Please find my submission requesting a ban on rural burning. My request is based on the numerous high quality quantitative studies undertaken by the world’s foremost authoritative lung health organisations including the American Thoracic Society and The Canadian Thoracic Society. The enclosed excerpts are a limited selection of published data confirming the detrimental health effects of agricultural burning.

I find your statement “If research suggests that there are far reaching human health effects associated with this [rural outdoor burning] practice, we will also consider introducing buffer areas around residential areas to ensure that communities are not exposed to undue health risks” inept, myopic and uninformed. I fail to understand how Environment Canterbury can choose to ignore the plethora of international research which demonstrates beyond question the dangerous effects on health associated with rural/agricultural burning.

I offer the following and am happy to supply further articles on request

These findings are very useful to our efforts to reduce air pollution levels in Canada," said Brian Graham, CEO of the Lung Association of Saskatchewan. "Despite hundreds of publications that demonstrate that exposure to air pollution is associated with flare-ups in lung problems such as asthma and COPD, there are still some lobbyists that claim that direct evidence between exposure and health effect is missing. These new findings will add greatly to our arsenal of proof of the adverse health effects of air pollution." Many people in Saskatchewan take clean air quality for granted but in reality, we have lots of room for improvement. Currently, Saskatchewan residents with lung disease are particularly concerned about the smoke from northern forest fires. Although forest fires cannot be regulated, other types of burning can. The Lung Association frequently receives calls from people who experience breathing problems due to stubble burning, back-yard fire pits and smoke from residential fireplaces and woodstoves. Idling diesel engines are also a major source of harmful carbon particles.

One of the biggest problems with people staying indoors during smoke events is the risk of heat stress. Fire season is often accompanied by high temperatures, and for those who depend on open windows and doors for ventilation, keeping them closed can be a problem. Older individuals and those in frail health run the risk of heat exhaustion or heat stroke. Smoke events can last several weeks or months. These longer events
Variations in pulmonary function tests (PFTs) due to agriculture crop residue burning (ACRB) on children between the age group of 10 to 13 years and the young between 20 to 35 years are studied. The effects of exposure to smoke due to rice wheat crop residue burning on pulmonary functions like Force Vital Capacity (FVC), Force Expiratory Volume in one second (FEV ), Peak Expiratory Flow (PEF) and Force Expiratory Flow in 25 to 75% of FVC (FEF25 75%) on 40 healthy subjects of rural/agricultural area of Sidhuwal village of Patiala City were investigated for a period from August 2008 to July 2009. Measurements were taken by spirometry according to the American Thoracic Society standards. High volume sampler (HVS) and Anderson impactor were used to measure the concentration levels of SPM, PM 10 and PM 2.5 in ambient air of the Sidhuwal village. A significant increase in the concentration levels of SPM, PM10 and PM 2.5 was observed due to which PFTs of the subjects showed a significant decrease in their values, more prominently in the case of children. PFTs of young subjects recovered up to some extent after the completion of burning period but the PFT values of children remained significantly lower (p<0.001) even after the completion of burning episodes. Small size particulate matter (PM 2.5 and PM 10) affected the PFTs to a large extent in comparison to the large size particulate matter (SPM). The study indicates that ACRB is a serious environmental health hazard and children are more sensitive to air pollution, as ACRB poses some unrecoverable influence on their PFTs.© 2010 Elsevier B.V. All rights reserved.
eyes and airways, and may cause or aggravate respiratory illness and heart disease. In some rare cases, breathing smoke can cause death.

Smoke from an open fire can seriously pollute your neighbourhood. This is especially true when burning takes place on calm days with no wind. The particles and gases produced can build to levels that are harmful for days. A haze may cover whole communities and reduce visibility. Calm days are often the times that people choose for open burns, because they are concerned about forest fires and do not want to blow smoke into their neighbours' yards.

Closing doors and windows will not help. Smoke can easily waft through small cracks and holes, resulting in polluting your indoor air as well as the outdoor air.

**Symptoms caused by open burning**

Even smoke from leaf burning can irritate the eyes, nose and throats of healthy adults. Smoke from open burning can be much more harmful to small children, the elderly, and people with lung problems such as asthma or chronic obstructive pulmonary disease (COPD). This is because the visible smoke from leaf fires is made up almost entirely of tiny particles that can reach deep into lung tissue and cause symptoms such as coughing, wheezing, chest pain and shortness of breath. These symptoms may not occur until several days after exposure to large amounts of leaf smoke.

What's in smoke from open burning?

Besides being an irritant, smoke contains many hazardous chemicals potentially harmful to human health. These include:

- **Acrolein** is an alcohol aldehyde that smells bad, and irritates eyes and airways.
- **Formaldehyde** is a preservative and a carcinogen, and can cause headaches and airway irritation.
- **Carbon monoxide**
- **Nitrous oxides** are gases that make it difficult to breathe and trigger asthma attacks.
- **Particulate matter** are microscopic particles that can be breathed deep into the lungs.
- **Polycyclic aromatic hydrocarbons (PAH's)**
- **Volatile organic compounds (VOCs)**
- **Dioxins** can cause a variety of health problems. Dioxin exposure has been linked to: increased risk of cancer, developmental problems in children, heart disease, diabetes and harm to the immune system.

Awaiting your response

Shirley Harris
The human and fiscal cost of Burn offs

The vast majority of fire crews in the Canterbury region are volunteers. These volunteers are put at risk of physical injury and there is a financial cost incurred. As volunteers these crew members are often employees and as such attend fires at a financial cost to the employer.

There appears to be an overwhelming history of verbal/written warnings for infringements rather than prosecutions. One would question the legitimacy of such a limited official response.

I offer examples of non-compliance and resultant non-action

Otago

There will be no prosecution taken by the Otago Regional Council in relation to a burn-off at Hillend Station, Wanaka, last October, despite many official complaints about smoke from the fire blanketing the town. The property is owned by TradeMe founder Sam Morgan and managed by Mike Scurr.

Following the burn-off, which was handled by Mr Scurr and permitted by the Otago Rural Fire Authority, ORC enforcement officers interviewed staff who attended the incident and members of the public who had complained to the council or other organisations.

ORC lawyer Peter Kelliher said the council could only take action if it was satisfied it could prove beyond reasonable doubt an offence had been committed - that the fire was offensive or objectionable beyond the boundary.

"And in this instance we couldn't ... from an independent view looking at it from the outside in, we weren't comfortable that we had sufficient [evidence] to prove to the required standard."

A formal warning would be issued to the person responsible for the fire.

"And that is the end of the matter."

"We don't have enough to get us over the line for an infringement or anything else."

ORC environmental monitoring and operations director Jeff Donaldson said during the interview process a large number of people had "backed off".

"Then they determined it wasn't such a major incident as far as most people were concerned."

"There is a difference of opinion of the seriousness of the effects of the fire that emerged from the interviews that occurred and ... because there was nobody Fire authorities want farmers to think of their neighbours before they set the first match to 20,000 hectares of crop stubble in Canterbury next year.

The authorities have told mid-Canterbury farmers that emergency callouts for 22 fire escapes from stubble burning was too many this year and prosecutions could result if serious neglect was proven.

Ashburton

Ashburton District Council principal rural fire officer Don Geddes said most farmers took stubble burning seriously, but there were cases where farmers had inadequate water or "suppression" equipment in the event of a fire getting out of control.

"If they haven't got adequate fire suppression once it gets out of the fire break they are powerless to do anything about it."
The callouts were above the 10-13 incidents usually handled by fire services. A series of fires at the peak required 300 voluntary hours to control and cost $127,000 during strong northwesterly winds.

Geddes said most fire escapes occurred when people had inadequate fire breaks and fire equipment and misjudged wind speed conditions or rushed to burn stubble before an approaching southerly front.

"I have seen people light up stubble fires with 40 litres (of water) on a quad bike thinking this is sufficient," said Geddes at a Foundation for Arable Research field day at Chertsey. "Will that stop an escape? No. Think about your neighbours and a fire destroying shelter belts and sheds. We are appealing to your better nature."

The council is looking at farmers carrying a minimum of 500l of water and at least a 20m hose.

During an open fire season burners still have a duty to look after fire and require a permit with conditions during a restricted fire period. Fires are forbidden during total prohibition.

An offender could face a maximum prison sentence of seven years if arson is proven - defined as fire recklessly lit that damages other people's property - and danger to life carries heavier sentences.

Instant infringements of $500 can be issued by council officers for incidents such as a hedge catching fire.

Environment Canterbury had allowed stubble burning to continue in the short to medium term, said Geddes.

I strongly request that you review and reconsider rural burn off practices. I base my request on, most importantly, the extensively documented detrimental health effects and secondly on the associated fiscal and personal burden.

Many thanks

Shirley Harris
Vegetation fire emissions and their impact on air pollution and climate

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\textbf{ABSTRACT}

Gaseous and particulate emissions from vegetation fires substantially modify the atmospheric chemical composition, degrade air quality and can alter weather and climate. The impact of vegetation fire emissions on air pollution and climate has been recognised in the late 1970s. The application of satellite data for fire-related studies in the beginning of the 21st century represented a major break through in our understanding of the global importance of fires. Today the location and extent of vegetation fires, burned area and emissions released from fires are determined from satellite products even though many uncertainties persist. Numerous dedicated experimental and modeling studies contributed to improve the current knowledge of the atmospheric impact of vegetation fires. The motivation of this paper is to give an overview of vegetation fire emissions, their environmental and climate impact, and what improvements can be expected in the near future.

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1. Introduction

Vegetation fires represent an important source of atmospheric trace gases and aerosol particles. Here the term vegetation fire denotes open fires of various vegetation (savannah, forest, and agricultural residues) and peat that are set by humans or occur naturally, e.g. by lightning. The more general and often used term, biomass burning comprises prescribed and wild fires, as well as biofuel use, such as wood or peat for heating and cooking. We focus our attention on vegetation fires (prescribed and wild fires) and exclude domestic fires from this discussion.

Elevated concentrations of trace gases (e.g. ozone, carbon monoxide) and aerosol particles have been observed in connection with vegetation fires in various regions of the world (e.g. Crutzen and Andreae, 1990; Cooke et al., 1996; Andreae and Merlet, 2001; Forster et al., 2001; Heil and Goldammer, 2001; Duncan et al., 2003a; Damoah et al., 2004; Hodzic et al., 2007) which can have considerable inter-annual variability (Langenfelds et al., 2002; Wotawa et al., 2001). Air pollution is increased due to the direct emissions from fires or by trace species that are generated in the atmosphere from these direct emissions through chemical reactions or microphysical modifications. The dominant fraction of vegetation fire emissions is released as carbon with CO\textsubscript{2} and CO being responsible for about 90–95\% of the total carbon emitted (Andreae and Merlet, 2001). Most of the remaining carbon is composed of CH\textsubscript{4} and other volatile organic carbon compounds. Less than 5\% of the carbon is emitted as particulate matter (Reid et al., 2005). These smoke aerosols perturb radiation budgets locally, regionally and globally due to their light-scattering and absorption effects (Hobbs et al., 1997; Podgorny et al., 2003; IPCC, 2007), their influence on cloud formation (Koren et al., 2004; Feingold et al., 2005) and on cloud microphysical processes (Andreae et al., 2004).

Vegetation fires have occurred for thousands of years in connection with human activities, for example in Indonesia (Haberle et al., 2001) and Australia (e.g., Lynch et al., 2001, and references therein). Despite the large number of fires and their effects on the environment, the global extent of vegetation fire emissions was not fully recognised until the late 1970s (e.g. Seiler and Crutzen, 1980). At that time, information from regions where fire was important was sparse, in particular for the tropics and subtropics.

More recently, remote sensing data became available for active fire and burned area detection (e.g. Ferrare et al., 1990; Stricker et al., 1995; Hsu et al., 1996; Herman et al., 1997; Malingreau, 1990; Cooke et al., 1996; Olson et al., 1999; Justice et al., 2002; Wooster et al., 2005; Giglio et al., 2006; Lentile et al., 2006; Generoso et al., 2007; Labonne et al., 2007). Early global vegetation fire emission inventories that accounted for the inter-annual variability of fire emissions by using satellite products for fire counts (Arino and Rosaz, 1999) were published e.g. by Schultz (2002), Duncan et al. (2003b) and Generoso et al. (2003). The most recent generation of

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fire emission inventories is based on a combined approach using burned area and active fire counts from satellites, accompanied by biogeochemical modeling of the available fuel load (e.g. Hoelzemann et al., 2004; Ito and Penner, 2004; van der Werf et al., 2004; Schultz et al., 2007).

Even though vegetation fire emission inventories have improved considerably in recent years, large uncertainties remain in the temporally and spatially highly variable vegetation fire emissions (e.g. Ito and Penner, 2005; van der Werf et al., 2005). The purpose of this paper is to summarise the current knowledge on vegetation fire emissions and their impact on air pollution and climate. In addition, we discuss possible improvements which can be expected and would be wishful in the near future. Section 2 gives a summary of the major factors which determine vegetation fire emissions and discusses the related uncertainties. In Section 3, the global and seasonal distribution of vegetation fires and their emissions is presented. The impact of atmospheric fire products on air pollution and climate is described in Section 4. Section 5 provides recommendations for future research.

2. Determination of vegetation fire emissions

2.1. Combustion process

The amount and composition of the trace gases and aerosol particles released from a fire depends primarily on the composition of the fuel and combustion conditions (Lobert and Warnatz, 1993; Andreae and Merlet, 2001). Any type of fuel which is subject to ignition undergoes thermal degradation beginning with a drying/distillation step, in which water and volatiles are released. This is followed by pyrolysis (Yokelson et al., 1996), during which thermal cracking of the fuel molecules occurs. When temperatures in the fuel bed exceed 450 K, the process becomes exothermic and, at about 800 K, glowing combustion begins. The complex mixture of tar and gas products released and formed during the distillation and pyrolysis processes forms a flammable mixture together with ambient oxygen. When ignited, flaming combustion occurs forming CO$_2$ as a major product (Yokelson et al., 1996). When the fuel can no longer provide enough volatiles, smouldering combustions begins (Yokelson et al., 1997). The exothermic reactions during the smouldering phase of burning are the gas–solid reactions between oxygen and carbon in the char layer at the fuel surface, yielding predominantly CO at temperatures below 850 K. Smouldering combustion also occurs when the oxygen supply is limited, e.g. in densely packed biomass such as peat (Kasischke et al., 2005).

Throughout the evolution of a fire, the proportion of flaming and smouldering combustion can vary considerably depending on fuel moisture and structure, and on the development of the flame front. The complex burning process can only be considered in a simplified way when determining vegetation fire emissions over large spatial and temporal scales. Traditionally, fire emissions (E) for a specific species (i) are calculated as the product of burned area (A), fuel load (FL), combustion completeness (CC) and specific emission factors (EF) (Sellers and Crutzen, 1980):

$$E(i) = A \times FL \times CC \times EF(i)$$  \hspace{1cm} (1)

Each single factor in equation (1) has considerable spatial ($i_x$,$i_y$) and temporal ($i_t$) variability, so that fire emissions should read as $E(i_{x,y,t})$. The spatial and temporal dependencies have been omitted in equation (1) to increase readability. Representing these variations is a challenge for fire emission inventories. In the following, each of the factors in equation (1) and, additionally, the height of injection of fire emissions into the atmosphere are discussed in detail.

2.2. Burned area

Areas that have been burned are easily visible by eye due to their dark appearance. Detecting burned area over large scales from satellite, however, has proven to be a difficult task. Table 1 provides an overview of global burned area products from satellites. An advantage of the burned area products over active fire detection (fire counts, see below) is that observational gaps due to cloud cover and satellite revisit time can be filled thanks to the persistence of the burn scar. In general, most algorithms aim to detect persistent changes in a vegetation index using red and/or infrared bands (Roy et al., 1999). The first global burned area products were pilot studies for the year 2000 (GBA2000 [based on SPOT-VEGETATION] Gregoire et al., 2003; GLOBSCAR [based on ATSR2] Simon et al., 2004).

On regional scales, the first multi-year burned area assessment was provided for Africa by Barbosa et al. (1999) based on AVHRR Global Average Cover (GAC) data. The algorithm was later refined to develop a global burned area product for 1982–1999 (Carmona-Moreno et al., 2005). Due to the limitation inherent to GAC data, the authors note that this burned area product is more useful for assessing spatial and temporal variability in fire activity than for a quantitative burned area assessment. Boschetti et al. (2004) also found major discrepancies in estimated burned area between GBA2000 and GLOBSCAR, but good agreement in temporal and
spatial variability. Several burned area products are currently in the latest stages of development. These products are all based on high quality, moderate resolution satellite data and include burned area based on MODIS (Roy et al., 2005) and SPOT-VGT (Tansey et al., 2008). The GLOBSCAR burned area product will also be improved and will be available for multiple years in the near future.

Due to a lack of multi-year burned area information, active fire detections (fire counts, see Table 1) have been used for a long time, not only to assess the spatial and temporal variations in fire activity but also as a proxy for burned area. These fire count products are based on the detection of the thermal radiation emitted by a fire. In contrast to burned area products, fire count products can be made available in near real time, e.g. the MODIS Rapid Response System (http://rapidfire.sci.gsfc.nasa.gov). Fire count algorithms vary: the ATSR night-time product (Arino and Rosaz, 1999), for example, flags a grid cell as fire if the 3.7 µm channel reaches 308 K or if it saturates (312 K). This product currently provides the longest continuous time series of global fire activity, starting in mid-1996 and is still being processed in near real time. Other products also detect fires during day-time which requires a more complicated algorithm because hot surfaces or sun glint detections need to be omitted. Examples include fire counts from NOAA-AVHRR (e.g. Stroppiana et al., 2000) and MODIS (Justice et al., 2002). Although not providing global coverage, the VIIRS sensor on board of TRMM has also been used to develop a fire count products for the tropics and subtropics which has the advantage of covering the whole diurnal cycle of fires due to the drifting overpass of the TRMM satellite (Giglio et al., 2003). Besides fire count products from orbiting satellites, fires have also been extensively detected by geostationary satellites, providing a much higher temporal resolution at the cost of a lower spatial resolution, for example the GOES Automated Biomass Burn Detection (ABBAD).

Due to the difficulty in estimating burned area over large regions, relations between fire counts and burned area for selected regions have been used to construct global burned area estimates for multiple years (e.g. Giglio et al., 2006). Relations between fire counts and burned area are complex, but depend – among others – on the spread rate and fuel loads of fires. Savannah fires burn fast and short, and are, thus, difficult to detect by the occasionally overpassing satellite. This translates in large amounts of burned area per detected fire compared to forest fires that burn longer (van der Werf et al., 2003). With new burned area products emerging, this hybrid approach may become redundant at some point. Fire counts, however, will always be an important source of information for several reasons including the ability of near real time fire monitoring, the possibility to estimate the duration of a fire, and because small fires can be detected while burned area products usually require a substantial part of the grid cell to be burned.

2.3. Fuel load and combustion completeness

Fuel load is the second most important parameter in quantifying fire emissions. Fuel load depends on vegetation type, climate, soil type, time since last fire or other disturbance, and other competing processes such as herbivore and fuel wood collection. Fuel load is not identical to biomass since not all biomass is subject to a fire. In savannah ecosystems for example, trees are usually not combusted as long as the flames do not reach the tree canopy and the fire passes relatively rapidly so that the thick bark can protect the stems. In general, highest fuel loads are found in tropical forest ecosystems, especially if the forest is grown on peat (Page et al., 2002). Boreal forests also contain large amounts of fuel, both above and below ground, while fuel loads in savannahs and grasslands are in general up to two orders of magnitude lower (e.g. van der Werf et al., 2006). Compared to surface vegetation fires, the uncertainties of emission estimates of peat fires are even higher, as peat can burn repeatedly to different depths so that not only the area burned but also the volume (depth) burned needs to be determined. In addition, bulk density and carbon fraction vary with depth (Kasischke et al., 2005). Peat fires are mostly restricted to the boreal region (Kasischke et al., 2005; Turquety et al., 2007) and Southeast Asia (Page et al., 2002), but emissions can be very high due to large fuel loads. Levine (1999), for example, emphasised that during the 1997 fires in Indonesia peat contributed only about 20% to the total area burned but nearly 90% to the total emissions. Peat fires are generally of smouldering type and emit large amounts of reduced compounds and relatively little amounts of fully oxidised species (Christian et al., 2003).

Early studies aiming to estimate fuel loads used biome-averaged values (e.g. from Olson et al., 1999) but more recently numerical biogeochemical models have been used as they are expected to better simulate spatial variability in fuel loads (van der Werf et al., 2003, 2006; Hoelzemann et al., 2004; Ito and Penner, 2004; Jain et al., 2006). Often a fire model is implemented in an existing biogeochemical model, which allows one extra pathway of biomass to be released to the atmosphere depending on the amount of burned area.

Another relevant parameter that can be derived from biogeochemical models is the combustion completeness. It describes the fraction of the available fuel that is combusted during a fire event, depending on the type of fire, the type of fuel and its moisture content. Most models simulate different types of fuel (e.g. stems, leaves, and litter) and moisture conditions, allowing for a detailed description of combustion completeness (e.g. van der Werf et al., 2006) although the number of studies measuring combustion completeness is probably too small for a thorough validation. The effect of atmospheric conditions (e.g. humidity, wind speed) on the combustion completeness is not yet taken into account in these models.

2.4. Emission factors

Emission factors (EFs) which translate biomass burned into trace species emissions, have been reviewed and summarised by Andreae and Merlet (2001) for more than 100 trace species for tropical forest, extra-tropical forest, savannah and grassland. EFs are generally calculated as the mass of a species emitted in gram per kilogram dry matter burned. EFs have a typical uncertainty in the order of 20–30% for the frequently measured species (e.g. CO), but uncertainties can be considerably higher for compounds and biomes that have not been studied in such detail (e.g. HCHO or peat). EFs exhibit large variability for different biomes and they vary throughout a season because of variable water content and weather conditions (e.g. Korontzki et al., 2003). However, such variability is not yet considered in vegetation fire emission inventories. The fraction of emitted carbon that is CO₂ is usually referred to as combustion efficiency (CE). The finer the fuel and the more efficient the fire, the higher is CE.

2.5. Emission injection height

Emissions from vegetation fires always coincide with a transport mechanism to vertically displace these emissions, namely the convection induced by the heat and moisture released by the fire. Ambient meteorological conditions, fire released energy and moisture determine the injection height of fire emissions in the atmosphere.

The global distribution of fire injection height has been analysed recently by Mazzoni et al. (2007) and Labonne et al. (2007). It was shown that most fires deposit their emissions into the atmospheric boundary layer, i.e., below about 5 km. However, there is growing evidence that under favourable meteorological (high atmospheric
2.6. Fire emission inventories

The first global vegetation fires emission inventories represented climatologically annual totals based on biome-averaged fuel loads and fire return times (e.g., Andreae, 1990). However, some studies used a more mechanistic determination of the injection height depending on the buoyancy induced by the fire (e.g., Freitas et al., 2006; Hodzic et al., 2007).

The latest fire emission inventories are based on a combined approach using burned area and active fire counts from satellites, accompanied by biogeochemical modeling of the available fuel (e.g., Hoelzemann et al., 2004; Ito and Penner, 2004; van der Werf et al., 2004; Schultz et al., 2007). The applied methodologies, however, are rather different and only partly comparable due to different assumptions. Hoelzemann et al. (2004), for example, determined only fire emissions from forest and savannah fires for the year 2000 while Schultz et al. (2007) categorized agricultural waste burning as an anthropogenic activity to be excluded from the vegetation fire emission inventory. Besides these differences, a common conclusion is that the estimated vegetation fire emission inventories reveal a considerable uncertainty in particular due to the quality of information on burned area and fuel load.

Recently, new algorithms have been developed that directly quantify the fire radiative power (FRP) from space (Kaufman et al., 1998; Wooster et al., 2003, 2005; Ichoku and Kaufman, 2005; ...
America, though the inter-annual variations in these regions are
sphere Africa. Widespread vegetation fires also occur in Indonesia
(austral and boreal springs), Central America (April-May), and the
tropics, especially Southeast Asia and Africa. The second
occurrence and related emissions around the globe (Dwyer et al.,
tropical regions that burn during the hemisphere's winter and
mainly caused by burning in South America and southern hemi­

terrestrial forest regions (May-September) of Eurasia and North
spring. As tropical and subtropical fires are typically set to clear
fields and pastures in anticipation of the arrival of seasonal rains,

Table 2
Total carbon emissions from vegetation fires: a comparison of different vegetation fire emission inventories.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Global carbon emissions [Tg C year⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seiler and Cruzten (1980)</td>
<td>1760</td>
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<tr>
<td>Galanter et al. (2000)</td>
<td>2771</td>
</tr>
<tr>
<td>Andreae and Merlet (2001)</td>
<td>2310</td>
</tr>
<tr>
<td>van der Werf et al. (2003)</td>
<td>2096</td>
</tr>
<tr>
<td>Ito and Penner (2004)</td>
<td>1428</td>
</tr>
<tr>
<td>Hoelzemann et al. (2004)</td>
<td>741</td>
</tr>
<tr>
<td>van der Werf et al. (2006)</td>
<td>2460</td>
</tr>
<tr>
<td>Schultz et al. (2007)</td>
<td>2078</td>
</tr>
</tbody>
</table>

Roberts et al., 2005). In several field experiments, FRP has been
shown to relate directly to the rate of fuel consumption, which is
proportional to fire emissions. The FRP method thus has the
potential to significantly reduce the uncertainty of fire emission
estimates, because it does not depend on specific knowledge of the
fuel load and combustion completeness.

3. Global and seasonal distribution of vegetation fire emissions

The annual global distribution of carbon released from vegetation
fires is illustrated in Fig. 1, averaging data from 1997 to 2006
from the Global Fire Emission Database, version 2, which is freely
available from http://esse.Less.uci.edu/%7Eranders/data/GFED2/
(van der Werf et al., 2006). We use this data set to explain and
describe the general global spatial and temporal distribution of
vegetation fires. We also compare various global emission invento­
ries in Table 2. A comparison of the available regional vegetation fire
emission inventories is beyond the scope of this review paper. In the
tropics and subtropics most vegetation fire emissions stem from
savannah burning in Africa – about 50% of the global total (Barbosa
et al., 1999; Korontzki et al., 2003). Large-scale savannah burning
also takes place in Australia (Hurst et al., 1994) and South America
(Pрис and Menzel, 1992). Deforestation fires occur in Central and
South America, Africa and Southeast Asia (Achard et al., 2002). These
emissions are not compensated for by re-growth and provide a net
source of CO2 to the atmosphere. In the northern hemisphere mid­
and high latitudes, vegetation fires in boreal forests, grassland and
peat take place over much of North America and Eurasia (Kasischke
et al., 2005; Turquety et al., 2007). Emissions from these mid­
and high latitude fires are about 10% of global carbon emissions, and
somewhat higher for reduced gas emissions like

\[ \text{HCHO} \]

due to more incomplete combustion compared to savannah regions.

There is a pronounced seasonal variability in vegetation fire occurrence and related emissions around the globe (Dwyer et al.,
2000; Carmona-Moreno et al., 2005) as illustrated in Fig. 2 which
presents the location of the peak fire month. Generally, fire activity
peaks during longer lasting dry weather conditions. Though
burning occurs year-round and globally, there are two distinct maxima in vegetation fire emissions each year caused by fires in
tropical regions that burn during the hemisphere's winter and
spring. As tropical and subtropical fires are typically set to clear
fields and pastures in anticipation of the arrival of seasonal rains,
the first maximum peaks from about January through April. It is
mainly the result of burning in the Northern Hemisphere tropics
and subtropics, especially Southeast Asia and Africa. The second
maximum peaks from about August through November and is
mainly caused by burning in South America and southern hemi­

sphere Africa. Widespread vegetation fires also occur in Indonesia
(austral and boreal springs), Central America (April–May), and the
boreal forest regions (May–September) of Eurasia and North
America, though the inter-annual variations in these regions are
high. Figs. 1 and 2 indicate that vegetation fire emissions are

a global and continuous phenomenon occurring during all seasons
on both sides of the equator only excluding permafrost and desert
regions which are not prone to fire.

The average annual global carbon emissions from different
vegetation fire inventories range from 1428 Tg C year⁻¹ (Ito and
Penner, 2004) to 2771 Tg C year⁻¹ (Galanter et al., 2000) (Table 2).
Early estimates of Seiler and Cruzten (1980) attributed almost two­
thirds of the global carbon emissions from vegetation fires to
tropical forest fires and less than one-third to savannah fires, while
recent vegetation fire emission inventories agree on the dominance
of savannah fires with annual carbon emissions between 1200 and
1700 Tg C year⁻¹.

Inter-annual variability (Fig. 3) of global vegetation fire emis­
sions has also been investigated (e.g. Langenfelds et al., 2002;
Duncan et al., 2003b; van der Werf et al., 2004, 2006; Schultz et al.,
2007). No annual or seasonal trends in vegetation fire emissions of
CO were found by Duncan et al., 2003b) over the last two decades
of the 20th century globally or for any region, but they found
significant inter-annual variability, especially for Indonesia,
Malaysia, Brazil, Southeast Asia and the boreal regions. Schultz et al.
(2007) reported an average global total carbon emission flux from
vegetation fires of 2078 Tg C year⁻¹ for the period 1960–2000.

Minimum emissions occurred in 1974 (1410 Tg C year⁻¹), and
maximum emissions were derived for the year 1998 (3139 Tg C year⁻¹)
(Fig. 3). van der Werf et al. (2006) also reported large inter-annual variability in vegetation fire emissions with a range of more than 1000 Tg C year⁻¹, a maximum in 1998 (3183 Tg C year⁻¹) and a minimum in 2000 (2038 Tg C year⁻¹).

The variability of vegetation fire emissions is largely driven from
the signal in South America, Indonesia, and the boreal region. During
El Niño years, droughts in equatorial Asia, Central and South America
lead to enhanced fire activity. Humans take advantage of drought
conditions, setting fires to clear land, sometimes causing fires to
burn out of control (van der Werf et al., 2004). During the strongest El
Niño event of the last century in 1997, Indonesian vegetation fires
contributed about 50% to the global annual vegetation fire emis­
sions, largely stemming from the combustion of peat (Page et al.,
2002). Contrary to Duncan et al., 2003b), the analysis of Schultz et al.
(2005) suggests that there was an increasing global trend for carbon
emissions from vegetation fires between 1950 and 2000 going in
parallel with an increasing deforestation trend (Achard et al., 2002),
in particular since 1970 in Southeast Asia.

At the global scale, burned area and vegetation fire emissions
were largely decoupled over the 1997–2004 period (van der Werf et al.,
2006) because most of the burned area is located in savannah
regions that have relatively low fuel loads and emissions. Burned
area within forest biomes accounted for less than 20% of global
burned areas during 1997–2004. Burning in forest contributed most
of the variability except in 1997 when fires in tropical peat lands with
higher fuel loads than forests dominate – burned area of forest was
average. Schultz et al. (2007) reported a strong correlation of burned
areas with the ENSO index for Indonesia, but not for other regions.

4. Fire products in the atmosphere

The combustion of vegetation releases significant amounts of
gaseous and particulate trace species into the atmosphere. The
dominant products of any combustion process involving carbona­
ceous material are CO2 and H2O. Incomplete combustion in vege­
tation fires results in numerous additional compounds being
emitted. These include carbon-containing trace gases like CO, CH4,
C2H6, C2H4, and higher alkanes and alkenes, CH3OH and higher
alcohols, HCHO and other aldehydes, and organic acids (Andreae
and Merlet, 2001). In addition, nitrogen containing compounds
(e.g. NOx = NO2 + NO, N2O, HCN), sulphur-containing compounds
(e.g. SO2), and halogen-containing compounds (e.g. CH3Cl, CH3Br)
are released in substantial amounts. The particles emitted consist mainly of carbonaceous material being dominated by organic carbon (Reid et al., 2005). Depending on fire type and burning conditions, between about 5 and 10% of the emitted particle mass can be attributed to black carbon (Reid et al., 2005). Inorganic compounds such as potassium, chloride and calcium make up only a small fraction of the aerosol mass. Gaseous (e.g. acetonitrile) and particulate (e.g. levoglucosan) trace compounds have been identified as markers for vegetation fire emissions, because of their long atmospheric residence time and the large contribution of biomass combustion to their atmospheric budgets (e.g. Fraser and Lakshmanan, 2000).

Vegetation fire emissions contribute substantially to the global budgets of several trace species. According to IPCC (2007), deforestation and changing agricultural practices contributed 25% to the increase in atmospheric CO₂ since pre-industrial time (fossil fuel combustion is responsible for 75%). Globally, the average annual contribution of fire emitted species to the total species budget is about 40% for CO, 20% for NOx and 35% for carbonaceous aerosol particles (IPCC, 2001) with pronounced regional, seasonal and inter-annual variability (Section 3). Fire emissions are clearly dominating the atmospheric chemical composition in the vicinity of vegetation fires.

4.1. Air pollution

Particulate pollution generating smoke-haze is the most relevant impact of vegetation fires on air quality, human health and crop productivity. The most significant impact of particulate pollution on air quality is restricted to the proximity of fires because of their relatively short atmospheric lifetimes of the order of days to weeks (Seinfeld and Pandis, 1998). The emissions of CO, CH₄ and higher organic hydrocarbon compounds in combination with nitrogen oxides lead to photochemical formation of tropospheric ozone which is harmful to life and plants, and is also an effective greenhouse gas. Vegetation fire emission can affect ozone concentrations substantially beyond the region of fire activity (e.g. Thompson et al., 1996).

The impact of vegetation fire emissions on air quality has been extensively documented. During the burning seasons in Africa and South America, air pollution is substantially enhanced on regional scales (Reid et al., 1998; Sinha et al., 2003; Bremer et al., 2004). In Southeast Asia, an extreme event of air pollution occurred during the strong El Niño of 1997/1998, when land-clearing fires became uncontrolled in Indonesia due to severe drought conditions. Total particulate matter (TPM) concentrations of up to 4000 µg m⁻³ were reported close to the main fires on Borneo and Sumatra (Heil and Goldammer, 2001). Such concentration levels exceed any air quality standard and reach dangerous levels for human health. Cross-boundary transport of these polluted air masses led to dilution but still impacted air quality in neighbouring countries such as Singapore and Malaysia with TPM concentrations up to 300-1000 µg m⁻³. From September to November 1997, the smoke plume ranged from Papua New Guinea in the east into the Indian Ocean south of India (Nakajima et al., 1999). Smaller scale perturbations of air quality caused by vegetation fires occur worldwide, e.g. during
summer 2003 in Portugal (Hodzic et al., 2007) and in California (Wu et al., 2006), and in summer 2002 in the Northeast US (DeBell et al., 2004; Sapkota et al., 2005).

During dry weather condition, and in particular for large injection heights, the aerosol particles can be transported over thousands of kilometres before they are removed from the atmosphere by wet deposition. One example for intercontinental transport of vegetation fire aerosols in the atmosphere is given in Forster et al. (2001) who report Lidar measurements of thin atmospheric layers with increased aerosol concentrations over Europe resulting from vegetation fires in Canada. Damoah et al. (2004) provide information on hemispheric-scale transport of forest fire smoke from Russia in May 2003. Evidence for the degrading effect of distant fires on urban air quality by long-range transport is provided by Wotawa and Trainer (2000). Morris et al. (2006) report substantially enhanced ozone levels in Houston, Texas on two days in July 2004 due to pollution from boreal forest fires in Alaska and Canada. Gloudemans et al. (2006) showed how emissions from South American fires led to enhanced CO concentrations over Australia using satellite measured CO. Jaffe et al. (2004) and Bertschi and Jaffe (2005) found enhanced pollutant levels (ozone, carbon monoxide, and aerosol) on the West Coast of the US resulting from Siberian boreal fire emissions during summer 2003. Fires in Eastern Europe lead to record-level pollution levels in the Arctic in spring 2006 (Stohl et al., 2007).

4.2. Climate impact

The impact of vegetation fires on climate is manifold. Fire emissions contribute to the global budgets of greenhouse gases and aerosol particles, resulting in direct and indirect modifications of solar irradiation. They also contribute to the deposition of black carbon aerosols leading to modifications of the surface albedo of bright ice and snow surfaces. The change of vegetation cover by the fire itself modifies locally surface albedo, soil water holding capacity and surface evaporation, resulting in complex interactions and feedbacks within the climate system. Vice versa, climate variability and climate change modify fire frequency. Kaschke et al. (1999), Gillett et al. (2004) and Westerling et al. (2006), for example, present evidence that climate change has contributed to an increase in fire frequency in North America and Eurasia. The contribution of vegetation fire emissions to the atmospheric burden of greenhouse gases (CO$_2$ and CH$_4$) can be seen as "fast respiration" thereby partly destroying carbon reservoirs such as tropical and boreal forest and peat. The build-up of atmospheric CO$_2$ by land use changes which are dominated by deforestation is estimated to range from 500 to 2700 Tg C year$^{-1}$ (IPCC, 2007) with considerable inter-annual variability compared to average CO$_2$ emissions of 7200 Tg C year$^{-1}$ due to fossil fuel combustion and cement production for 2000 to 2005 (IPCC, 2007). The fires in Indonesia in 1997 emitted between 810 and 2570 Tg C (Page et al., 2002) and contributed substantially to the large atmospheric CO$_2$ increase in 1997 (Fig. 3).

Aerosol particles emitted from vegetation fires modify the atmospheric radiation budget by scattering and absorbing solar radiation. The current estimate of the direct global radiative forcing at the top of the atmosphere from vegetation fire aerosols is 0.03 ± 0.12 W m$^{-2}$ (IPCC, 2007). The high standard deviation shows that the sign of the direct radiative forcing of vegetation fire aerosols is still in question. The light-absorbing properties of the particles and their vertical distribution in the atmosphere are crucial to estimate their direct radiative effect. Both are highly variable. During the strong El Niño event in 1997, for example, the smoke–haze aerosol reduced the seasonal average solar radiation absorbed by the equatorial Indian Ocean by 30–60 W m$^{-2}$ from September to November 1997 (Podgorny et al., 2003) with a top of the atmosphere radiative forcing from 5 to 15 W m$^{-2}$ for cloudy skies. Absorption and scattering of solar radiation by smoke aerosols from vegetation fires can also lead to a reduction of cloud cover thereby cooling the surface and heating the atmosphere as it has been observed over the Amazon (Koren et al., 2004; Feingold et al., 2005) and the Mediterranean area (Pace et al., 2005) resulting in a positive radiative forcing at the altitude of the aerosol layer and an increased atmospheric stability. Aerosol particles emitted from vegetation fires have the potential to act as cloud condensation nuclei (e.g., Hobbs and Radke, 1969; Vestin et al., 2007) and, hence, modify the microphysical and optical properties of clouds. They can reduce the average cloud droplet size, they enhance the lifetime of existing clouds and their efficiency to reflect solar radiation (e.g. Kaufmann and Fraser, 1997; Reid et al., 1999; Lohmann and Feichter, 2005). The interaction of aerosol particles with clouds can also result in modifications of the processes that form precipitation. A delay in the onset of precipitation is reported by Rosenfeld (1999) and Andreae et al. (2004). Andreae et al. (2004) presented in situ measurements of the microphysical evolution of convective clouds under different aerosol conditions in the Amazon region. They found a significantly reduced warm droplet growth under polluted conditions, suggesting an enhanced availability of liquid water at the freezing level, which could lead to more vigorous convective clouds under smokier conditions. Results from a recent satellite study in the Amazon basin are consistent with the conclusions drawn by Andreae et al. (2004), suggesting a large-scale impact of vegetation fire aerosol on cloud properties and precipitation (Lin et al., 2006). However, the overall climatic effect of the modification of precipitation by any kind of aerosols remains unclear and therefore a hot topic in the research community (Lohmann and Feichter, 2005). Deposition of black carbon aerosols from vegetation fires onto bright ice and snow surfaces results in a substantial decrease of surface albedo (Stohl et al., 2006) inducing a positive radiative forcing (e.g. Hansen and Nazarenko, 2004). Changing vegetation cover at the fire site itself also leads to a change of surface albedo (e.g., Govaerts et al., 2002; Jin and Roy, 2005) that has to be considered when the overall effect of vegetation fires on climate is addressed. In a pioneering study, Randerson et al. (2006) estimated the overall climate impact of boreal forest fires considering the effect of greenhouse gases (CO$_2$, CH$_4$, and O$_3$), modification of surface albedo by deposition of black carbon and modified vegetation cover, and the direct aerosol effect. They conclude that boreal fire activity results in positive radiative forcing during the first year, but a negative radiative forcing when averaged over an 80-year fire cycle. This study emphasises the importance of considering the complex interactions and feedbacks in the climate system before reliable conclusion on the overall impact of fire activity on climate can be drawn.

5. Future research recommendations

We offer suggestions for further research as a consequence of the major uncertainties existing in today's vegetation fire emission estimates related to their application to estimate environmental and climate impacts.

To date, most emission studies have used biome-averaged emission factors (Section 2.4). Field studies, however, have reported large spatial and temporal variability in EFs due to changing moisture conditions and varying fire practices. Including this variability may improve the spatial and temporal variations in trace gas and aerosol emissions.

Currently, no single satellite products can provide quantitative estimates of vegetation fire emissions with reasonable accuracy and consistency across the globe as discussed in Sections 2.2, 2.3, 2.6 and 3. Several remote sensing products of fire counts, burned
areas and recently fire radiative energy have been released, but often with conflicting results. Validation of satellite fire products is often restricted to selected regions, leaving the global performance unclear (see Section 2.2). The detailed information on the spatial distribution of fires from polar-orbiting systems should be combined with detailed temporal information from geostationary platforms to determine realistically the diurnal variation of the burning activity similar to the use of satellite data for numerical weather prediction (Montzka et al. 2007). For the forecasting of vegetation-fire-related pollution episodes, near real time information is required. However, at present, only two systems provide near real time global analysis (Table 1) to enable such forecasts. An integrated effort to synthesize the available information is needed in order to generate an operational system for accurate global fire emissions monitoring, e.g. the construction of a Global Fire Assimilation System (GFAS) from the best available satellite products. These data need to be integrated into a state-of-the-art numerical model by so-called data assimilation which provides the most efficient and consistent method for integrating a large variety of observational data in near real time as demonstrated by operational systems for numerical weather prediction (Bengtsson et al., 1982; Upsala et al., 2005). Recently, major efforts have started to enable 'chemical weather forecasts' (Lawrence et al., 2005), e.g. within GEMS (Global and Regional Earth-System Monitoring using Satellite and in situ Data – http://www.ecmwf.int/research/EU-projects/GEMS). This project plans to extend the forecasting system of the European Centre of Medium Range Weather Forecast by the forecast of atmospheric gases and particles. A GFAS covers one topic of such a system. It should have a flexible structure to allow for continuous improvements when more detailed information (e.g. high temporal resolution on fuel consumption) becomes available. It should produce emission estimates with sufficient accuracy and adequate resolution in space and time for use in high resolution air quality models.

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