Smouldering Fires and Natural Fuels

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Overview

Smouldering is the slow, low-temperature, flameless burning that represent the most persistent type of combustion phenomena and which leads to the largest and longest burning fires on Earth. Smouldering megafires in peat and coal deposits occur with some frequency during the dry session in, for example, North America, Siberia, the British Isles, the subartic and South-East Asia.

Smouldering fires propagate horizontally and vertically through organic layers of the ground and can reach deep into the soil where large cracks or natural piping systems exist. These threaten to release ancient carbon stored in the soil (>10k years old carbon). Once ignited, they are particularly difficult to extinguish despite extensive rains, weather changes, or fire-fighting attempts, and can persist for long periods of time (months, years, or even centuries), spreading into the ground and over extensive areas.

Recent figures at the global scale estimate that average annual greenhouse gas emissions from smouldering fires are equivalent to 15% of man-made emissions.

Introduction

Combustion is considered the most important reaction for the human race [Burke and Schumann 1928, Wrangham and Carmody 2010] for obvious technological reasons such as its use since ancient times in cooking, heating, warfare, and power generation, but also for its threat to safety [Drysdale 2011]. In addition, it is of central importance to nature, because the top of the Earth crust is the interface where the abundant organic matter of plants meets an atmosphere rich in O_2. This mixture is flammable, and can lead to wildfires after an initiating ignition event. Wildfire plays an essential role for life on Earth [Lovelock 2000; Belcher et al 2012, this volume; Lenton 2012, this volume].

Despite this central importance, our understanding of fire remains limited. Hottel (1984) stated that "*A case can be made for fire being, next to the life processes, the most complex of phenomena to understand*". It comes as no surprise, then, that the discipline

of fire science is intrinsically immature compared to most others. It patiently waits for many more decades of fruitful incoming research.
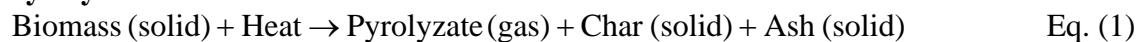
In the following sections, the combustion phenomena in wildfires are briefly discussed. One type of combustion, that of smouldering (fire without a flame), is then explained in detail. The term *megafire* is a relatively new one and refers to very large wildfires. It is not rigorously defined what large means, but it has been used in terms of firepower, speed, safety threat, or suppression costs. This chapter argues than smouldering combustion leads to megafires as measured terms of the total biomass consumed.

The following sections review the current knowledge on smouldering fires in the Earth system regarding combustion dynamics and chemistry, while highlighting differences with flaming fires. It shows that smouldering combustion of natural ground fuels, like peatlands, leads to the largest and longest burning fires on Earth, and show that they create a positive feedback mechanism to climate change. It is therefore absolutely crucial for us to expand our limited knowledge of not only flaming, but particularly on smouldering fires.
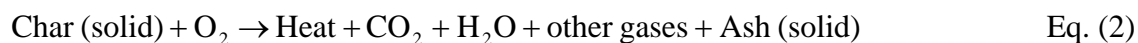
Smouldering vs. Flaming Combustion

An overall exothermic reaction is the essential chemical phenomenon driving combustion. It involves the exchange of atoms between two reactants brought together, a fuel and oxidizer. In wildfires, the fuel is the biomass and the oxidizer is the oxygen in the air. The reaction results in the release of heat and both gaseous and solid products of combustion. In general, the process can involve millions of elementary chemical reactions, but the overall combustion reaction of a solid fuel can be approximated by the two most important lumped chemical pathways: a pyrolysis (Eq. 1) and an oxidation (Eqs 2 or 3).
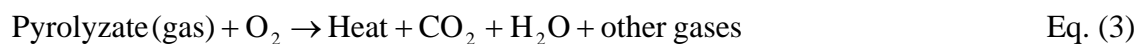
Pyrolysis:

$$\text{Biomass (solid)} + \text{Heat} \rightarrow \text{Pyrolyzate (gas)} + \text{Char (solid)} + \text{Ash (solid)} \qquad \text{Eq. (1)}$$

Solid Oxidation:

$$\text{Char (solid)} + O_2 \rightarrow \text{Heat} + CO_2 + H_2O + \text{other gases} + \text{Ash (solid)} \qquad \text{Eq. (2)}$$

Gas Oxidation:

$$\text{Pyrolyzate (gas)} + O_2 \rightarrow \text{Heat} + CO_2 + H_2O + \text{other gases} \qquad \text{Eq. (3)}$$

There are two types of combustion: smouldering and flaming. The dominant type depends on which product of pyrolysis oxidizes. If the solid char is oxidizing (Eq. 2), then the burning is on the same location where pyrolysis took place (in-situ oxidation), and it

leads to smouldering[1] combustion (see Fig 2.1). If the fuel is the gaseous pyrolyzate (Eq. 3), then the oxidation is at a different location than the pyrolysis (ex-situ oxidation) and airborne. It leads to flaming combustion (see Fig. 2.1)
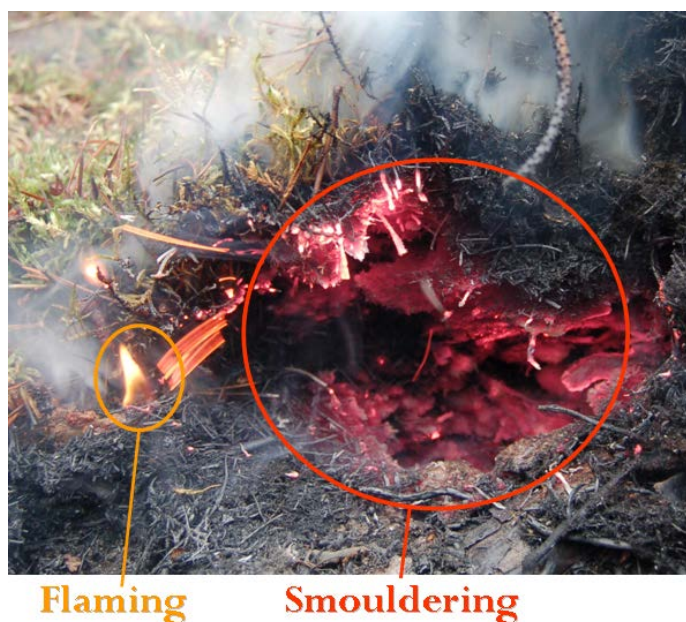
Figure 2.1: Snapshot showing the two regimes of biomass burning during a wildfire; flaming of the grass and smouldering of the organic soil. For scale reference, the flame is about 10 mm tall. By G Rein, CC BY license.

Pyrolysis is the chemical decomposition of a solid organic material[2] by heating, and does not involve oxidation reactions. When a solid organic material heats up, it eventually reaches a temperature threshold where it begins to break down chemically. This process is called pyrolysis and is similar to gasification but with one key difference – pyrolysis is the simultaneous change of chemical composition (e.g., long hydrocarbon chains to shorter chains) and physical phase (i.e., solid or liquid to vapour), and is irreversible. It is an endothermic reaction, meaning that it needs an external supply of heat to continue because the products carry more chemical energy than the original fuel. Pyrolysis results in gas and solid products. These are shown schematically in Eq. (1). The pyrolyzate is a complex gaseous mixture of organic species released to the air. Typical species present

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[1] Smouldering combustion is referred sometimes as *heterogeneous combustion*. Although the term is technically correct (smouldering involves heterogeneous chemical reactions), it is traditionally used to describe also flaming combustion of droplets, sprays and particles. *Smouldering combustion* is the preferred term in fire science.

[2] Organic liquids can also pyrolyse but this is of little interest in wildfires

are volatile organic compounds (VOC), hydrocarbons (eg, CH_4), poly-aromatic hydrocarbons (PAH) and particle matter. Some H_2O vapour and trace levels of CO and CO_2 are possible. Only under intense heat (i.e., from the flame), some organic components of the pyrolyzate rearrange to form soot which is a collection of airborne carbon particles. The resulting char is a carbon-rich porous material, and the ash is the mineral-rich residue. Of these products, both the pyrolyzate and the char are susceptible to subsequent oxidation.

Oxidation in this context is the reaction between a product of pyrolysis and the oxygen in the air. It is an exothermic reaction, meaning that it releases heat as it takes place because the products carry less chemical energy stored in their bonds than the reactants. If the reaction is complete and the fuel is a hydrocarbon, the products are carbon dioxide and water. However, in natural conditions complete combustion is rare and thus other gases typical of incomplete combustion are produced (e.g. CO, CH_4, C_3H_8, CH_3OH, PAH, NH_3). When char is burning (Eq. 2), oxidization is in-situ and on the surface of the solid, and more ash is produced as the by product, however no soot is produced because the heat from smouldering is not intense enough to initiate soot chemistry. When the pyrolyzate is burning (Eq. 3), oxidation is ex-situ and airborne, and additional gaseous products are soot and NO_x.

Flaming Combustion
A flame is the thin sheet of gas where the combustion of the pyrolyzate is taking place, resulting in gaseous and particulate products at high temperature. These gases and airborne particles are typically hot enough that they radiate their own light, and thus a flame is visible to the naked eye (see Fig. 2.1). The one-step overall reaction taking place in a flame is shown in Eq. (3). Because both the fuel and the oxidizer are in the air, only one phase is involved (gas/gas) and leads to homogenous chemical reactions.

There are two basic flame structures depending on when the mixing process of the gaseous reactants takes place; premixed and diffusion flames (see also Torero 2012, this volume). In premixed flames, fuel and oxygen are mixed well before combustion. The process inside a gasoline engine or the burning of a flammable could are good examples. In diffusion flames, fuel and oxygen are initially separated and mixed at the flame location in the same instant as the combustion takes place.

Flaming wildfires exhibit diffusion flames with negligible presence of premixed flames (which are of interest mostly in power generation and propulsion). The diffusion flame establishes at some distance on top of the surface of the solid fuel. The pyrolysate fuel released from the solid (Eq. 1) is transported away towards the flame where it reacts. At the same time, oxygen is transported with the entrained air from the surroundings atmosphere to the flame. At the diffusion flame, the chemical reaction rate can be considered infinitely fast and thus, the burning rate is typically determined by the rate

of pyrolysate production [Drysdale 2011]. The pyrolysate production rate is dominated by the rate of heat transfer from the flame to the solid [Drysdale 2011].

Smouldering Combustion

Smouldering combustion is the slow, low-temperature, flameless burning of porous fuels [Rein 2009]. It is sustained by the heat evolved when oxygen directly attacks the surface of the solid fuel [Ohlemiller 1985]. Because the fuel remains solid and the oxidizer is in the air, two phases are involved (solid/gas) and this leads to heterogeneous chemical reactions.

Both the biomass fuel and the pyrolysis char can oxidize, but the most exothermic reaction is that of char. Thus, smouldering chemistry is approximated as a two-step process: biomass pyrolysis (Eq. 1) produces the char that is then oxidized in-situ (Eq. 2) [Hadden et al 2012]. The oxidation reaction occurs on the surface of the solid but it can take place in-depth inside porous materials. When smouldering is particularly strong, the fuel surface may glow (for example, see Fig. 2.1) but this is not the case in most cases of importance for wildfires (for example, see Fig. 2.2). The glowing characteristic cannot be part of the definition of smouldering.

Transition between Smouldering and Flaming

Smouldering and flaming are tightly related, and one can lead to the other. The persistent smouldering of thick fuels (ie, tree branches, trunks) typically observed for days after a flaming wildfire has passed by is called *residual smouldering combustion* (see Fig. 2.2) and has received some attention in the literature e.g. [Bertschi et al. 2003]. The reverse, the transition from smouldering to flaming is less often observed in wildfires because it requires less usual thermodynamic conditions, but it is possible for example under enhanced oxygen supply (i.e., strong winds). The transition is a spontaneous gas-phase ignition supported by the smouldering reaction which acts both as the source of gaseous fuel (pyrolyzate, Eq. 1) and of heat to ignite the flame (Eq. 3) [Tse et al 1996]. This transition has received very little attention and the current understanding of the process is somewhat limited.

Figure 2.2. Smouldering combustion burning inside a log many hours after a flaming wildfire has passed by. With permission of F. de Souza Costa[3]

Ignition and Extinction

Once ignited, subsurface biomass layers such as those in peatlands, carbon-rich soils or coal seams burn slowly for long periods of time, spreading deep into the ground and over extensive areas.

Possible ignition events can be natural (lightning, self-heating, volcanic eruption) or anthropogenic (land management, accidental ignition, arson). Smouldering fires can be initiated by weak sources of ignition. For instance, smouldering ignition of porous synthetic foam occurs with a minimum radiant heat flux of 8 kW/m^2, while flaming ignition occurs only above 15 kW/m^2 [Hadden and Rein 2012].

Moreover, spontaneous ignition without any external event is possible in smouldering fuels, even at ambient temperatures, via the phenomena of self-heating. This refers to the tendency of certain organic materials to undergo spontaneous exothermic reactions in oxidative atmospheres at low temperatures [Drysdale 2011]. It is a well known problem in facilities managing large amounts of carbon-rich materials (eg, waste, biomass, coal heaps, haystacks, organic powders). Initially, a pile of the material releases small amounts of heat by very slow oxidation. This heat accumulates in the long term if the pile is well insulated, resulting in a sustained increase of temperature without any external heat source. Large pile sizes and poor ventilation facilitate build up of heat.

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[3] See context of smouldering logs in [Costa and Sandberg 2004]

Above a certain ambient temperature, the process self-accelerates and leads to thermal runaway. This results in a smouldering fire, which may undergo transition to flaming if the reaction breaks through to the free surface. For example, a large mass of dry organic soil accumulated in the subsurface offers the perfect conditions for self-heating to take place and develop hot spots and fires within weeks or months. This happened in 2009 at the wetlands of *Las Tablas de Daimiel* National Park, Spain. See Fig 2.3. After several years of severe drought, the organic soil had become very dry (<20% moisture content in dry base) [Moreno et al 2011] and smouldering fires developed independently in at least four different self-heating hot spots. The fires burned for more than five months. Despite intense fire fighting attempts, only the very heavy winter rains of that year (wettest winter in the last 50 years) resulted in extinguishing of the fires.

Figure 2.3. This photo shows dry organic soil smoldering at the wetlands of *Las Tablas de Daimiel* National Park, Spain, during a severe drought episode in 2009. Photo by G Rein, CC BY license.

Smouldering combustion is the most difficult type of combustion to extinguish. It requires much larger amounts of water than flaming fires; >50% larger mass of H_2O per mass of burning fuel as experimentally measured in a smouldering coal heap [Hadden and Rein 2011]. Based on ignition experiments, we know smouldering would require a lower oxygen concentration when using the suppression method of smothering; ~10% [O_2] for smouldering vs. 16% for flaming, as measured experimentally for an organic fuel in [Hadden et al 2012][4] and [Belcher and McElwain 2008][5] respectively. And it requires much longer holding times for smothering; months for smouldering vs. minutes for

[4] For ignition of dry peat under forced flow conditions

[5] For ignition of a range of natural fuels under quiescent conditions

flaming as calculated in [Hadden and Rein 2011]. These values help design suppression strategies in the field, with the caveat that these apply only when the reacting core has been located and the suppression agent reaches the core[6].

For these two reasons, easy ignition and difficult suppression, smouldering is the most persistent type of combustion phenomena on Earth. Smouldering fires burn for very long periods of time (e.g., months, years, decades) despite extensive rains, weather changes and fire-fighting attempts. Indeed, the oldest continuously burning fire on Earth is *The Burning Mountain* in New South Wales, Australia, a large coal seam that has been smouldering for approximately 6,000 years [Ellyett and Fleming 1974].

Given its proven persistence and presence in a wide range of modern ecosystems, it can be argued that smouldering also had a leading role in ancient ecosystems that existed on Earth millions of years ago (paleofires) (e.g. see [Belcher et al 2012, this volume]). Given its ease of ignition and difficult suppression, it is reasonable to think that significant periods of deep time were dominated by smouldering fires, such as the Carboniferous period 359-299 million years ago, when there was not only extensive accumulation of soil organic matter in large peatlands but also superambient atmospheric oxygen ($[O_2]>21\%$) [Belcher et al 2012, this volume]. It has been instinctively assumed that the first fires on Earth were of a flaming nature, but the smouldering hypothesis has not been tested yet. Paleofire studies have traditionally focused exclusively on flaming combustion, and so far, only two papers in the literature have considered the possibility of smouldering fires in deep times [Belcher and McElwain 2008, Belcher et al 2010]. This may be due to the difficulty of identifying a smouldering vs. flaming fire in the fossil record, and also due to limited knowledge on smouldering combustion.

Behavior of a Smouldering wildfire

The characteristic temperature, spread rate and firepower (heat released rate) during smouldering are low compared to those in flaming combustion. Typical peak temperatures for smouldering are 500-700 °C, and 6-12 kJ/g for the effective heat of combustion; compared to typical values for flaming of around 1500-1800 °C and 16-30 kJ/g respectively [Rein 2009]. Because of these characteristics, smouldering spreads in a creeping fashion, typically around 10-30 mm/h, which is approximately two orders of magnitude lower than the spread rate of flaming fires.

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[6] The mass of suppressant agent (water or smothering gas) lost to leaks and surroundings could be many times larger than the mass required to extinguish the core.

For most smouldering fuels under typical conditions, the two controlling mechanisms of smouldering spread are the oxygen supply feeding the reaction, and the heat losses from the reaction zone [Ohlemiller 1985]. Atmospheric oxygen feeds smouldering in all cases. This supply decreases with soil depth (or distance to air channels) but increases with the permeability of the soil. The losses of heat hinder smouldering. These increase with wind speed because of convection but decrease with soil depth because of the ground insulating effect.

Many natural fuels can sustain a smouldering reaction, including peat, organic soils (see Fig 2.2), duff, humus, forest litter, wood, and coal. In general terms, the fuel consists of a permeable medium formed by grains, fibres or a porous matrix. This aggregate nature facilitates the surface reaction with oxygen by providing a large surface area per unit volume and permitting in-depth transport of oxygen. At the same time, it acts as thermal insulation that reduces heat losses providing a high characteristic thermal time, this is, i.e. heating and cooling takes longer in smouldering fuels than in isolated fine fuels.

An important source of heat losses are the water and mineral contents of the fuel mass. Indeed, moisture content of organic soils is the single most important property governing the ignition and spread of smouldering fires. For example, the critical moisture content for ignition (also called the moisture of extinction) of boreal peat has been measured at 125% in dry base (sample with a mineral content of 8%) [Rein et al. 2008]. Any peat drier than this is susceptible to combustion. Similar values for peat and other organic soils are reported in [Frandsen 1997]. The second most important property is the mineral content[7]. There is a decreasing linear relationship between the mineral content for smouldering and its critical moisture: lower mineral content means soil can ignite at even higher moistures [Frandsen 1997]. After these two, other important properties are bulk density, porosity, flow permeability and organic composition [Rein 2009]. The prominent role of moisture is such that natural or anthropogenic-induced droughts are the leading cause of very large smouldering fires (megafires).

Smouldering wildfires can burn in shallow or deep fronts. Each has significantly different dynamics because the different role played by each of the controlling mechanisms of oxygen supply and heat losses. While the former have been the subject of some experimental and fieldwork, the latter remains mostly unstudied.

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[7] The water and mineral contents are related to the organic content, since the sum of the three contents is equal to the total mass of the fresh sample (the wet weight).

Biomass beds located close the surface of the soil burn in shallow fires (typically <2 m under the surface). They have a good supply of atmospheric oxygen, but are exposed to large convective heat losses. They propagate laterally and downwards along the organic layers of the ground. After the event, shallow fires leave voids of soil on the surface. This has suggested that fuel consumption could, in principle, be estimated by the depth of burn from the original soil height [Page et al. 2002, and Ballhorn et al. 2009]. See section ahead *Depth of Burn* for more details.

Deep fires take place in organic subsurface layers (>2m under the surface) fed by oxygen infiltrating the ground via large cracks, piping systems or channels. For example, it is known that peatlands have an in-built natural piping system for water movement [Holden and Burt, 2002] that when desiccated becomes the delivery network for oxygen transport to deeper locations and smoke exhaust to the atmosphere. Deep fires have a poorer supply of atmospheric oxygen but are better insulated from heat losses that shallow fires. This affects the emissions. Combustion by-products contain more CO_2 when oxygen supply is larger, whereas they contain more CO when the supply is poorer. Thus, the emissions from deep fires are expected to have an even higher CO/CO_2 ratio than shallow fires [Rein et al 2009]. This difference in the ratio suggests a method to detect on-going deep fires from sensing atmospheric emissions. Deep smouldering wildfires have not been studied yet but share many similarities with coal fires, which is a smouldering phenomenon that has attracted a relatively large amount of research, especially from geologist [Stracher et al. 2010].

Figure 2.4 illustrates the hypothetical propagation of a shallow fire that spreads downwards to become a deep fire. Deep fires can become endemic to the ecosystem by switching to a dormant state in the subsurface during the dry or cold seasons but spreading upwards to the surface during the dry or hot sessions. The peat fires observed in Botswana since the 19th century show this endemic behavior [Gumbrich et al, 2002]
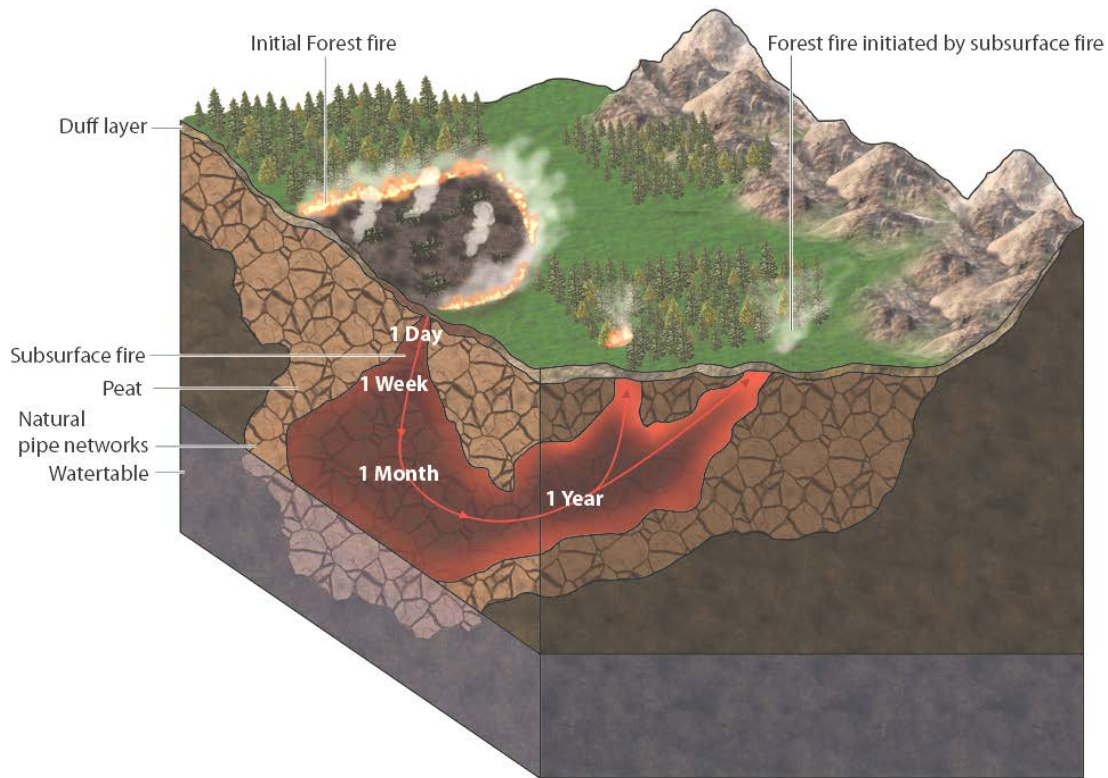
Figure 2.4. Illustration of a smouldering peat fire initiated by flames in the surface. It starts as a shallow fire and spread to become a deep fire following the piping system typical of dry peatlands. Illustration by E. Burns and G. Rein, CC BY license.

Fate of organic matter

As a smouldering fire spreads, it first converts the organic soil into char, and then the char into ash. At the end, only a thin layer of ash and some small char pieces remain, leaving a void in place of the biomass. The great majority of organic content of the biomass (>90% for peat [Rein et al 2008]) is released as gas emissions. Visually, this is seen in Fig. 2.5 showing the spread of a shallow fire over a horizontal bed of dry peat. The fire spreads laterally and downwards through the thickness of the bed. This downward spread is discussed in more detail in the section *Depth of Burn*.
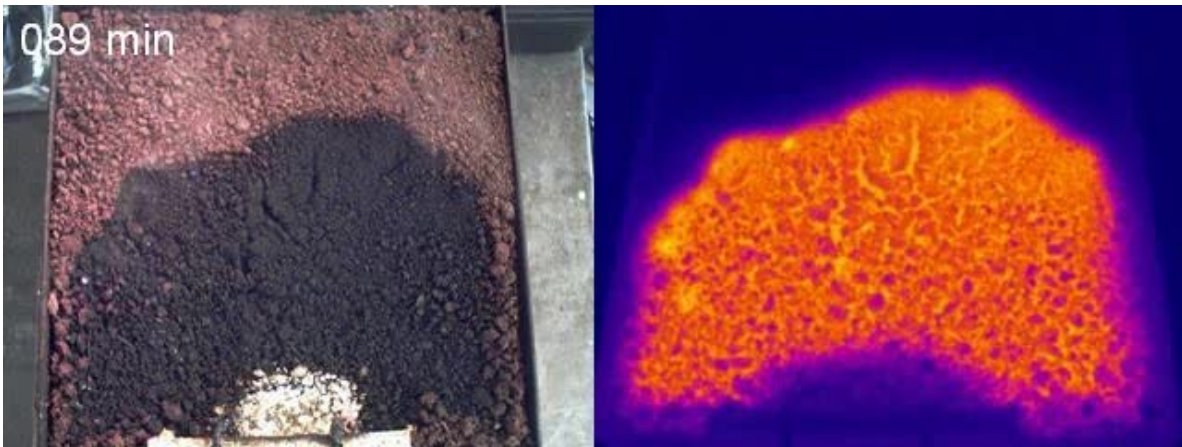
Figure 2.5. Instantaneous shot during the spread of a smouldering fire over a horizontal layer of dry peat. Laboratory experiment of a shallow fire on a peat bed of 5 cm deep and inside a 20 x 20 cm tray. Ignition was forced with 100 W of heat from an electric coil at the bottom of the photo, where the white ash is first seen. Left) Visual image showing the presence of peat (brown), char (black) and ash (white). Right) Infrared image showing the presence of oxidation (higest temperatures are reached where the heat is released). By R Hadden, E Cazaly and G Rein, CC BY license.

Any arbitrary horizontal location of the peat bed in Fig 2.5 sees the successive arrival of four distinct thermal and chemical waves that form the structure of a smouldering front. Each wave is a sub-front. The pre-heating, drying and the pyrolysis fronts consumed thermal energy and move ahead of the oxidization front where the heat is released. The evolution in depth and time of the structure of a shallow fire, as could be seen in any arbitrary location of Fig 2.5, is illustrated in Fig 2.6. Each of the sub-fronts is discussed below.

Preheating. Heat from the oxidation reaction is conducted ahead towards the undisturbed biomass heating it up to temperatures where water evaporation takes place. This front does not involve chemical reactions nor does it emit gases in any significant quantity.

Evaporation. This endothermic reaction occurs within a range of temperatures below 100 °C, typically being significant above 50°C [Filkov et al. 2012], emitting water vapour and leaving behind dry biomass.

Pyrolysis. The temperature continues to increase due to the heat from the fire, and at temperatures above 150°C [Chen et al 2011], pyrolysis of the dry biomass dominates the chemistry. Subsequent heating above this temperature increases the pyrolysis rate until all biomass has reacted. Char and pyrolysate are formed as products (Eq. 1). The char remains in-situ and the pyrolysate is released to the atmosphere directly (shallow fires) or via a piping system (deep fires).

Oxidation. This front moves behind the others and is the closest to the oxygen source[8], the atmosphere in shallow fires, or the piping system in deep fires. It involves the exothermic oxidation of both the dry biomass and the char, but char oxidation is much stronger (Eq. 2) [Hadden et al 2012]. Oxidation of carbon-rich materials dominates at temperatures above 280°C [Chen et al 2011, Cancilleri et al 2011]. Subsequent heating above this temperature increases the oxidation rate until all char has reacted. This front overlaps with the pyrolysis front, and at high temperatures both reactions could compete for biomass consumption, depending on the oxygen availability and thermal conditions [Hadden et al 2012].
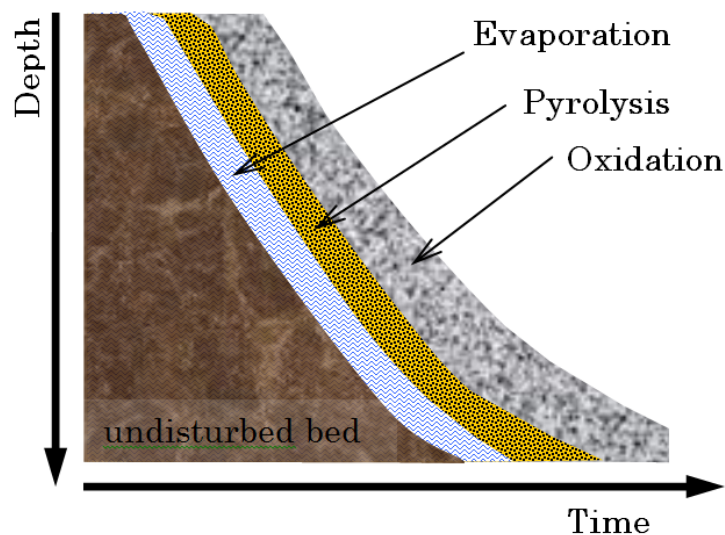
Figure 6. Sketch in depth vs. time of the thermal and chemical processes seen at any fixed horizontal location in the peat bed of Fig 2.5. By G Rein, CC BY license.

The chemical compositions of the three main solid species involved in smouldering fires (biomass, char and ash) are shown in Table 1 for the case of sphagnum moss peat. It shows clearly how pyrolysis concentrates carbon in the char while a large fraction of the hydrogen is released, while the oxidation releases most of the carbon and concentrated the minerals in the ash which H, C and N contents are negligible. The fraction of carbon in char is ~1.5 times higher than in peat, and ~35 times higher than in ash. The change is even greater in terms of carbon density, it increases from 77 kg-C/m^3 in the peat to 133 kg-C/m^3 in the char, to then sharply drop to 0.7 kg-C/m^3 in ash.

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[8] This explanation implies that the front propagates in forward mode [Rein et al 2007], where the supply of oxygen moves in the same direction as the front. It is the most observed propagation mode for smouldering wildfires.

Species	Carbon %	Hydrogen %	Nitrogen %	Bulk density kg/m^3	Carbon density kg-C/m^3
Peat	51±1	5±0.5	1±0.2	151±3	77±2
Char	70±12	2±1	2.7±0.5	189±4	133±26
Ash	2±0.5	0.1±0.1	0.2±0.1	36±2	0.7±0.1

Table 1: The mass fractions of carbon, hydrogen and nitrogen (dry base), density and carbon density for the three main solid species involved in the smouldering of sphagnum peat. Values obtained by rounding the measurements from laboratory measurements in [Hadden et al. 2012].

Char is formed by pyrolysis and consumed by oxidation. So at the beginning of a smouldering fire there is no char, and at the end only a small amount of char remains, but in between substantial amounts of char were momentarily formed. Smouldering produces and consumes its own char: it initially produces char through pyrolysis before being consumed by char oxidation reactions. The competing nature of the production and consumption char reactions has been experimentally shown in the laboratory by [Haddden et al 2012] and is reproduced Fig 2.7. The top of a small bed of dry peat was exposed to a strong radiant heat source for 1 min inducing a smouldering front which spread through the sample unassisted. Tracking the amounts of peat and char at any given time shows that first char is formed. It reaches a maximum fraction (~50% of the initial mass) in 20 min and then slowly the char is consumed down to ash (10% mass). At the end of the experiment, 90% of the initial mass has been released as gases, leaving a void and a thin layer of ash.
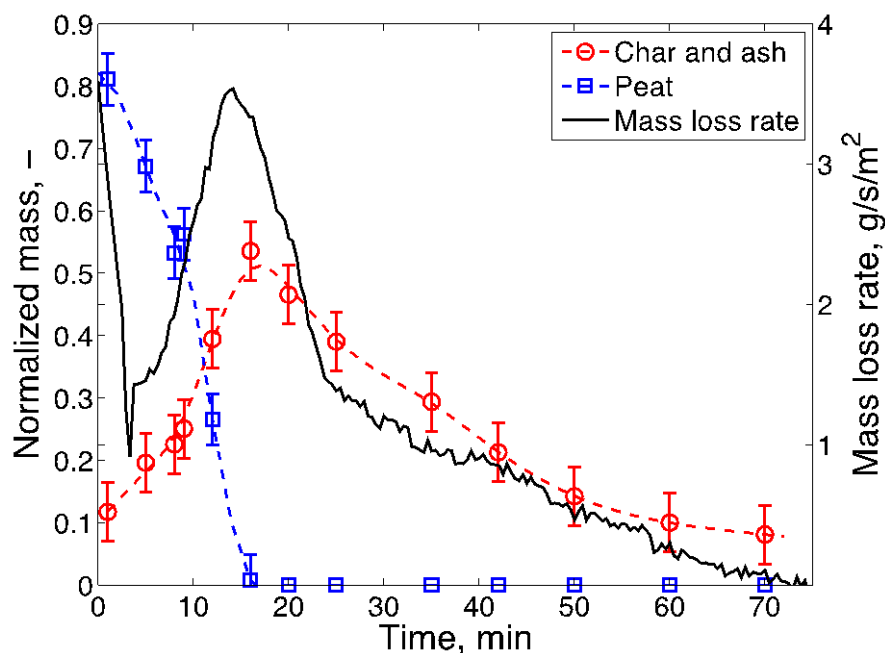
Figure 2.7. The evolution of the mass fractions of peat and char when a small bed of peat is exposed to strong radiant heat. Note that data with red circles are for char + ash mass, but the ash contribution is very small (max 10%) so it can be neglected. Data from [Hadden et al 2012].

The fact that little char is left after smouldering fires suggests why smouldering combustion has hardly been considered in Earth's geological history. It could be due to the difficulty of finding the char signature of such fires in the fossil record as it is normally done for flaming fires.

Most of the carbon is released in the form of CO_2 and CO [Rein et al 2009]. But volatile organic compounds (VOC) and Polycyclic aromatic hydrocarbons (PAH) are present as well because smouldering is characteristically an incomplete combustion reaction and thus it emits these atmospheric pollutants at a higher proportion than flaming. The total CO and CO_2 yields for smouldering peat have been measured to be 59±16% g/g in terms of the mass of dry peat burn, and the CO to CO_2 ratio was 0.43±0.1 (compare to ~0.1 in flaming combustion). This has been confirmed in the field by [Bertschi et al. 2003] in the tropical savanna which show that the smouldering phase of these fire releases on average 130% more CO and 670% more hydrocarbons, but 15% less CO_2 and no NO_x compared to the flaming phase.

Depth of Burn

Because a smouldering fire continuously spreads horizontally and vertically (laterally and downwards as seen in Fig. 2.5), it is a volumetric phenomenon, as opposed to flaming that is a surface phenomenon. A flaming wildfire spreads mostly horizontally. In

comparison, its vertical spread is instantaneous and covers a fixed height of lighter forest biomass (crown, surface or both). Flaming fires lack the significant in-depth spread into denser soil layers characteristic of smouldering fires.

The volumetric spread process is illustrated in Fig 2.8. It shows a cross section of the biomass bed as seen from the side along a vertical slice of Fig 2.5. The smouldering front spreads between the leading edge and the trailing edge, leaving a 3-dimensional void behind. The leading edge is given by the arrival of the evaporation and pyrolysis fronts to the biomass. The trailing edge is given by the end of the oxidation reaction when the char is consumed, and burns down to the bottom of the bed. The thin layer of ash left at the bottom, behind the trailing edge, contains some charred remains that do not burn because the end of the bed quenches the oxidation reaction. The in-depth spread is responsible for the depth of burnt h_b (also called burn scar). Thus, there are three spread rates, leading edge S_l, trailing edge S_t, and in-depth S_d (in general $S_l > S_t >> S_d$).
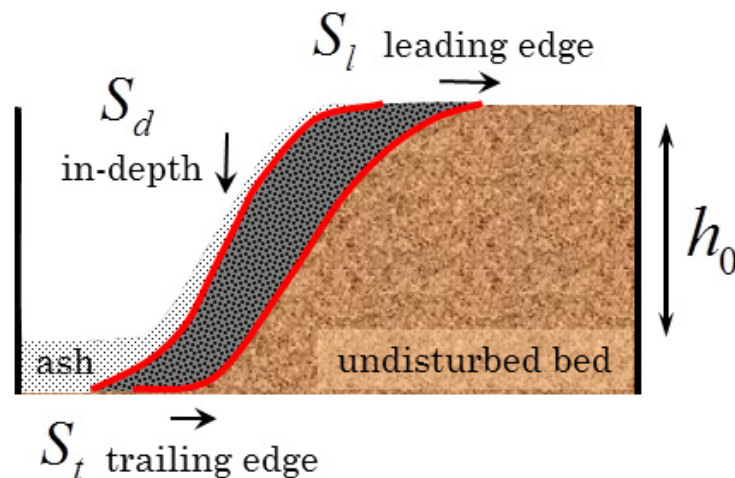
Figure 2.8. Cross section of the biomass bed as seen from the side along a vertical slide of Fig 2.5. It shows the horizontal and vertical spreads and edges of the fire. By G Rein, CC BY license.

The total amount of biomass consumed by the fire, m_t, can be estimated by the volume of the void left multiplied by the density of the biomass bed, ρ_0. The ash layer is thin compared to h_b so the mass of ash can be safely neglected (typically ~2 to 8% of the dry biomass). The volume of void can be approximated as a circular cylinder. The radius spreads at a rate S_l, and the height at S_d. If we assume that the spread rates are approximately constant, then the radius growth as t^2 and the depth as t. The total consumption can be calculated by Eq. (4).

$$m_t(t) = \int_0^t \dot{m}_t(t)dt = \pi \rho_0 S_d S_l^2 t^3 \qquad \text{Eq. (4)}$$

where t is the time elapsed since spread started. Note that Eq. (4) is cubic in time, because of its volumetric nature. The total mass consumption in flaming fire gives an expression that is quadratic in time ($\propto t^2$) [Drysdale 2011] because there is no significant in-depth burning. As mentioned before, smouldering fires burn for much longer durations, whereas flaming wildfires last maximum three to six days. This leads to very different biomass consumption behavior. See Fig. 2.9 for a graphical comparison of the two growth curves.

It is most common to measure the mass consumption per unit area, m'' after a wildfire. This is given by the depth of burn h_b multiply by the bed density ρ_0. If we assume that the spread rate of the depth is approximately constant, h_b is given by $S_d t$. Then, the consumption per unit area can be calculated by the Eq. (5).

$$m''(t) = \int_0^t \dot{m}''(t)dt = \rho_0 S_d t \qquad \text{Eq. (5)}$$

This expression says that during a smouldering fire, and because of the in-depth spread, m'' increases linearly with time. This compares to flaming fires, where m'' is approximated as a constant because it quickly (within minutes) reaches its maximum value (see Fig. 2.10).

The final depth of burn h_0 is the maximum value reached by h_b and is determined by the instant t_{max} when the vertical spread is quenched by one of the following events: a) the presence of the mineral soil layer; b) the presence of a thick wet layer (>125% moisture content, see section *Behavior of a Smouldering Wildfire*); or c) the timing of flooding, heavy continuous rains or firefighting. This in turn determines the final biomass consumption per unit area of the fire, given in Eq. (6).

$$m''_{max} = \rho_0 h_0 = \rho_0 S_d t_{max} \qquad \text{Eq. (6)}$$

The behavior captured in Eqs (4) and (5) can be put into perspective with some approximate values. Taken the density of a bed of dry peat given in Table 1, a fire with a small depth like that in the experimental peat bed in Fig 2.5 ($h_0 = 5cm$) gives an approximately biomass consumption m''_{max} of 7.5 kg/m^2. The scientific literature reports that the final depth of burn measured in the field following a smouldering peat fires ranges from 0.1 to 1 m [Page et al 2002, Rein et al 2008, Ballhorn et al. 2009], with the most typical value being around 0.5 m. This gives m''_{max} of 75 kg/m^2. This can be

compared to the typical consumption for flaming fires where m''_{max} ranges from 0.2 to 5 kg/m². This shows that the in-depth spread through the thick soil layers that typically experience smouldering fires leads to more than two orders of magnitude (~100 times) larger fuel consumptions than that of flaming fires. For this reason and in terms of fuel consumption, these are megafires. This simple calculation has been confirmed by the field measurements of [Langmann and Heil 2004] who reported that smouldering fires of peat layers led to fuel consumption that was 90 times larger than in flaming fires of surface fuels. Needless to say that quantifying biomass consumption may represent a way to calculate the carbon emissions from a fire.

The recently introduced term *megafire* refers to very large wildfires, usually measured in terms of firepower, speed, safety threat, or suppression costs. Based on the material presented in this section, we argue than smouldering combustion leads to megafires as measured in terms of the total biomass consumed. Indeed, these are the largest fires on Earth.
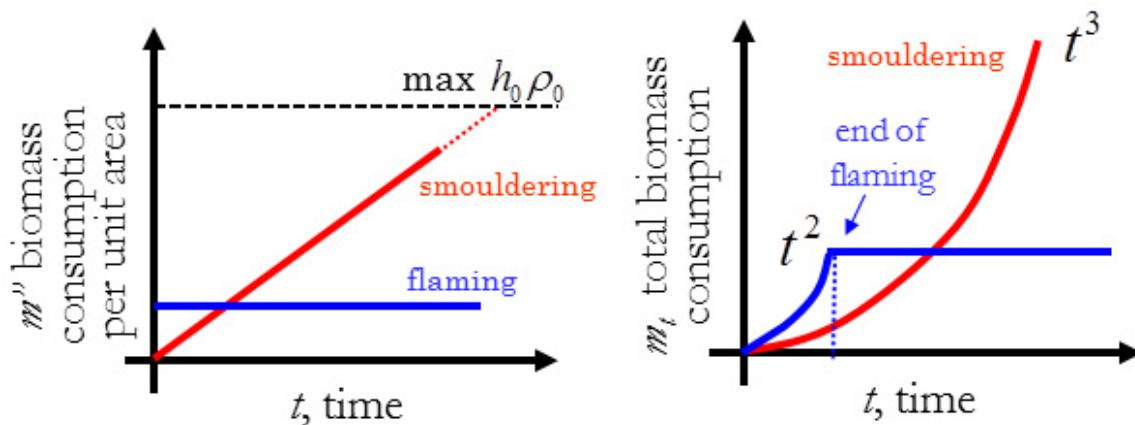
Figure 2.9. Comparison of biomass mass consumption behavior in smouldering and flaming fires. Left) Fuel consumption per unit area (Eq. 5) and its maximum value (Eq. 6). Right) Total fuel consumption (Eq. 4). By G Rein, CC BY license.

Damage to the soil

The changes to the soil produced by fires are driven by two factor: the resident time and the loss of mass. The thermal severity can be described by the temperatures reached on the soil and the residence time of this heating (Hartford and Frandsen, 1992; Rein et al 2008).

Smouldering fires can have greater detrimental effects on soil properties and soil micro-flora and -faunas because not only does the fire consume the soil (>90% mass loss) but

the long residence time of the fire means that heat penetrates deep into the soils as opposed to fast moving flaming fires which result in shallower heating [Hartford and Frandsen, 1992].

Flaming fires produce high temperatures above the ground for short periods of time (i.e. in the order of 15 min max). This results in minimal heating of the soil below depths of a few centimeters, reaching peak temperatures of 300 °C at very superficial layers (>10 mm) and below 80 °C at depths around 40 mm [Hartford and Frandsen. 1992] (see Fig 2.10). This superficial heating can leave soil and its flora and fauna relatively unharmed [Doer and Shakesby, 2012, this volume]. Note than flaming megafires spread very rapidly and at this high speed the heating of the soil could be minimal and much lower than the values given here.

However, smouldering fires lead to enhanced heat transfer to the soil for much longer durations (i.e. in the order of one hour) and peak temperatures of 500 °C [Rein et al 2008]. These thermal conditions are more severe than medical sterilization treatments, and mean that the soil is exposed to conditions that are lethal to biological systems (see Fig 2.10).
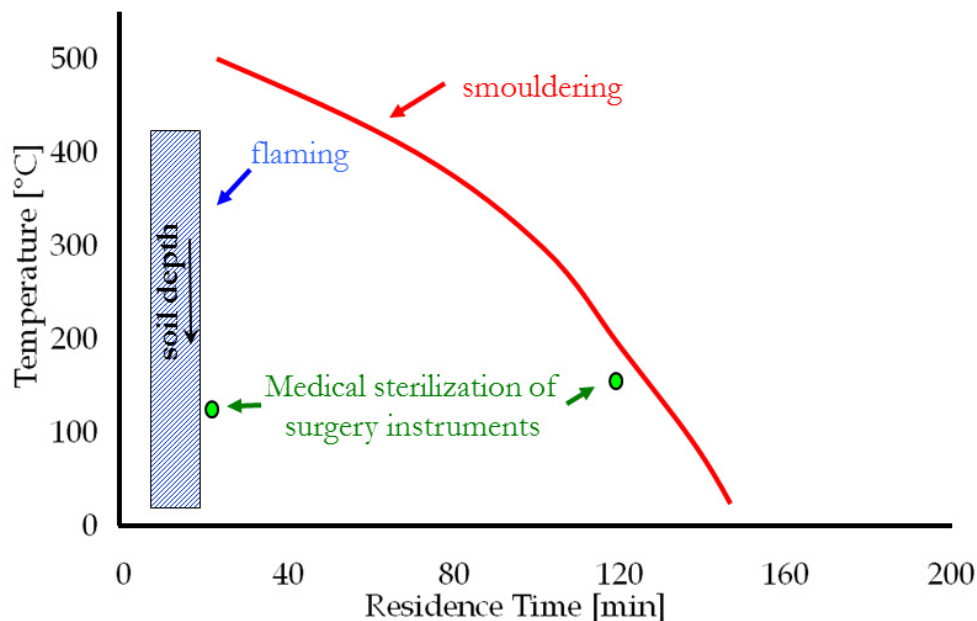
Figure 2.10. Thermal fire severity of smouldering vs. flaming measured as the average residence times above a given temperature threshold. Severity used in medical sterilization for autoclave and dry heat are included for reference. Data from [Rein et al 2008]. By G Rein, CC BY license.

Case Study: 2006 Rothiemurchus peat fire

A case of a shallow smouldering fire causing major damage to the landscape and a forest ecosystem is the wildfire that occurred in the 15 ha plantation of 40-year old lodgepole pines in Rothiemurchus near Aviemore, Scotland, during July 2006 [Rein et al 2008]. The flaming part of the fire was extinguished by the fire service in three days, but the peat underneath the forest continued smouldering for more than 40 days despite the occasional rain. To suppress it, the Fire Service with the help of the Regional Army dug a trench 5 m wide and 0.5 to 2 m deep (down to the mineral layer) around the perimeter of the fire to remove the peat and create a smouldering fire-break. Figure 2.11 shows photographs of adjacent forest stands at the fire site. While the flaming fire scorched the trees up to 1 m from the ground, and consumed some of the ground covering vegetation, the smouldering fire burned the peat up to depths of 0.5-1 m removing large quantities of the organic soil. The root systems and tree bases were by far the most affected areas by smouldering.

Figure 2.11. Photographs of adjacent forest stands from the July 2006 Rothiemurchus peat fire in Scotland, UK. The fire involved flames for three days and then smoldered for six weeks. a) Stand not affected by the fire showing the trees and the peat layer. b) The

tree trunks have been lightly charred by flames while the organic soil has been consumed down to the roots in a layer ~0.5 m by smouldering. Photos by G Rein, CC BY license.

During the field visit to Rothiemurchus after the fire, the author observed many smouldering pan-shape voids around forest stands and single trees all over the burned area. These were caused by shallow fires. One example is shown in Fig. 2.12. These were formed by the consumption of large masses of soil in approximately circular areas 0.5 to 3 m around the tree bases and exposing the mineral soil layer beneath. It was observed that soil consumption decreased with distance from the tree bases. This dependence of soil consumption on distance has been observed in other smouldering fires (see [Rein et al 2008] for a review of these). The most plausible explanation for this is that of moisture distribution. Near the bases of trees, where crown cover reduces the impact of rainfall and where roots are actively drawing up water, soil moisture is lowered and smouldering therefore stronger. When an approaching smouldering front reaches the outer edge of a root system, the fire spreads faster along the direction of the roots towards drier soils. Upon reaching the tree base, it then spreads radially from it creating the circular pattern illustrated in Fig 2.11. When trees and roots are closed together as part of a stand, the resulting pan-shape voids join and form a continuous void pattern shown in Fig. 2.12.

Figure 2.12. Photograph of pan-shape void created around the root system of a tree by the smouldering wildfire during the July 2006 Rothiemurchus peat fire in Scotland, UK. For reference, the tree is approximately 5 m tall. Photo by G Rein, CC BY license.

Smouldering fires at the Global Scale

The first smouldering phenomena reported in the scientific literature is that of the coal fires near Newcastle, UK, and documented by the Royal Society in letters written in 1673 to the eminent scientist Robert Boyle [Durant 1673]. Maybe the oldest known case of smouldering wildfire is the report from early explorers in the 19th century who observed the frequent peat fires at the Okavango Delta, Botswana [Gumbrich et al, 2002]. Indeed, dry peat is very prone to fire [Rein et al 2008], and this perturbed state makes dry peatlands probably the most flammable ecosystem on Earth. This is because peatlands in drought conditions leave a large mass of organic matter exposed to ambient air, thus leading to large smouldering fires also known as megafires. Such fires have been reported in tropical, temperate and boreal forests, and arctic tundra.

Peatlands are one of the largest reserves of terrestrial organic carbon (representing one third of the world's soil carbon [Joosten and Clark, 2002]). There are 337 Mha of peatlands within the circumpolar boreal region alone, containing 397–455 Gton of carbon [Joosten and Clark, 2002]. This large carbon pool plus that of other organic soils exceeds that of the world's forests and is comparable to the amount of carbon in the atmosphere. Peatlands play an important role in the global carbon balance and recent environmental changes, such as climate change and human activities, have raised questions regarding their vulnerability to fire.

This vulnerability was brought to the forefront of debates with the publication of the scientific study of the 1997 extreme haze event in South-East Asia. This led to the global recognition of the severe environmental and economic threats of smouldering fires and how these become a disproportionate contributor to atmospheric emissions under drought conditions. The haze was caused by the spread of smouldering megafires, mostly in the isle of Borneo, burning peat layers for months during the El Niño climate event (see Fig. 2.13). It was been estimated that these fires released between 0.81 and 2.57 Gton of carbon gases [Page et al 2002]. This is equivalent to 13-40% of global man-made emissions of the year 1997, and contributed to the largest recorded increase in atmospheric CO_2 concentration of the period. Records shows that smouldering peat fires have occurred frequently in Indonesia since 1960 [Field at al. 2009], and haze events continue to occur in South-East Asia every few years. Another landmark paper by Ballhorn et al 2009 studied the peat fires in Borneo during the 2006 El Niño and estimated that between 23 and 76 Mton of carbon were released. This number represents 10-33% of the carbon emissions from transport in the European Union. Recent figures at the global scale estimate that the average carbon gas emissions from peat megafires is equivalent to >15% of man-made emissions [Poulter et al 2006].
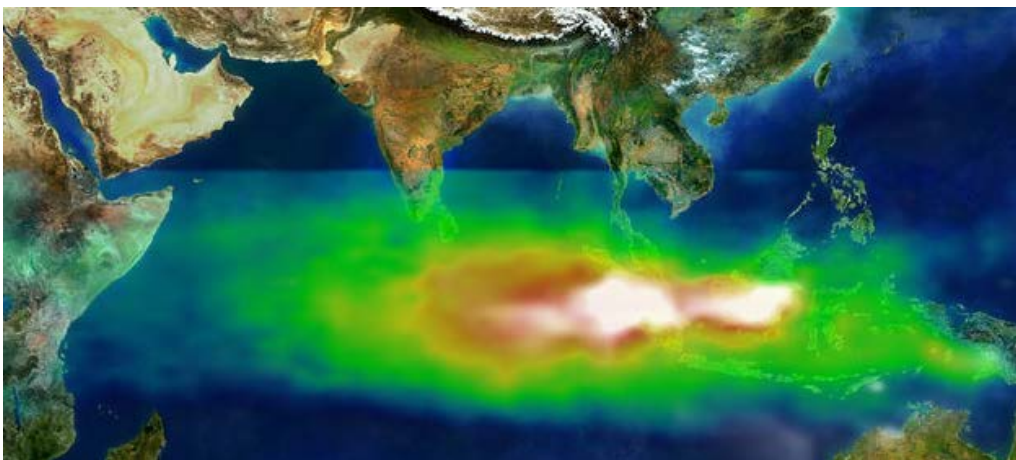
Figure 2.13. Aerosol imaging by NASA TOMS on Oct 1997 shows the vast smoke haze released by smouldering peat fires in Indonesia. Photo by NASA.

In the context of carbon budgets and global emissions, it is worth noting the role of smouldering in the case of peatlands. Undisturbed peatlands are a natural sink for atmospheric CO_2 because carbon is stored for the long term as peatlands grow. Depending on the balance between intake and loss rates, a peatland can become a net sink or a net source of atmospheric carbon. The carbon loss mechanism that receives most attention is respiration; the slow release of carbon gases (mainly CO_2) during natural peat degradation. However, smouldering fire is in reality the fastest loss mechanisms of carbon from these ecosystems. Laboratory studies have measured that the carbon emissions from smouldering peat fires are 3,000 times larger the natural respiration flux from peatlands [Rein et al 2009]. And recent field studies show that one single peat fire is equivalent to the loss of several hundred years of peat accumulation [Turetsky et al 2011].

Feedbacks in the climate system

Smouldering megafires of peatlands, the largest fires on Earth, involve the burning of an ancient carbon fuel. The term ancient is used here to imply a carbon age than is much larger than the response time of the climate system (from decades to centuries according to [Knutti et al 2008]) such that the induced greenhouse effect by its atmospheric release is complete. Peat is a sub-fossil fuel made of carbon sequestered in excess of 10k year ago. Thus, smouldering peat is a carbon-positive phenomenon in terms of greenhouse effect. This extends to smouldering coal fires [Stracher 2010], a fossil fuel representing carbon sequestered over geological timescales (millions of years).

This release of ancient carbon creates a positive feedback mechanism in the climate system, a self-accelerating process (see Figure 2.14). Warmer climates at a global scale would result in more frequent and more extensive smouldering fires worldwide from areas where warmer and drier soils are induced [Tarnocai et al. 2009]. Smouldering ignition probability and self-heating are known to be strong functions of soil moisture [Frandsen 1997, Rein et al 2008] and soil temperature [Drysdale 2011]. Also, more frequent flaming wildfires would be expected worldwide under warmer climates [Flannigan et al. 2009] and lead to more frequent residual smouldering events.

Related events are now reported in the scientific literature. Warmer temperatures at high latitudes might already be resulting in unprecedented permafrost thaw [Tarnocai et al. 2009]. Thawing leaves large carbon pools susceptible to fires for the first time since millennia.

Note the different with flaming combustion (see Fig 2.14). Flaming wildfires do not release ancient carbon because forest surface fuels are younger than the response time of the climate system. Thus, over a cycle of a flaming fire on a stand-replacing forest and

regrowth, the balance is usually carbon neutral [MG. Ryan, 2011]. Only when regeneration does not occur (deforestation), flaming fires can be carbon-positive.
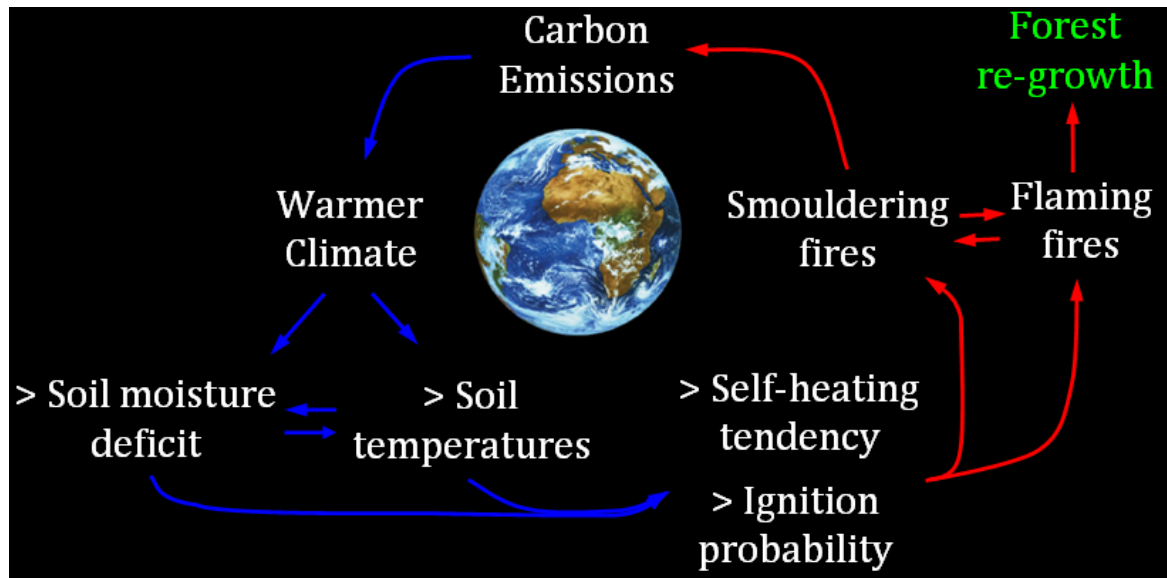
Figure 2.14. Schematic of the feedback loop between smouldering fires and climate change. Red arrows are physical mechanisms discussed in this chapter. Blue arrows are studied in the literature. By G Rein, CC BY license.

Concluding Remarks

World energy use and climate change science have led to concerns about sustainability, man-made burning of fossil fuels, and carbon emissions. Most attention is paid to energy efficiency, clean technologies and new resources. But unintentional and non-anthropogenic sources contributing to the problem have been largely ignored. Smouldering megafires, the largest and the longest burning fires on Earth, take place in in six continents, and burn ancient carbon (peat, organic soils and coal). In the current context of energy from fossil fuels and climate change, these phenomena might be best described as the *accidental burning of sub-fossil and fossil Fuels*.

While flaming wildfires have disproportionally received more attention than smouldering fires, this chapter aims at reversing the trend and hopes to bring new forward thinking efforts and ideas into the important study of flameless fires.

Preventing the accidental burning of peat and coal deposits is an engineering task at the Earth-scale. The Royal Academy of Engineering (RAEng) in the UK, states that "*geoengineering provides options in which the Earth's climate is deliberately manipulated to offset the effects of global warming due to increasing levels of greenhouse gases*" [RAEng2008]. This sounds like a very high level of geointervention in a complex system. While we come to terms to the implications of the RAEng definition,

this chapter proposes that through the study of the ignition, spread, emissions, and suppression of smouldering fires, we might aim to develop both fundamental understanding and provide technological solutions to the problem. This is perhaps best described as low-level geo-intervention geoengineering or the deliberate large-scale suppression of smouldering fires on the Earth system.

Acknowledgements

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