An experimental assessment of the ignition of forest fuels by the thermal pulse generated by the Cretaceous-Paleogene impact at Chicxulub

Abbreviated title: **K-Pg impact wildfire potential**

Authors:

Claire M. Belcher[a*+], Rory M. Hadden[b,+^], Guillermo Rein[b,] Joanna V. Morgan[c],
Natalia Artemieva[d, e], Tamara Goldin[f^],

Affiliations:

[a]College of Life and Environmental Sciences, University of Exeter, Exeter, EX4 4PS

[b]Department of Mechanical Engineering, Imperial College London, London, SW7 2AZ, UK
^now at School of Engineering, University of Edinburgh, Edinburgh, EH9 3JL

[c]Department of Earth Science and Engineering, Imperial College London, SW7 2AZ, UK

[d]Planetary Science Institute, Tucson, Arizona, 85719, USA

[e]Institute for Dynamics and Geospheres, Moscow, 119334, Russia

[f]Department of Lithospheric Research, University of Vienna, 1090 Vienna, Austria
^Now at Nature Geoscience, Nature Publishing Group, London, N1 9XW, UK

[*]**To whom correspondence should be addressed** email: c.belcher@exeter.ac.uk

[+]CMB and RMH contributed equally to this manuscript

Keywords

Cretaceous-Paleogene, impacts, asteroids, wildfires, thermal radiation

Word Counts: Text 7080 References 1428 Tables and Figure Captions 252

Abstract

A large extraterrestrial body hit the Yucatán Peninsula at the end of the Cretaceous period. Models suggest that a substantial amount of thermal radiation was delivered to the Earth's surface by the impact leading to the suggestion that it was capable of igniting extensive wildfires and contributed to the end-Cretaceous extinctions. We have reproduced in the laboratory the most intense impact-induced heat fluxes estimated to have reached different points on the Earth's surface using a Fire Propagation Apparatus and investigated the ignition potential of forest fuels. The experiments indicate that dry litter can ignite, but live fuels typically do not suggesting that any ignition caused by impact-induced thermal radiation would have been strongly regional dependent. The intense, but short-lived, pulse downrange and at proximal and intermediate distances from the impact is insufficient to ignite live fuel. However, the less intense but longer-lasting thermal pulse at distal locations may have ignited areas of live fuels. Because plants and ecosystems are generally resistant to single localized fire events, we conclude that any fires ignited by impact-induced thermal radiation cannot be directly responsible for plant extinctions implying that heat stress is only part of the end Cretaceous story.

It has been widely held that an extraterrestrial body struck the Earth approximately 65 million years ago (Alvarez et al. 1980) forming the ca. 200km wide Chicxulub crater on the Yucatan Peninsula in Mexico (Hildebrand et al. 1991) and that this must have had severe consequences for life at the time. Much of Earth's megafauna was lost at the end of the Cretaceous, yet animals suggested as being able to shelter or hibernate appear to show preferential survival (Robertson et al. 2004). One of the extreme environmental effects that follows a large impact with the Earth is the emission of thermal radiation from the hot expanding plume of vapor and debris produced immediately following the impact (Toon et al. 1997; Shuvalov & Artemieva 2002) and hot impact ejecta, as they reenter the atmosphere and decelerate (Melosh et al. 1990; Goldin & Melosh 2009). An impact-induced thermal pulse at the Cretaceous - Paleogene (K-Pg) boundary has been suggested to have resulted in the ignition of extensive wildfires (Melosh et al. 1990) and thereby explains soot found at multiple K-Pg boundary localities around the globe (Wolbach et al. 1985). However, the apparent low abundance of charcoal in the North American fossil record and the presence of abundant non-charred plant material deposited during and after the event has caused considerable debate over whether the observational evidence supports the ignition of widespread wildfires (Belcher et al. 2003; Belcher et al. 2005; Robertson et al. 2013) and the role that they may have played in the disruption to ecosystems at the time.

To date no experiments have been undertaken that directly test the ability of a transient pulse (i.e. rise, peak, decay) of thermal radiation like that delivered to the Earth's surface following the Chicxulub impact to ignite vegetation. Previous studies have compared thermal radiation estimates derived from impact physics to fire safety ignition testing data on wood (e.g. Melosh et al. 1990). However, these data are for pre-prepared non-natural state pieces of wood without protective bark that were exposed to constant heat fluxes of varying magnitudes (Simms & Law 1967) and were intended for use in fire safety assessments of the built environment. Firstly, relating experiments on barkless timber is unrealistic for application to natural wildland fuels as bark provides thermal protection. Secondly, the experimental conditions are not representative of an impact scenario as the samples were heated at a single unchanging heat flux, whereas the heat flux from an impact is expected to rise and decay with time. Moreover, ignition of thermally thin components of vegetation, such as leaves, that are easier to ignite has yet to be assessed. As such previously published fire safety data on the ignition and flammability of wood has been difficult to directly apply to the K-Pg wildfire question due to the thermally thick nature of the fuels tested and the mode of ignition used.

Using a state-of-the-art Fire Propagation Apparatus (FPA) (Fig. 1) (Tewarson 2008), we tested the potential of vegetation to ignite under the heat fluxes consistent with the estimated delivery of the K-Pg thermal radiation to the Earth's surface. The distributions of heat flux pulses around the globe were taken from the numerical simulations of Morgan et al. (2013) (see materials and methods below). Investigating the ignition of a forest fuel sample exposed to a transient heat flux pulse is novel to both fire safety science and the Earth sciences and represents a significant step forward in collaboration between our disciplines. It was our intention with the experiments to test whether the most severe estimates for thermal radiation following the Chicxulub impact were capable of igniting, or causing thermal degradation of vegetation. Numerical models of the Chixculub impact calculate that the greatest thermal pulse was in the downrange direction (Morgan et al. 2013). We have therefore recreated a selection of representative downrange model outputs, that assume no cloud cover, as we anticipated these were more likely to cause ignition of forest fuels. The aims of our experiments are to: 1) provide realistic quantitative ignition and combustion data for natural fuels 2) provide qualtitative observations of the products formed during heating of the plant samples and reconcile these with the fossil record and 3) use these datasets and observations to assess the impact that thermal radiation and or wildfires may have had on end Cretaceous plant communities.

Materials and Methods

K-Pg Thermal Radiation

We have used predictions of the thermal radiation delivered from the K-Pg impact developed by Morgan et al. (2013). The 3D hydrocode SOVA (Shuvalov 1999), which uses the ANEOS equations of state for geological materials (Thompson & Lauson, 1972), was used to model the impactor colliding with the Earth and the ejection of material away from Chicxulub (Artemieva & Morgan 2009). An impact angle of 45^{o} is used as this is the most likely angle of impact and because it can broadly reproduce the observed mass and meteoritic composition of the red clay (ejecta) layer that is found across the globe (Artemieva & Morgan 2009). Once above the atmosphere the ejecta is assumed to travel on a ballistic path and then SOVA is used to model the heating of ejecta as it travels through the atmosphere. The models provide values for the mass flux of the arriving ejecta but the particle-size distribution is unknown. The model outputs we include here are for two different scenarios in which 1) the particle size and arriving velocity are constant for the whole duration, and 2) particle size decreases and velocity increases with time, where the latter is considered to best represent the real arrival of ejecta at the top of the atmosphere. Estimates of the radiative heat flux delivered as the ejecta arrives at the top of the atmosphere are shown for distances of 2000–2500 km (proximal), 4000–5000 km (intermediate) and 7000–8000 km (distal) from Chicxulub (see Fig 2 and Fig 3), in two different directions from Chicxulub: 0-30 and 30-60 degrees azimuth (where 0 degrees is downrange). Figure 3 shows the model outputs (MO) of the thermal flux estimated to have reached the Earth’s surface from the Morgan et al. (2013) model. MO1 to MO4 are for models that treat the ejecta particle velocity and size as constant whilst, MO5 assumes that particle velocity increases and particle size decreases with time. The latter leads to an increase in both the maximum peak and duration of the thermal flux (Fig. 3c); Morgan et al. (2013) argue that this is more likely to reflect the real arrival of ejecta at the top of the atmosphere. If the same scenario of increasing velocity and decreasing particle size is applied to the outputs at intermediate distances (Fig. 3b MO3 and MO4) the resultant pulses would both have a higher peak and longer duration, and be more comparable to the pulse in MO5. The profile of the thermal radiation varies considerably with distance from the crater both in magnitude and duration. The model outputs used here are for a 45 degree impact angle, but other impact angles show the same pattern with larger peak heat fluxes of short duration (less than 1 minute) close to the impact site (e.g. Fig. 3a and 3b, MO1-3) whilst distal locations receive a lower peak flux but the flux is delivered over considerably longer duration (~ 6 minutes) (e.g. Fig. 3c, MO4-5). The heat fluxes that we have selected for flammability testing had either a high maximum peak and/or a long pulse duration as these are assumed to be the most severe.

State-of-the-art Fire Propagation Experiments

We have used the state-of-the-art FM Global Fire Propagation Apparatus (FPA) (Tewarson 2008) to investigate the ignition of a range of forest fuels (Fig. 1; Fig. 3) under the transient heat flux predicted by the impact models. The heat pulse is delivered to the sample by four halogen lamps, which can be programmed to deliver a time-varying heat flux uniformly across the surface of a sample. The FPA has been previously used to study ignition of natural fuels such as peat (Hadden et al. 2013) and pine needles (Schemel et al. 2008). Ignition by exposure to non-constant heat fluxes has previously been studied by Reszka et al. (2012) for application to polymeric materials.

The heat fluxes reproduced in the FPA for each scenario are shown in Fig. 3. In all cases, the heat flux was varied at a rate of 0.2 Hz and the data recorded at 1 Hz. There is good agreement between the heat flux delivered (as measured by a water cooled heat flux meter) and the numerical model. For the proximal case [Fig. 3a Model Output 1 (MO1)], the measured experimental heat flux is marginally lower than the maximum predicted by the numerical model (due to the time required for the lamps to stabilize at a given heat flux). The intermediate scenarios (Fig. 3b MO2-3) show similar behaviour. There is a small lag and the maximum heat flux is slightly lower than the modelled value but there is generally good agreement. During the cooling phase, the heat fluxes are slightly higher than those predicted by the model. The longer durations and lower peak of the distal cases (Fig. 3c MO4-5) mean that there is better agreement both temporally and with respect to the heat flux magnitude.

Dried and live, thermally thin (leaves and needles) and thermally thick (wood) samples were tested. Thermal thickness is commonly used to refer to the ease of ignition of a solid fuel. A thermally thick fuel is one in which there exists a temperature gradient across the solid upon heating of one surface. Conversely, for a thermally thin fuel, any temperature gradient across the solid is negligible and the fuel will be easier to ignite than a thermally thick sample because the heat losses into the sample are lower and less energy is required to reach the ignition temperature. Thermally thick and thermally thin fuels and living vs dried fuels represent the extremes of the range of possible fire behaviour. Therefore, by testing these fuels we are able to provide a realistic and broad assessment of the ability of the downrange K-Pg thermal pulse to ignite forest fuels.

In total, five fuels were tested: two dry leaf litters from *Pinus pinaster* (PP) and *Quercus robur* (Q), live forest canopy type fuels of *Pinus sylvestris* (PS) needles and dry woody biomass represented by dry *Populous tremuloides* (PT) and *Picea glauca* (PG) branch fragments (wood including bark). Dry litter was chosen as fuels of this nature are the easiest to ignite while live needles and small branches were tested to explore the effect of the heat flux on living and thermally thick forest material respectively. All samples contained <10% moisture except for the live PS needles that were 16.2% moisture. Wood samples were approximately 8cm long and 2cm wide and one stick of each was used per test. Fuels were placed in a porous sample holder in a manner that simulated their natural litter density; equal volumes of litter fuel were tested in each case. All fuel and heat flux ramp combinations were tested in duplicate and in some cases triplicate. There was a high degree of reproducibility between the tests (see Table 1).

All experiments were filmed and still pictures taken of the samples before and after exposure to the heat flux pulses. Samples were weighed before and after each test and in addition, the mass loss was also recorded in real time (Table 1). No pilot flame or spark ignition source was used in these tests, as would be the case for ignition by thermal radiation generated by the impact.

Results

The reaction of a solid fuel to an imposed heat flux will fall into one of the following categories: drying (no ignition), pyrolysis (no ignition, endothermic, thermal degradation releasing pyrolysate vapours), smouldering ignition (pyrolysis and heterogeneous oxidation reactions on the solid surface), sustained smouldering combustion (smouldering that persists after the external heat flux is terminated) or flaming combustion (autoignition of the pyrolysate vapours) (Hadden et al. 2013). Figure 4 serves as a visual guide as to what remained of the plant samples tested according to the five thermal flux scenarios. The results in Table 2 indicate that both the magnitude and duration of the thermal flux is important in determining the ignition behaviour of the sample. The long duration of the pulse created by the model scenario in which ejecta re-entry velocity increases and particle size decreases over time (Fig. 3c, MO5) led to flaming ignition in dry leaf litters of PP and Q and in live PS needles. Moreover, it led to self-sustained smouldering in both wood types as well as considerable pyrolysis and charring indicating heterogeneous oxidation of these fuels. Therefore, both the magnitude and duration of the pulse must be considered when assessing the severity of the heat flux received at the fuel surface. Consequently this (e.g. MO5) suggests that surface fires could have been ignited at both distal and intermediate locations downrange and would lead to a more detrimental effect on ecosystems.

For those scenarios that assumed constant particle velocity and size (MO1-4) both the proximal and intermediate downrange scenarios resulted in flaming combustion of the dry litter fuels although the onset of flaming ignition took around twice as long in the intermediate 30-60^{o} scenarios MO2-3 (Fig. 3b) (see Table 1). Nevertheless the post-exposure plant remains appear visually the same for both the proximal and intermediate scenarios irrespective of time taken to ignite (e.g. Fig. 4). Smouldering of the wood samples exposed to MO2 resulted in the surface of the wood appearing charred (Fig. 4) with the presence of some ash. In all other constant particle velocity and size scenarios the wood samples, despite undergoing some pyrolysis, remained essentially non-charred (Fig. 4). All live fuel samples experienced drying and a degree of pyrolysis leading to a small amount of charring of the topmost needles but the bulk of the fuel was left un-charred (Fig. 4) except in the case of increasing particle velocity with decreasing particle size (MO5), which resulted in flaming ignition.

Discussion

The nature of K-Pg wildfires

These data indicate that there is potential for ignition of plant material in the downrange impact direction. However, it is clear that the extent and nature of wildfires is dependent on the distance from the impact and assumptions made regarding the re-entry of ejecta. Flaming ignition was observed in most of the dry litter tests (except the distal scenario with constant velocity and particle size Fig. 3c MO5) and because smouldering fires can transition to flaming (Rein 2013) our results reveal that surface fires could have been ignited in dry litter fuels at large distances downrange from the impact. These fires may transition to crown fires under the correct conditions. However, the current state-of-the-art limits our predictive capability estimate the potential for surface fires to transition to crown fires and would require reconstruction of major end-Cretaceous ecosystems including tree architecture, forest spatial arrangement and canopy bulk density. Our results show however, that live fuels, even those that are considered most flammable (e.g. resin rich *Pinus sylvestris* in our test case) are resistant to direct ignition in most cases. This strongly implies that the relatively short duration of the thermal flux, delivered to locations proximal to the crater, may not have directly ignited crown fires (entire forests), despite high peak heat fluxes.

The ignition behaviour observed in our experiments is consistent with the fossil record of the Western Interior of North America. For example the K-Pg rock layers at Teapot Dome in Wyoming contain clumps of pollen from four angiosperm pollen types. It is suggested that these monotypic pollen clumps represent failure to be dispersed from the anther in the flower indicating that the anther fragments themselves were shed from the plant suggesting a disruption to the normal life cycle of plants (Spicer & Collinson 2014). These clumps are of significance to fires in so much as flowers and their reproductive parts (e.g. anthers) are fragile and would not likely be capable of surviving a crown fire, implying that high intensity crown fires cannot have been ignited at this location. This is consistent with our experimental observations that suggest that live fuels cannot be ignited by the heat flux received at this distance from Chicxulub and implies that any locally ignited surface fires did not transition to crown fires in this area. Moreover, the remains shown in figure 4 are interesting in the context of the fossil record of the Western Interior because, whilst it shows the destruction of dead and dry litter by the K-Pg thermal radiation, it reveals little destruction of live fuel and woody material and little charring. Therefore it is likely that a spectrum of products would be formed as a result of the thermal radiation pulse acting on vegetation. This would include non-charred remains as well as the formation of char and ash and would be highly dependent on the nature and moisture content of the fuel available in the ecosystem at time of the impact as well as the sites distance from the impact. These observations are consistent with the fossil record of plant remains found within and just above the K-Pg event horizon in North America (Belcher et al. 2003; Belcher et al. 2005). The K-Pg rock layers contain on average 225 particles of mesofossil charcoal particles per cm^3 and 48,956 non-charred particles per cm^3 (calculations assuming a unit surface area of $1cm^2$, rock thickness 1.5cm and density $2.5gcm^3$).

The distal scenario with increasing velocity and decreasing ejecta size (MO5 Fig. 3c) was shown to have the ability to ignite live fuel and led to self-sustained smouldering in wood, implying that crown fuels could potentially be ignited. It should be noted however, that increased moisture content of both litter and crown fuels, above those that we have tested, would strongly decrease the probability of fire ignition and spread, such that wildfires might be quite limited, even in the worst-case downrange scenarios tested. The more severe pulses at distal locations downrange from Chicxulub may have been most detrimental in terms of thermal damage to plants. Because our experiments reveal that both the duration and intensity of the thermal pulse determine the effect on the fuel future work should fully consider local wildfire markers, ecosystem structure, plant species and moisture content at distal locations in order to test this hypothesis.

Wildfires and disruption to Earth's flora at the K-Pg

The extent to which the K-Pg thermal radiation and/or wildfires would have the ability to cause extinctions in land plants is debatable, particularly as by nature plants are typically well adapted to physical destruction (Wing, 2004). Wildfires occur every day on our planet, with at least 40% of Earth's modern ecosystems being considered fire prone (Bond et al. 2005). Wildfires were a common feature of the Cretaceous landscape based on the high abundances of fossil charcoals found in rocks from this period (Belcher et al. 2005; Glasspool & Scott 2010; Brown et al. 2012). Moreover, high fire frequencies in the Cretaceous appear to have driven plant adaptations to fire at this time; for example *Pinus* have been shown to evolve the fire adaptive traits of thick bark and serotinous cones between 129 and 89Ma (He et al. 2012), implying that some plants were becoming increasingly adapted to fire throughout this period. Our experimental results imply that surface fires could have been ignited in areas where litter was seasonally dry, but that at proximal and intermediate distances from the impact direct ignition of canopy fuels was unlikely. Surface fires in modern ecosystems are generally considered less destructive than crown fires, which typically cause mass mortality in forests, but not ultimate destruction of the ecosystem; for example some species like Black Spruce require stand replacement fires (Johnstone et al. 2009). It seems likely that those plants that had evolved serotiny for example would have shed their seeds if ignited by the thermal flux delivered from the impact ejecta ready to re-grow. This highlights that plants do have traits that allow them to resist the impacts of fires and therefore also likely the K-Pg thermal pulse. Resistance traits include thick insulating bark that provides effective insulation against heat. Bark thickness has been shown to be a dominant factor in determining the extent of living tissue damage in fires (van Mantgem & Schwarz, 2003). An example species with fire protective thick bark is *Sequoiadendron giganteum*, which has a long fossil record. Thick bark is also believed to have evolved in *Pinus* around 129 Ma (He et al. 2012) both observations imply that trees with thick bark did exist in the Cretaceous. Some trees today (e.g. eucalypts) have insulated shoots within their trunks, this provides protection of the shoots against fire which then grow after damage to the tree, enabling new vegetative regrowth of the plant (Davies, 2013). Our experiments indicate that the thermal pulse was not capable of igniting small dead bark covered branches (Fig 4) and in many cases these underwent little pyrolysis, suggesting that the thermal pulse likely inflicted minimal damage to living woody tissue and that vegetative regrowth would have been possible assuming the post impact conditions were conducive. Vegetative regrowth is not only restricted to trunks; many plants can grow from rhizomes buried deep in the soil. Soil is highly insulating and protects rhizomes from thermal damage. For example, ferns today are capable of high productivity by vegetative regrowth from rhizomes alone, this strategy is observed in the earliest Paleocene evidenced by a fern spore spike in the rock record (Spicer 1989). Therefore, vegetative regrowth likely occurred relatively rapidly after the impact implying that the thermal pulse with or without local fires did little damage to either buried rhizomes and/or spore and seed banks.

Trees that shed their lower branches are able to lower their risk of crown fires by removing “ladder fuels” which prevents more easily ignitable surface fires climbing to the canopy. Whole branch apoptosis has been present in some conifers since the Permian (Looy, 2013) implying that such trees may have means to mitigate the risk of any surface fires ignited by the impact transitioning to crown fires. Plants also exhibit traits that allow them to persist after fires even if the parent plant itself is killed. Serotiny (mentioned above) is a form of canopy seed storage where seeds are only dispersed after the fruiting structure (often a cone) is burnt or heated. Serotiny is present in both gymnosperms (e.g. *Pinus*) dating back at least as far as the Cretaceous (He et al. 2012) and angiosperms (e.g. *Banksia*) dating back at least as far as 60.8 Ma (He et al. 2011). Plants that have large seed banks, which are capable of germinating after fires are more likely to survive and many plants possess very long-lived seeds which can survive in the ground in some cases for centuries (Spicer & Collinson 2014). However, we note that fire adaptations are difficult to prove in the fossil record at present although there is a growing body of evidence supporting the idea that our ecosystems have had fire adaptations dating back 100s of millions of years (e.g. He et al. 2012) and possibly as far back as the Permian (Looy, 2013). Changes to fire frequency and/or fire regime are typically more likely to cause lasting ecosystem changes than individual fire events alone. Therefore, whilst it is difficult to assess the individual characteristics of any localised surface fires that may have been ignited in downrange end Cretaceous ecosystems, because plants can resist and persist it seems unlikely that fires or thermal stress would be capable of causing extinctions in plants alone.

Effect of thermal pulse on end Cretaceous vegetation

It is clear that land plants were regionally disturbed at the K-Pg (Spicer, 1989; Wing, 2004). For all downrange thermal flux scenarios, significant heat induced dessication, necrosis and, in some cases, pyrolysis of live fuels was observed in our experiments. Together these would likely have the ability to a) induce mass mortality (although not extinction) in forests and b) increase the probability of surface fires to transition to crown fires and/or the likelihood of dry forests being ignited later by other ignition mechanisms such as lightning (Shuvalov & Artemieva 2002). It seems that irrespective of whether wildfires were ignited that ecosystems were likely subjected to heat-induced desiccation, causing necrosis, particularly of leaves. The fraction of a tree's canopy that is killed is important in determining its survival (Wickman 1978). Fig. 5 highlights the ability of trees to survive a large volume of canopy kill; 80% of a tree's crown can be killed and it might still have a 50% chance of survival. We cannot estimate the extent of canopy kill from our experiments as this would depend on knowledge of forest canopy structure as well as estimates of heat penetration and shielding properties from canopy tops through to the forest understory. Such parameters would be ecosystem specific and may help explain the regional variations in rates of recovery following the K-Pg events. It appears however, that plants suffered less in wetland settings (swamps, mires and river flood plains) than for plants that grew in better-drained sites (Nichols & Johnson 2002; Johnson 2002; Hotton 2002; Wing 2004). This implies that the spatial distribution of ecosystems according to their environment, as well as the distribution of the thermal flux across the Earth's surface, are key criteria in determining the influence of the thermal pulse. It seems likely that wetland ecosystems would be less likely to suffer desiccation and necrosis and our results imply that live fuels, which are still moist, and therefore also ecosystems with moist litter layers would be relatively resistant to ignition of surface and crown fuels. It may be that wetland settings formed refugia of relatively unscathed communities and assisted with post-impact recolonisation.

Plant habit also appears to have influenced survival. Of note is the suggestion that deciduous plants appear to have fared better than their broad-leaved evergreen counterparts (Spicer 1989). It might be expected that deciduous trees could be better adapted to sudden canopy kill as they are able to survive long periods of dormancy over the winter months. Such survival may depend on the timing of the impact where deciduous trees preparing to enter a period of dormancy (e.g. autumn-fall) would be less likely to feel the effects of thermal necrosis than trees leafing out in spring. Plant extinction overall is estimated to be 75% in southern North America (~ 2500km from the impact) whilst extinction in the northern parts of North America is of the order of 24% with the Arctic and Antarctic apparently un-disturbed (Spicer 1989; Spicer & Hermann 2010). This is at odds with the thermal flux delivered to these zones where proximal locations (~2500km) received an overall lower thermal flux than locations at intermediate (4000-5000km) distance from Chicxulub, yet overall proximal locations indicate higher rates of floral extinction. This pattern is not unexpected because shock from a single phase of thermal stress with or without localised wildfires cannot generate mass extinctions in plants. The apparent wholescale dieback of plant communities in New Zealand (Vajda & McLoughlin 2004) does however, appear to be more consistent with the prolonged duration and therefore high total heat flux delivered to distal locations (7000-8000km away), it may be that enhanced fire severity in this area made recovery more difficult in the post-impact world. Vajda et al. (2001) suggest that the nature of extinctions and the floral recovery in New Zealand is more consistent with an "impact winter" scenario implying that enhanced destruction of vegetation by the thermal pulse shortly followed by darkness and cold may have strongly affected the normal ecological succession that would be expected after a fire or thermal stress. It is possible that soot from a significant number of local fires in the downrange direction could have added additional aerosols and soot to the already large volume of dust and aerosols ejected by the impact into the atmosphere. However, more accurate estimates of fire type and distribution would be required to assess the addition of fire-derived soot to the K-Pg atmosphere.

Our data supports that the idea that the thermal flux was detrimental to terrestrial ecosystems however, it seems unlikely that such a kill mechanism can lead to mass extinction in plants. Individual wildfires and their associated thermal flux to vegetation today do not typically kill whole ecosystems implying that other factor(s) appear to have disrupted the recovery of thermally affected ecosystems ultimately leading to the floral extinctions observed. Such observations highlight that consideration of location and plant palaeoecology is essential in disentangling the nature and patterns of floral extinction at the K-Pg because the spatial distribution of total floral extinctions shows no clear relationship to the thermal flux delivered alone. It appears that thermal shock and/or dispersed wildfires are just a part of the K-Pg story.

Indirect effects of thermal stress and wildfires on plant communities

The influence of thermal stress with or without wildfires on vegetation is unlikely to be directly capable of causing extinctions in plants. However, indirect effects of the thermal pulse may also have played a role in loss of plant taxa across the K-Pg. A large number of plant extinctions appear to be in zoophilous (particularly entomophilous) groups (Spicer & Collinson 2014). This is evidenced by significant alterations in palynofloral provinces across the K-Pg with a sudden loss of the

Aquilapollenites province (e.g. Bramen & Sweet 2012) within a few centimetres of the event horizons. The grains distinguishing the *Aquilapollenites* are typically large and thick-walled, features typical of pollens dispersed by animals (Spicer & Collinson 2014). Conversely the late Cretaceous *Normapolles* show gradual evolutionary changes moving into the Paleocene. *Normapolles* might be best considered similar to modern Amentiferae which today yield catkins and are wind pollinated. This opens up the possibility that loss of insect diversity in association with the K-Pg events may have had a positive feedback on the demise of certain plant groups.

Our experimental data suggests that land plants, downrange of the impact, would have suffered thermal shock following the impact and that surface fires may have been ignited assuming the abundance of the correct fuel loads (e.g. dry litter). The responses of insects to fire today (and therefore also likely thermal stress) tend to relate to the degree of exposure or shelter from lethal temperature, amount of stress experienced in the post fire environment before full vegetation regrowth, suitability of the new regrowth as a habitat and their ability to rebuild numbers at a site (Swengel 2001).

Insect populations have been shown to decline markedly after a fire. This decline can continue over several weeks post fire such that mortality occurs in a “shock phase” afterward from both exposure and starvation (Swengel 2001 and references therein). Such events have been reported to lead to extirpations (local extinctions) for specific populations of a few insect species (Swengel 2001). In particular specialist butterfly (pollinator insects) have been observed to become significantly reduced in density over the intermediate term following fire. Insects that are most effected tend to be those dependent on plant structures, such as flowers or fruits that may not regrow for several years after large fires and can remain effected for several generations (Swengel 2001).

There is evidence for disruption to insect communities in response to the K-Pg events. Herbivorous (non pollinator) records show a complete loss of specialised feeding damage on leaves across the K-Pg until the first million years into the Paleocene across most of N. America (Labandeira et al. 2002) although this pattern is not repeated across Europe, Argentina and New Zealand that suggest rich insect damage diversity in the earliest Paleocene (Wappler et al. 2009). This enhanced destruction of insect feeding closer to the impact and decreased depression at distal sites seems rather at odds with the distribution of thermal of radiation. However, these more distal data are from Paleocene sites (e.g. Menat is dated at ~61 Ma) so whilst they argue for good recovery they are not best placed to address extinction and loss of diversity at the K-Pg directly.

Butterflies (pollinators) are believed to have originated before the K-Pg with the Nymphalidae diversifying in the Late Cretaceous (Wahlberg et al. 2009). Molecular studies suggest that around 60% of butterfly lineages became extinct at the K-Pg. It seems likely that butterflies would not fare well in a thermal pulse, being fragile and not easily able to shelter. This does not preclude those in the pupae or egg stage surviving that could have found potential shelter. For example insects that are immature or flightless and that dwell in litter layers, soil or in bark and hollows often tend to be less exposed to fires (Swengel 2001). However, even if their immature stages survived, butterflies are ectothermic and are dependant on warmth from the sun implying that recovery from eggs/lavae in a possible impact winter would be problematic. Such data does not provide evidence as to the nature of the decline i.e. stepwise or sudden but does suggest that pollinators were affected by the K-Pg events and appears to show some relation to the decline in zoophilous plant taxa.

Pollinator insects tend to be flying insects. Flying insects typically recover rapidly after individual fire events by recolonising from nearby unburnt areas (Swengel 2001). However, in the case of the high thermal flux imposed across much of the globe the K-Pg presents a special case of no-where to hide, implying flying insects, often pollinators, would likely have been severely disrupted in the direct aftermath of the impact. Interestingly the timing of the impact might strongly influence insect demise. Several studies suggest that overwintering insects are less susceptible to fires (and we therefore also assume a thermal pulse) than when they are active in the spring and summer months. Therefore estimating the timing of the impact is of strong relevance to understanding the ecological consequences of the impact. Recent reassessment and additional data from the Teapot Dome locality (northern hemisphere) implies that angiosperms were in flower at the time of the impact owing to the shedding of pollen clumps from anthers which are preserved in the K-T rock layers. This may suggest that the impact occurred at the end of the flowering season (Spicer & Collinson 2014). This might also be supported the observation that deciduous plants appear to have suffered less which might be expected if the trees were coming towards the end of the growing season (late summer) (Spicer 1989). These small but perhaps significant observations may suggest that the impact occurred during the northern hemisphere's warm months, which would mean that the impact would have had maximum impact on insect communities in this hemisphere. Observations of management practices on insect populations indicate that cutting or mowing of plants in the summer causes greater insect declines than in spring or autumn, where summer cutting reduces the abundance and diversity of feeding and breeding sites (Swengel 2001 and references therein). Therefore mortality of plants either due to heat induced necrosis with or without additional wildfires would likely have an indirect effect on insect abundance that could persist for a relatively sustained period.

It seems likely that the direct effects of thermal stress with or without wildfires on insects including pollinators would have been detrimental to insect numbers and that indirect effects on ecosystem and habitat destruction following thermal shock and continued post impact environmental stresses ought to have had a profound effect on insect numbers. This may have fed back into the decline in pollination potential for zoophilous plants and could implicate thermal stress and fires indirectly in the demise of some land plant taxa as part of the K-Pg events. It should be noted however, that many plants possess the ability to self fertilise and can vegetatively reproduce (Spicer & Collinson 2014) thus recovery may have been possible even with a loss of pollinators. It seems likely that it was the chain of events at the end of the Cretaceous and into the earliest Paleogene that led to the losses in biodiversity observed and that no single mechanism can be attributed alone.

Relevance of our experiments to the K-Pg and future directions

Previous research has briefly drawn on data relating to the piloted ignition of non-natural state pieces of wood to suggest the likelihood of ignition of plant materials by the K-Pg thermal flux (e.g. Melosh et al. 1990). Our experiments have sought to build on this by testing small branches of wood still covered with bark as well as leaves in both litter and live form. This covers a broad range of physical properties from thermally thick to thermally thin fuels. Hence, in this intital study, we have treated our fuels more theoretically rather than choosing to directly testing analogue Late Cretaceous species. In this manuscript we have sought to provide realistic baseline data for the ability of the worst-case estimates of the K-Pg thermal radiation, in the downrange direction, to ignite natural forest fuels. We have developed a methodology to determine the ignition behavior of forest fuels exposed to a time-varying heat flux pulse. We have studied a range of fuels from both live and dead/dry thermally thin plant materials to dead thermally thick materials to ensure a broad range of fuel types in this initial study. We have further observed whether the thermal flux applied is able to pyrolyze (char) the materials or whether flaming or smouldering combustion occurs leading to consumption of the fuel. We have then assessed what remains in order to reconcile this with the fossil record. This provides a novel dataset that, for the first time, allows us to provide a comprehensive starting point for understanding the role that the thermal radiation delivered by the K-Pg impact at Chicxulub may have had upon plant communities and upon which further explorations can be made.

Our thermally thin fuels were leaves in the form of litter (dry) of both *Pinus pinaster* and *Quercus robur* and live needles of *Pinus sylvestris*. Our bark covered woody biomass was *Populus tremuloides* and *Picea glauca*. Although these are not species dominant in Cretaceous ecosystems (some of these families were regionally abundant particularly at more distal locations (e.g. China and Japan; Spicer & Collinson 2014) and hence may be partly relevant analogues for areas that received a high thermal flux). Moreover, it is known that the physical form of a fuel is a significant factor in determining the response to a thermal exposure. Therefore our results, allow the first realistic insight into the likelihood of ignition in fuel types after the K-Pg impact event. We plan to build upon the data presented herein and extend our experiments to analogue genera dominant in key Cretaceous ecosystems and by expanding the parameters that we measure. This research has indicated that areas that would have had dry litter could be ignited by the estimated levels of thermal radiation delivered by the impact event in the downrange direction. Whereas, in most cases, live fuel could not. The possibility of ignition therefore warrants further more detailed studies that should consider how plant/litter type and fuel moisture might have influenced the behaviour of those fires. Moreover, the ability of the thermal pulses to ignite fuels that typically undergo smouldering combustion (such as peat) will also be important to consider the effect of the pulse on wetland ecosystems. This would enable data to be gathered that is more specific to individual Late Cretaceous ecosystems.

Ignition is not the only descriptor of a material’s flammability in fact a whole range of dynamics are required to express fires behavior in an ecosystem. Future work should consider ignition as well as differences in the heat release rate and total heat release for Late Cretaceous analogue taxa in order to build a more complete picture of both heat induced plant trauma and/or the behaviour of wildfires following the impact. Such information could enable estimates of fire spread and fire severity to be made providing a better understanding of the direct environmental consequences of the K-Pg thermal flux.

Conclusions

We have been able for the first time to recreate model predictions of the thermal flux delivered around the globe by the K-Pg impact in the laboratory. This has enabled us to present the most complete experimental analysis of the ability of the K-Pg impact at Chicxulub to ignite forest materials to date. In contrast to previous work that over-simplified the fall-back of high velocity ejecta around the globe in predictions of thermal radiation, our experiments incorporate recent numerical modelling that suggests that the magnitude and duration of the heat flux pulse received by the Earth's surface would have varied with both distance and direction from Chicxulub. Consequently, our methodology and results are able to assess long-standing debates regarding the ignition of forest fuels at the K-Pg boundary.

Our results show that the chance of live fuels being ignited may increase with distance from the impact crater and that enhanced dessication and charring might be expected, at more distal sites. This is because a lower but prolonged thermal pulse has a more severe effect than a rapid high thermal pulse. The thermal pulses at distances proximal to and at intermediate distances from Chicxulub were likely insufficient in duration to ignite canopy fuels. However, the long duration of the thermal pulse at distal locations may have been capable of igniting crown fires. Our experimental results suggest that where dry litter was available, that surface fires may have been ignited locally in the downrange direction at proximal through to distal locations. However, it is currently beyond the state-of-the-art to accurately predict whether any surface fires could have transitioned to crown fires in a desiccated canopy. We further highlight that the impact models that we selected to recreate in the laboratory are the most severe fluxes predicted in the downrange direction and therefore that our results represent an absolute worst-case K-Pg scenario. This highlights that ignition of vegetation outside the downrange area is strongly unlikely. None-the-less our experiments imply that "global firestorms" (Robertson et al. 2013) were not an immediate consequence of the K-Pg impact, and we argue that local wildfires and a single phase of thermal stress cannot lead directly to mass extinctions in plants. What these data do imply is that the thermal radiation likely had distinctly regional effects, which coupled to observations of plant palaeoecology and analyses of the post impact environment may assist in making future interpretations of extinction and survival of terrestrial life at this time.

Acknowledgements

We thank Bob Spicer, Gary Upchurch and Vivi Vajda for their useful reviews that assisted us in improving this manuscript. CMB acknowledges funding from a Marie Curie Career Integration Grant (PyroMap PCIG10-GA-2011-303610) and a European Research Council Starter Grant ERC-2013-StG-335891-ECOFLAM and The Univeristy of Exeter. JVM acknowledges funding from the Leverhulme Trust. GR and RMH acknowledge EPSRC Doctoral Prize funding from Imperial College London. TG acknowledges funding from the Lise Meitner Program of the Austrian Science Fund (FWF). We also acknowledge the influence of Elisabetta Pierazzo, who passed away during the early phases of this research, whose drive to “Bridge the Gap” between Geologists, Modellers and Experimentalists, influenced the conception of this research.

References

Alvarez L.W. Alvarez, W. Asaro, F. & Michel, H.V. 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science*, **208**, 1095-1108.

Artemieva, N.A. Morgan, J.V. 2009. Modeling the formation of the K-Pg boundary layer. *Icarus*, **201**, 768-780.

Belcher, C.M. Collinson, M.E. Sweet, A.R. Hildebrand, A.R. & Scott, A.C. 2003. “Fireball passes and nothing burns”- The role of thermal radiation in the K-T event: Evidence from the charcoal record of North America. *Geology*, **31**, 1061-1064.

Belcher, C.M. Collinson, M.E. & Scott, A.C. 2005. Constraints on the thermal power released from the Chicxulub impactor: new evidence from multi-method charcoal analysis. *Journal of the Geological Society of London*, **162**, 591-602.

Bond, W.J. Woodward, F.I. & Midgley, G.F. 2005. The global distribution of Ecosystems in a world without fire. *New Phytologist*, **165**, 525-537.

Braman, D.R. & Sweet, A.R. 2012. Biostratigraphically useful Late Cretaceous-Paleocene terrestrial palynomorphs from the Canadian Western Interior sedimentary basin. *Palynology*, **36**, 8-35.

Brown, S.A.E. Scott, A.C. Glasspool, I.J. & Collinson, M.E. 2012. Cretaceous wildfires and their impact on the Earth system. *Cretaceous Research*, **36**, 162-190.

Davies, G.M. 2013. Understanding fire regimes and the ecological effects of fire, *in* Belcher, C.M., eds., Fire phenomena and the Earth system an interdisciplinary guide to fire science, wiley Blackwell, p. 97-124.

Gardner, J.J. & Whitlock, C. 2001. Charcoal accumulation following a recent fire in the Cascade Range, northwesten USA, and its relevance for fire-history studies. The *Holocene*, **11**, 541-549.

Glasspool, I.J. & Scott, A.C. 2010. Phanerozoic atmospheric oxygen concentrations reconstructed from sedimentary charcoal. *Nature Geoscience*, **3**, 627-630.

Goldin, T.J. & Melosh, H.J. 2009. Self-shielding of thermal radiation by Chicxulub impact ejecta: Firestorm of fizzle? *Geology,* **37**, 1135-1138.

Hadden, R.M. Rein, G. & Belcher, C.M. 2013. Study of the competing chemical reactions in the initiation and spread of smouldering combustion in peat. *Proceedings of the Combustion Institute,* **34**, 2547-2553.

He, T. Pausas, J.G. Belcher, C.M. Schwilk, D.W. & Lamont, B.B. 2012. Fire-adapted traits of Pinus arose in the fiery Cretaceous. *New Phytologist,* **94**, 751-9.

He, T. Lamont, B.B. & Downes, K.S. 2011. Banksia born to burn. *New Phytologist*, **191**, 184-196.

Hildebrand, A.R. Penfield, G.T., Kring, D.A., Pilkington, M., Camargo, A., Jacobsen, S.B., & Boynton, W.W. 1991. Chicxulub crater: A possible Cretaceous-Tertiary boundary impact crater on the Yucatan Peninsula, Mexico. *Geology*, **19**, 867-871.

Hotton, C.L. 2002. Palynology of the Cretaceous-Tertiary boundary in central Montana: evidence for extraterrestrial impact as a cause of the terminal Cretaceous extinctions. *In*: Hartman, J.H. Johnson K.R. & Nichols D.J. (eds) The Hell Creek Formation and the Cretaceous-Tertiary boundary in the northern Great Plains: an integrated continental record of the end of the Cretaceous. Geological Society of America Special Papers, **361**, 473-502.

Johnson, K.R., 2002. Megaflora of the Hell Creek and the lower Fort Union Formations in the western Dakotas: vegetational response to climate change, the Cretaceous-Tertiry event, and rapid marine transgression. *In*: Hartman, J.H. Johnson K.R. & Nichols D.J. (eds) The Hell Creek Formation and the Cretaceous-Tertiary boundary in the northern Great Plains: an integrated continental record of the end of the Cretaceous. Geological Society of America Special Papers, **361**, 329-392.

Johnstone, J. Boby, L. Tissier, E. Mack, M. Verbyla, D. & Walker, X. 2009. Postfire seed rain of black spruce, a semiserotinous conifer, in forests of interior Alaska. *Canadian Journal of Forest Research*, **39**, 1575-1588.

Labandeira, C.C. Johnson, K.R. & Wilf, P. 2002. Impact of the terminal Cretaceous event on plant-insect associateds. *Proceedings of the National Academy of Sciences*, **99**, 2061-2066.

Looy, C.V. 2013. Natural history of a plant trair: branch system abscission in Paleozoic conifers and its environmental, autecological, and ecosystem implications in a fire-prone world. *Paleobiology*, **39**, 235-252.

McGhee Jr, G.T. Sheehan, P.M. Bottjer, D.J. & Droser, M.L. 2004. Ecological ranking of Phanorozoic biodiversity crises: ecological and taxonomic severities are decoupled. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **211**, 289-297.

Melosh, H.J. Schneider, N.M. Zahnle, K.J. & Latham, D. 1990. Ignition of global wildfires at the Cretaceous/Tertiary boundary. *Nature,* **343**, 251-254.

Morgan, J.V. Artemieve, N. & Goldin, T. 2013. Revisiting wildfires at the K-Pg boundary. *Journal of Geophysical Research: Biogeosciences,* **118**, 1508-1520.

Nichols, D.J. & Johnson, K.R. 2002. Palynology and microstratigraphy of Cretaceous-Tertiary boundary sections in southwestern North Dakota. *In*: Hartman, J.H. Johnson K.R. & Nichols D.J. (eds) The Hell Creek Formation and the Cretaceous-Tertiary boundary in the northern Great Plains: an integrated continental record of the end of the Cretaceous. Geological Society of America Special Papers, **361**, 95-144.

Raup, D.M. & Boyajian, G.E. 1988. Patterns of generic extinction in the fossil record. *Paleobiology,* **14**, 109-125.

Rein, G. 2013. Smouldering fires and natural fuels. *In:* Belcher C.M. (ed) Fire phenomena and the Earth system an interdisciplinary guide to fire science. John Wiley and Sons, p. 15-33.

Reszka, P. Borowiec, P. Steinhaus, T. & Torero, J. 2012. A methodology for the estimation of ignition delay times in forest fire modeling. *Combustion & Flame,* **159**, 3652-3657.

Robertson, D.S. McKenna, M.C. Toon, O.B. Hope, S. & Lillegraven, J.A. 2004. Survival in the first hours of the Cenozoic. *Geological Society of America Bulletin,* **116**, 760-768.

Robertson, D.S. Lewis, W.M. Sheehan, P.M. & Toon, O.B. 2013. K/Pg Extinction: Re-evaluation of the Heat/Fire Hypothesis. *Journal of Geophysical Research, Biogeosciences,* **118**, 329–336.

Schemel, C.F. Simeoni, A. Biteau H, Rivera., J.D. & Torero, J.L. 2008 A calorimetric study of wildland fuels. *Experimental Thermal Fluid Science,* **32**, 1381-1389.

Self, S. Widdowson, M. Thordarson, T. & Jay, A.E. 2006. Volatile fluxes during flood basalt eruptions and potential effects on the global environment: A Deccan perspective. *Earth & Planetary Science Letters,* **248**, 518-532.

Shuvalov, V.V. & Artemieva, N.A. 2002. Atmospheric erosion and radiation impulse induced by impacts, *In:* Koeberl, C. & MacLeod, K.G. (eds) Catastrophic events and mass extinctions: Impacts and beyond, Special Paper 356. Geological Society of America, Boulder, pp. 695-703.

Shuvalov, V.V. 1999. Multidimensional hydrodynamic code SOVA for interfacial flows: Applications to the thermal later effect. *Shock Waves,* **9**, 381-390.

Simms, D.L. & Law, M. 1967. The ignition of wet and dry wood by radiation. *Combustion & Flame,* **11**, 377-388.

Spicer, R.A. 1989. Plants at the Cretaceous-Tertiary boundary. *Philosophical Transactions of the Royal Society London B,* **325**, 291-305.

Spicer, R.A. & Colllinson, M.E. 2014. Plants and floral change at the Cretaceous-Paleogene boundary: Three decades on in. Keller, G., & Kerr, A.A. eds., Volcanism, Impacts and Mass Extinctions: Causes and Effects. Geological Society of America Special Paper 505.

Spicer, R.A. & Herman, A.B. 2010. The late Cretaceous environment of the Arctic: A quantitative reassessment based on plant fossils. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **295**, 423-442.

Sweet, A.R. 2001. Plants, a yardstick for measuring the environmental consequences of the Cretaceous-Tertiary boundary event. *Geoscience Canada,* 28, 127-138.

Swengel, A.B. 2001. A literature review on insect responses to fire, compared to other conservative managements of open habitat. *Biodiversity and Conservations*, **10**, 1141-1169.

Tewarson, A. 2008. Generation of heat and chemical compounds in fires. *In*: DiNenno, P.J. (ed), SFPE Handbook of Fire Protection Engineering.

Thompson, S.L. & Lauson, H.S. 1972. Improvements in the Chart D radiation-hydrodynamic CODE III: Revised analytic equations of state. Sandia National Laboratory Report SC-RR-71 0714, Albuquerque, U.S.A., 119pp.

Toon, O.B. Zahnle, K. Morrison, D. Turco, R.P. & Covey, C. 1997. Environmental perturbations caused by the impacts of asteroids and comets. *Reviews of Geophysics, **35***, 41-78.

Vajda, V.V. & McLoughlin, S. 2004. Fungal proliferation at the Cretaceous-Tertiary boundary. S*cience*, **303**, 1489.

Vajda, V. Raine, J.I. & Hollis, C.J. 2001. Indication of global deforestation at the Cretaceous-Tertiary boundary by New Zealand fern spike. *Science*, **294**, 1700-1702.

van Mantgem, P. & Schwartz, M. (2003) Bark heat resistance of small trees in Californian mixed conifer forests: testing some model assumtions. *Forest Ecology Management*, **178**, 341-352.

Wahlberg, N. Leneveu, J. Kodandaramaiah, U. Pena, C. Nylin, S., Freitas, A.V.L. & Brower, A.V.Z. 2009. Nymphalid butterflies diversify following near demiste at the Cretaceous/Tertiart boundary. *Proceedings of the Royal Society B*, **276**, 4295-4302.

Wappler, T. Currano, E.D. Wilf, P. Rust, J & Labandeira, C.C. 2009. No post-

Cretaceous ecosystem depression in European forests? Rich insect-feeding damage on diverse middle Palaeocene plants, Menat, France. *Proceedings of the Royal Society B,* **276**, 4271-4277.

Wickman, B.E. 1978. Tree mortality and top-kill related to defoliation by the Douglas-fir tussock moth in the Blue Mountains outbreak. U.S. Department of Agriculture Forest Service Research Paper PNW-233, 47 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Wing, S.L. 2004. Mass extinctions in plant evolution. *In*: Taylor, P.D., (ed) Extinctions in the History of Life. Cambridge University Press p. 61-97.

Wolbach, W.S. Lewis, R.S. & Anders, E. 1985. Cretaceous extinctions: evidence for wildfires and search for meteoritic material. *Science,* **230**, 167-170.

Wolfe, J.A. & Upchurch, G.R. 1986. Vegetation, climatic and floral changes at the Cretaceous-Tertiary boundary. *Nature,* **324**, 148-152.

Figure Legends

Figure 1 Images and schematic of the Fire Propagation Apparatus recreating the K-Pg thermal radiation.

Figure 2 Map of the Latest Cretaceous continental configuration indicating the regions receiving a proximal, intermediate or distal thermal flux.

Figure 3 Model predictions of the K-Pg thermal radiation (from Morgan et al. 2013) at different distances and azimuths: (a) proximal, 0–30° (b) intermediate, 0–30° and 30–60° (all with constant velocity and particle size), (c) distal 0–30° with constant velocity and particle size and distal 0-30° with velocity increasing and particle size decreasing with time. 0° is downrange. The heat flux ramps achieved in the FPA are shown by the solid line and the model estimates as crosses.

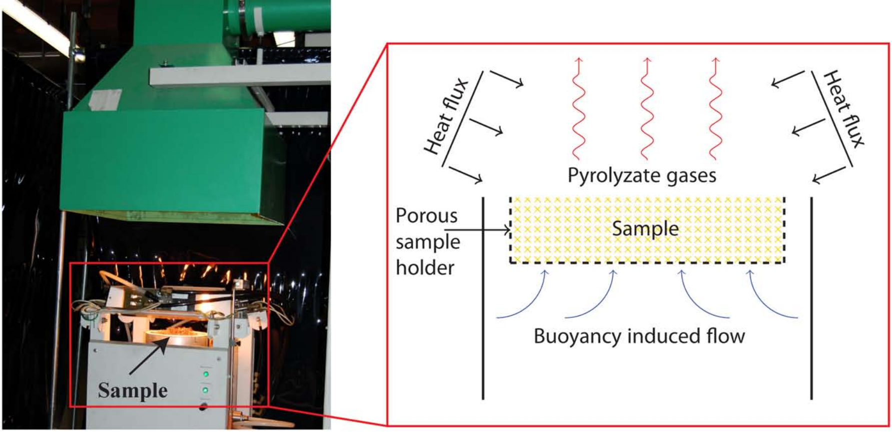
Figure 4 Images of the remains of the forest fuels following experiment flammability tests for the 5 thermal radiation scenarios.

Figure 5 Graph indicating the probability of mortality of trees based on crown kill ratio. Values estimated using Wickman, (1978).

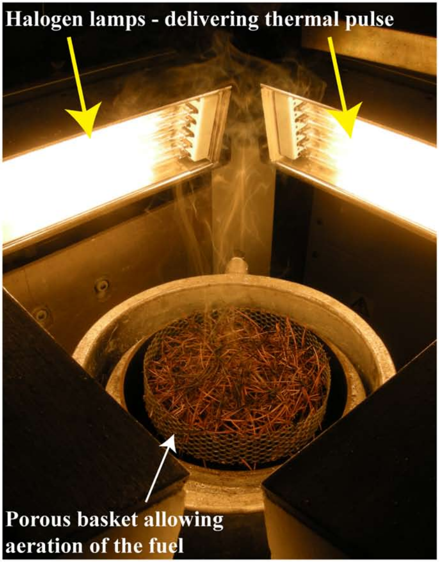
Table Legends

Table 1 Full observational results of the flammability experiments indicating time to onset of pyrolysis and time to flaming ignition in the plant materials. Total mass lost % is included and gives an indication of fuel consumption. Key a) constant particle velocity and mass b) increasing particle velocity and decreasing mass

Table 2 Flammability testing results for the 5 fuels tested over the 5 ignition scenarios. F = flaming ignition observations, P = pyrolysis only, S = smouldering, SS = self-sustained smouldering. *smouldering sample transition to brief flaming after 278 s.

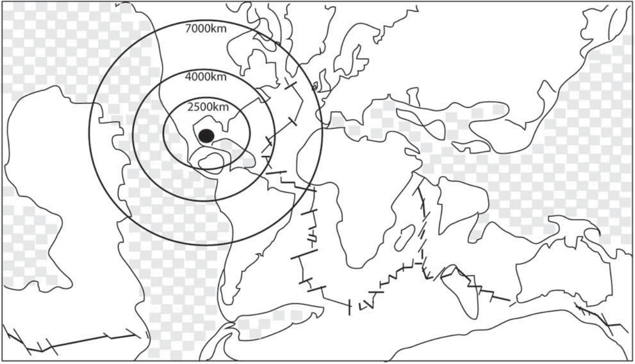


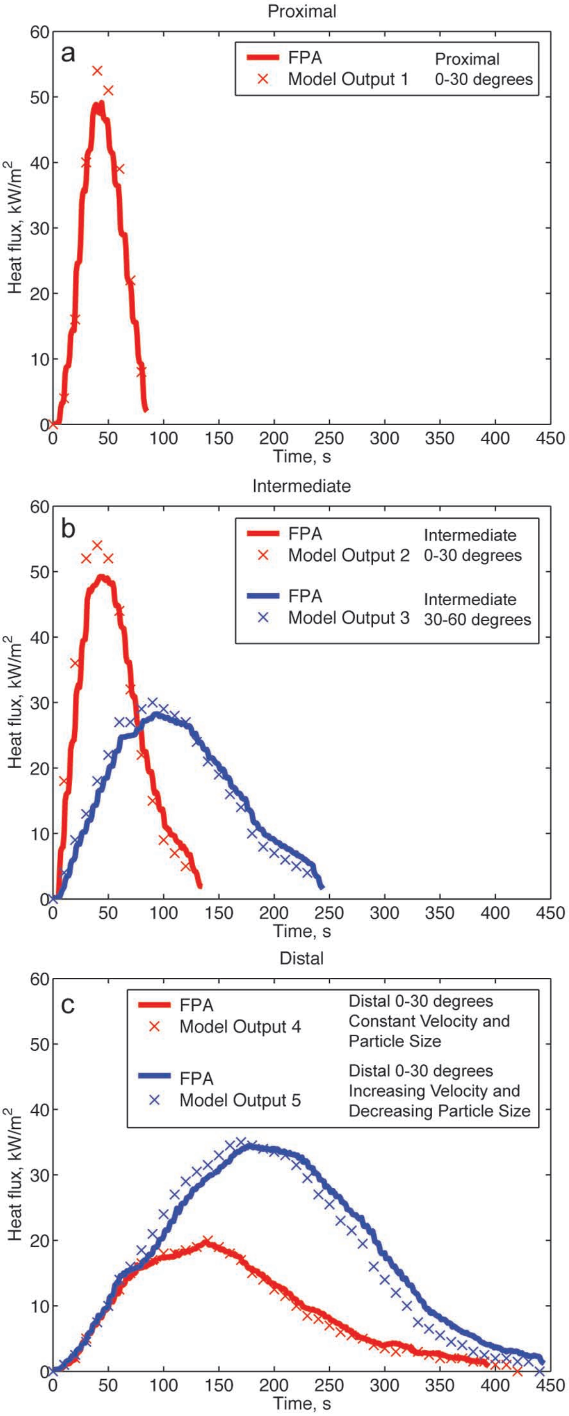
View of the Fire Propagation Apparatus

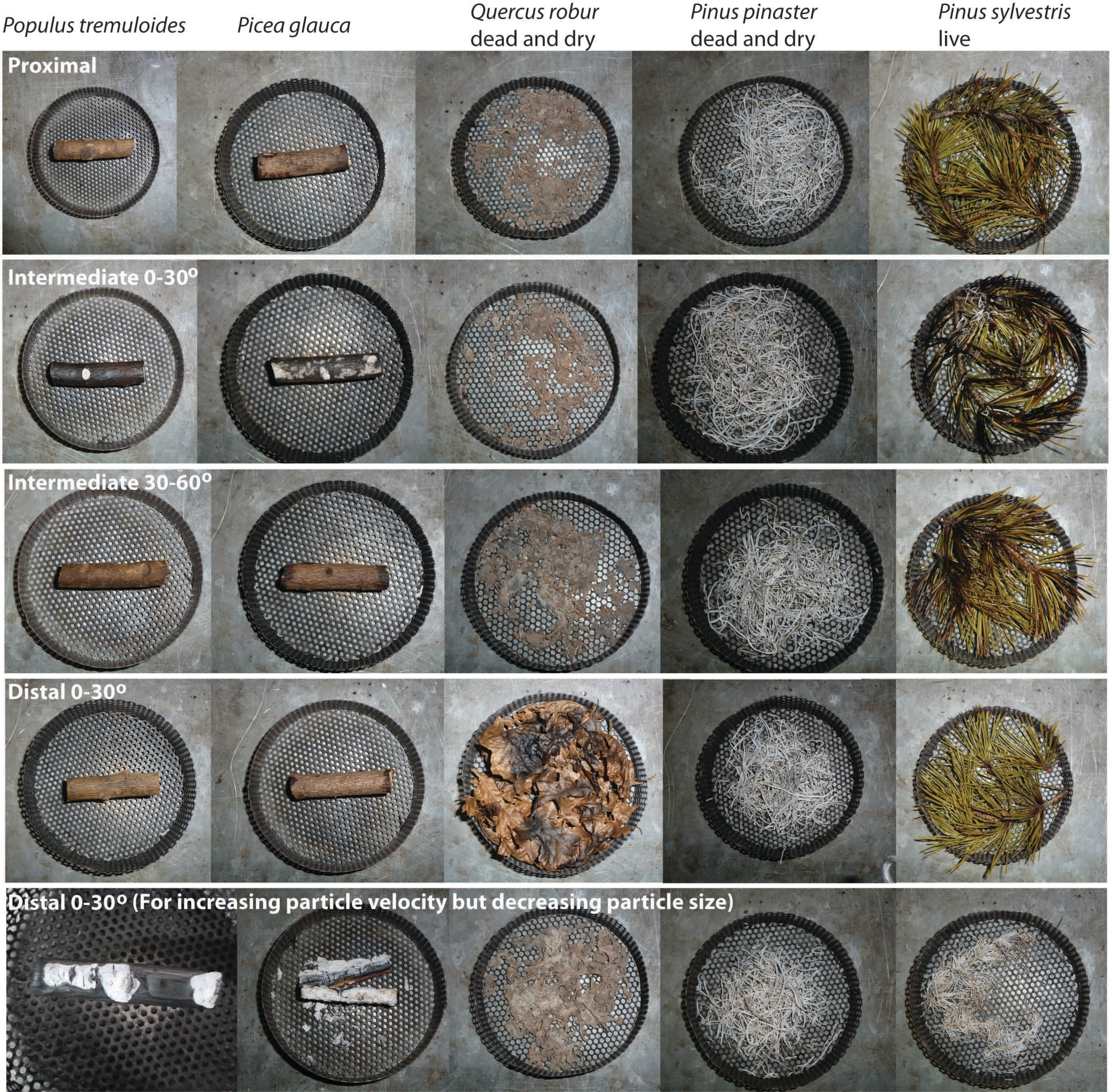


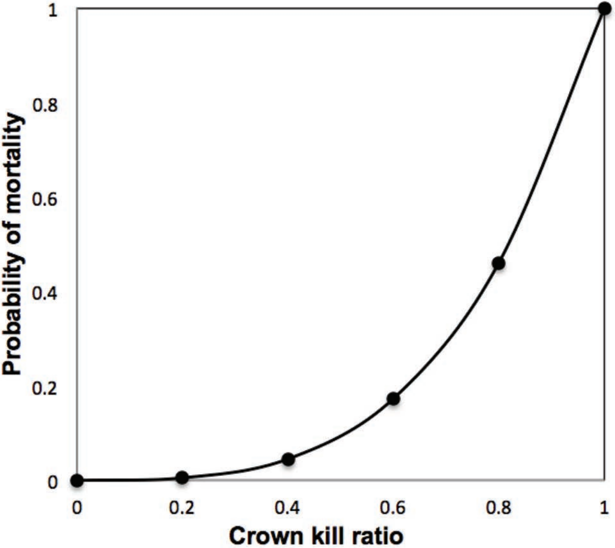
Dry *Pinus pinaster* litter being heated by the radiation from the halogen lamps

Flaming ignition of *Pinus pinaster* needles


7000km
4000km
2500km


Proximal
a
FPA
Model Output 1
Proximal
0-30 degrees
Heat flux, kW/m^2
Time, s
0
10
20
30
40
50
60
0
50
100
150
200
250
300
350
400
450
Intermediate
b
FPA
Model Output 2
Intermediate
0-30 degrees
FPA
Model Output 3
Intermediate
30-60 degrees
Heat flux, kW/m^2
Time, s
Distal
c
FPA
Model Output 4
Distal 0-30 degrees
Constant Velocity and
Particle Size
FPA
Model Output 5
Distal 0-30 degrees
Increasing Velocity and
Decreasing Particle Size
Heat flux, kW/m^2
Time, s


Populus tremuloides
Picea glauca
Quercus robur
dead and dry
Pinus pinaster
dead and dry
Pinus sylvestris
live
Proximal
Intermediate 0-30º
Intermediate 30-60º
Distal 0-30º
Distal 0-30º (For increasing particle velocity but decreasing particle size)


Probability of mortality
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
Crown kill ratio

Fuel	**Scenario**	**Total mass lost, %**	**Observations**	**Time to onset of pyrolysis, s**	**Time to flaming ignition, s**
PP	Proximal	98.1	Flaming	28	44
PP	Proximal	97.6	Flaming and residual smouldering	29	47
PP	Inter 0-30	97.3	Flaming	29	52
PP	Inter 0-30	98.0	Flaming and residual smouldering	28	47
PP	Inter 0-30	97.7	Flaming and residual smouldering	29	47
PP	Inter 30-60	97.6	Flaming	52	115
PP	Inter 30-60	97.8	Flaming	51	109
PP	Distal 0-30a	9.9	Pyrolysis	75	Not observed
PP	Distal 0-30a	97.7	Smouldering and transition to flaming	74	278
PP	Distal 0-30b	98.0	Flaming	74	146
PP	Distal 0-30b	97.8	Flaming	72	165
PP	Distal 0-30b	97.9	Flaming	71	143
Q	Proximal	96.7	Flaming	25	34
Q	Proximal	-	Flaming	25	35
Q	Inter 0-30	95.8	Flaming	25	37
Q	Inter 0-30	95.1	Flaming	24	36
Q	Inter 30-60	96.1	Flaming	47	142
Q	Inter 30-60	94.2	Flaming	50	88
Q	Distal 0-30a	60.7	Smouldering	71	Not observed
Q	Distal 0-30a	12.2	Pyrolysis	79	Not observed
Q	Distal 0-30a	12.3	Pyroysis	70	127
Q	Distal 0-30b	95.1	Flaming	67	123
Q	Distal 0-30b	96.0	Flaming	65	127
PT	Proximal	3.0	Pyrolysis	32	Not observed
PT	Proximal	3.7	Pyrolysis	35	Not observed
PT	Inter 0-30	7.7	Pyrolysis	35	Not observed
PT	Inter 0-30	6.0	Pyrolysis	37	Not observed
PT	Inter 30-60	5.5	Pyrolysis	68	Not observed
PT	Inter 30-60	6.0	Pyrolysis	70	Not observed
PT	Distal 0-30a	4.6	Pyrolysis	115	Not observed
PT	Distal 0-30a	5.4	Pyrolysis	94	Not observed
PT	Distal 0-30b	70.4	Pyrolysis and sustained smouldering	105	Not observed
PT	Distal 0-30b	42.1	Pyrolysis and sustained smouldering	104	Not observed
PG	Proximal	1.7	Pyrolysis	28	Not observed
PG	Proximal	6.0	Pyrolysis	33	Not observed
PG	Inter 0-30	11.7	Pyrolysis and smouldering	31	Not observed
PG	Inter 0-30	9.0	Sustained smouldering	35	Not observed
PG	Inter 30-60	4.6	Pyrolysis	60	Not observed
PG	Inter 30-60	3.8	Pyrolysis	71	Not observed
PG	Distal 0-30a	2.5	Pyrolysis	102	Not observed
PG	Distal 0-30a	3.3	Pyrolysis	116	Not observed
PG	Distal 0-30b	25.1	Sustained smouldering	94	Not observed
PG	Distal 0-30b	62.4	Sustained smouldering	124	Not observed

PS	Proximal	33.1	Pyrolysis	40	Not observed
PS	Proximal	34.5	Pyrolysis	31	Not observed
PS	Inter 0-30	46.5	Pyrolysis and ashing	36	Not observed
PS	Inter 0-30	42.8	Pyroysis and ashing	42	Not observed
PS	Inter 0-30	40.9	Pyrolysis	43	Not observed
PS	Inter 30-60	43.5	Pyrolysis	68	Not observed
PS	Inter 30-60	44.3	Pyrolysis	80	Not observed
PS	Distal 0-30a	42.0	Pyrolysis	125	Not observed
PS	Distal 0-30a	41.1	Pyrolysis	137	Not observed
PS	Distal 0-30b	99.6	Flaming	114	181
PS	Distal 0-30b	99.2	Flaming	107	197

Experimental Observations - Flammability testing results for the 5 fuels tested over the 5 ignition scenarios. F = flaming ignition observations, P = pyrolysis only, S = smouldering, SS = self-sustained smouldering. *smouldering sample transition to brief flaming after 278 s.

	Constant velocity and particle size				*Increasing velocity and decreasing particle size*
Fuel	**Proximal**	**Inter 0-30°**	**Inter 30-60°**	**Distal 0-30°**	**Distal 0-30°**
PP (dry-dead)	F	F	F	P/S*	F
Q (dry-dead)	F	F	F	P/S	F
PT (dry wood)	P	P	P	P	SS
PG (dry wood)	P	P/S	P	P	SS
PS (live)	P	P	P	P	F