1990, to derive a mean annual clearing rate for this period of 520,000 ha $yr^{-1}$ (Graetz 1998). The second and more detailed study also used satellite data for the subsequent period, 1990 - 1995 to record a mean annual clearing rate of 308,000 ha $yr^{-1}$ (Barson et al. 2000). The period 1995-2000 has not yet been surveyed.

Contemporary expert opinion on clearing for the 1980-2000 period is that there were very large interannual variations in rates of clearing (and burning) in response to variation in climate and commodity prices. Furthermore, there was an overall declining national trend from the peak in the 1970s when clearing rates may have been as high as 3 Mha $yr^{-1}$, to just less than 1 Mha $yr^{-1}$ in 1980 (Graetz 1998). *Thus, the annual clearing rate (A) is a trending series rather than a stationary one*.

Given the veracity of the above values and to capture both the variation and trend in the annual clearing rate over the 1980 – 2000 period, a lognormal distribution was used with a median of 475,000 ha $yr^{-1}$ and a geometric standard deviation of 1.2. The two parameters define a distribution where 50% of the values fall within the range of 420,000 – 537,000 ha $yr^{-1}$.

*Fuel Type*

The fuel components of this fire type are those of the aboveground biomass – stems, branches, bark and leaves as well as the fine and coarse litter components. The belowground components, the coarse and fine roots, are excluded. Because the canopy is mechanically felled and then left for at least one year to dry before burning, much of the mass of the fine elements (leaves, twigs) decomposes before the fire. Thus, at burning, the bulk of the fuel is coarse woody components and in most cases, this material is mechanically collected into windrows before burning, Figure C1.

Figure C1: Mechanically felled aboveground woody biomass was pushed into windrows in preparation for burning, usually within 12 months.

*Fire Type*

Because the land management objective is the removal of all woody material, the burning of the felled aboveground biomass is delayed until the fuel is dry and the windspeed is such that intense, all-consuming fires can be safely lit in the windrows.

*Fuel Loading*

The fuel loading at a site comprises the standing biomass at time of clearing less the small fine fraction that has subsequently decomposed, as well as the pre-clearing dead coarse woody debris. While standing biomass reflects the intrinsic productivity (NPP) of that site, it is a cumulative reflection. Therefore, an estimation of biomass requires a consideration of NPP as well as the disturbance history of that site.

Several factors combine to make estimates of the (aboveground) biomass in cleared areas much more uncertain than the fuel loads for the other fire types. The principal factor is that total aboveground biomass has only infrequently been measured, thus the literature can provide only a weak guide. In any year, clearing is being undertaken in landscapes with a wide range of intrinsic productivities and the relative proportions of these various landscapes or types of country, are unknown. Finally, the disturbance history, the discounting from a potential maximum biomass at any site, is also unknown.

While all three factors above are significant, it does not mean that estimates of the fuel loads are without value. Rather it signifies that given the very sparse database of measurements available expert judgement and plausibility will guide the credibility of the final values. An exacting study by Barrett et al. (2001) reached the influential conclusion that while reducing the uncertainty associated with the area term (A), that associated with *the aboveground biomass remains the major source of uncertainty in emissions calculations*. Furthermore, because of the nature of biomass, even with a substantial investment into a biomass sampling, it is unlikely the associated CoV can be reduced below 25%. While the inescapable conclusion is that variability is high, it is possible to reason the likely bounds of biomass values and the nature of its distribution between those bounds. This is the approach developed here. To transparently derive and substantiate plausible estimates of the aboveground biomass density (tDM $ha^{-1}$) that is representative of that cleared over the last twenty years, 1980 – 2000, the following argument is proposed.

Over the last 20 years, clearing of vegetation can be detected in most States and Territories. However, the clearing of interest – the clear felling and burning of native vegetation for agricultural and pasture intensification – is essentially a Queensland phenomenon. In this state there was and extensive and prolonged expansion and intensification of agriculture since WWII. In the period 1982 – 90, clearing in Queensland accounted for greater than 60% of the national total (Graetz 1998). In the period 1990-95, it accounted for more than 85% (Barson et al. 2000). Because either proscription or closer regulation of clearing in other states, it is highly probable that the proportion of the national clearing now occurring in Queensland will remain at, or increase from 85%. Thus, clearing is essentially a Queensland phenomenon, and this conclusion gives a focus to prescribing representative biomass values.

The clearing in Queensland is primarily for the establishment of pastures and secondarily for cropping. This implies that the style of clearing and subsequent biomass burning will be as described above in Fuel Type – all (but only) the aboveground biomass is burned, including the coarse woody debris. The belowground biomass eventually decays but the $CO_2$ flux from this source while relevant to increasing the atmospheric loading, is not liberated by fire, and thus is not considered here.

In the 1980 – 2000 period, the clearing essentially was of woodlands with a wide range of aboveground biomass loads. In addition, the pre-felling coarse woody debris was included in the windrows and burned. Guided by global studies, the biomass of coarse woody debris in these woodlands is set as a constant fraction (0.25) of the aboveground live biomass (Matthews 1997).

The decision to clear and burn woodlands is based on rational economic considerations in that the most productive land (which will have highest biomass) is cleared first. Then, given continuing favourable economic conditions, lower productivity land is cleared next, and so forth. Given that the extensive clearing began in the 1950's of the highest productivity woodlands ('Brigalow', *Acacia harpophylla*) and that the highest rates of 3 Mha $yr^{-1}$ occurred in the 1970's, then the frontier clearing of the last twenty years will have been of relatively much lower biomass woodlands. As well, there will be the clearing of a small component of high biomass remnants now too valuable to leave. Finally, economic considerations also set a lower biomass limit by delineating those woodlands whose productivity/biomass is too low to return the costs of clearing.

From the argument set out above, a lognormal distribution is chosen to provide the best description of the range of aboveground biomass cleared. This type of distribution has a sharp lower bound set by the poor country cut-off, and a long upper tail to capture the clearing of a few high biomass remnants. Guided by the values published by Burrows et al. (2000), the median of the distribution, 85 tDM $ha^{-1}$, is selected to capture a slow declining trend in biomass over the 1980 – 2000 period. A geometric standard deviation value of 1.5 contains the biomass distribution with a lower bound (5 percentile) of 44 tDM $ha^{-1}$ and an upper bound (95 percentile) of 166 tDM $ha^{-1}$. Fifty percent of the biomass values in this distribution are in the range 65 – 112 tDM $ha^{-1}$.

*Burning Efficiency*

In contrast to the previous fire types discussed, land managers attempt to maximize burning efficiency by collecting the fuel into well-aerated windrows and by selecting optimum weather conditions for a high efficiency burn. Reports of the burning efficiency for such situations appear non-existent. Based on measurements for rainforest conditions and the author's observations, a constant burning efficiency of 0.90 was used.

*Summary*

Based on the reasoning set out above, descriptive statistics were generated for the variables of area cleared (A) and the fuel loading (M), Table C1. A fixed burning efficiency (0.95) was employed.

Table C1: A statistical summary of the calculated area cleared (A), aboveground biomass and total aboveground biomass that includes the pre-clearing coarse woody debris.

| Percentiles | Area (Kha $yr^{-1}$) | Aboveground biomass (tDM $ha^{-1}$) | Total aboveground biomass (tDM $ha^{-1}$) |
|---|---|---|---|
| 5 | 352 | 44 | 55 |
| 25 | 420 | 65 | 81 |
| **50** | **475** | **85** | **106** |
| 75 | 537 | 112 | 140 |
| 95 | 641 | 166 | 207 |