BURNING QUESTIONS – HOW STATE OF THE ART FIRE SAFETY TECHNIQUES CAN BE APPLIED TO ANSWER MAJOR QUESTIONS IN THE EARTH SCIENCES

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INTRODUCTION

Forest fire is an important ecosystem level process, and its role in the global environment has begun to generate sustained scientific interest. 40% of Earth's present land surface is occupied by fire prone ecosystems (Bond et al., 2005) such as grasslands, savanna, Mediterranean shrubland and boreal forests. Forest fires contribute to the disruption of ecosystems by preventing the growth of vegetation i.e. fire prevents forests developing where other factors such as climate and soil might otherwise allow. By influencing the total biomass of vegetation, fires significantly alter the flux of nutrients that stimulate Earth's primary productivity. This means that by altering the total biomass of terrestrial vegetation forest fires have significant implications for global biodiversity, ecology and biogeochemical cycles (the movement of matter within or between ecosystems; caused by living organisms, geological forces, and/or chemical reactions. The cycling of nitrogen, carbon, sulfur, oxygen, phosphorus, and water in the Earth system are examples). It is therefore important to understand what causes variations in forest fire activity in order to understand the impacts of fire on the Earth system as a whole.

Fires require three fundamental inputs in order to burn. These can be described using the fire triangle (Drysdale, 1998), which illustrates that fire requires 1) a suitable ignition source, 2) sufficient atmospheric oxygen and 3) a suitable fuel source. The Earth is 4.54 billion years (Ga) old but throughout this huge tract of time has it always been flammable? It is likely that ignition sources have largely always present on the Earth in the form lightning strike and volcanic eruptions. Oxygen and fuel however, have not always been abundant. The oxygenation of Earth's atmosphere occurred following the evolution of photosynthesis that began to breath oxygen into our atmosphere ~ 3.2-2.4 Ga. However, the Earth's atmosphere did not become oxygenated until 2.2 Ga. Without fuel a fire cannot burn and it wasn't until the evolution of the first land plants ~ 420 million years ago (Ma) that the first fuels evolved on Earth capable of carrying a forest fire. This means that from ~ 420 Ma onwards conditions have existed on the Earth that could allow for forest fires to burn and influence the Earth system. A major challenge in the Earth Sciences is building an understanding of how future projected global warming trends might alter forest fire activity. We can begin to understand the effects of global warming on forest fire activity by using experimental techniques from fire safety engineering and placing them in an Earth science context.

ANCIENT CLIMATE CHANGE AS A POTENTIAL ANALOGUE FOR EARTH'S FIERY FUTURE

Numerical models suggest that the annual number of forest fires in the U.S. will increase by 44%, with a 78% increase in the area burned by fires (Price and Rind, 1994) in response to predicted future climate change. Fire seasons in boreal, temperate and Mediterranean regions (Flannigan et al., 2009) are predicted to increase in duration. Beyond modelling we cannot see into the future therefore, we can study periods of ancient climate change to understand if global warming might cause an increase in fire activity. Atmospheric carbon dioxide levels are estimated to have increased 4 fold in a global warming event that occurred 200 Ma (McElwain et al., 1999). This is believed to have significantly impacted Earth's ecosystems as evidenced by major changes in the types of vegetation (fuel for fires), revealed from fossil plants that existed before and during this event that are contained in rock deposits. We have studied the potential change in flammability associated with the change in vegetation across this event by assessing the vegetation for its flammable characters and by testing modern analogue vegetation for its flammability in a state of the art fire propagation apparatus.

METHODOLOGY

Estimating Flammability Characteristics of 200 Ma old Ancient Vegetation

Leaf arrangement and connectivity influence flammability (Carcaillet et al., 2001). Narrow leaves, have a lower surface area (per unit volume) and are considered to be more flammable than broad leaves, which have a large surface area (Cornelissen et al., 2003). The modern world's flammable ecosystems are dominated by narrow leaved plants with relatively low moisture contents, which create optimal conditions for fire spread (Bond and van Wilgren, 1996; Torero, 2008). This compares to less flammable ecosystems that typically have broader leaves with high moisture contents. This suggests that the morphology of plants leaves can be used to estimate the flammability of ancient fossil leaves.

We have taken a database of > 3000 fossil leaves (see McElwain et al., 2007) collected from East Greenland that represent the vegetation that grew before, during and after this 200 Ma old global warming event. The fossil leaves are taken from 6 horizons/levels of rock (beds) before the global warming event and 4 from the period known to have experienced high atmospheric carbon dioxide. These fossil leaves have been grouped into forms considered "flammable" (narrow leaf morphologies) and those considered "less flammable" (broad leaved morphologies) (see Belcher et al., 2010 for classification of flammable vs less flammable fossil leaf groupings). We have also quantified the abundance of fossil charcoal (a product of fire) in the rocks, which is considered a proxy for ancient fire activity.

The fossil leaves reveal that the vegetation at this time changed where plants with narrow leaf morphologies became more abundant during the global warming event (figure 1). This change in plant morphology occurred at the same time as a five fold increase in the abundance of fossil charcoal at the same location. This suggests that the newly abundant narrow leaved plants were more flammable than their broad leaved predecessors (Belcher et al., 2010).

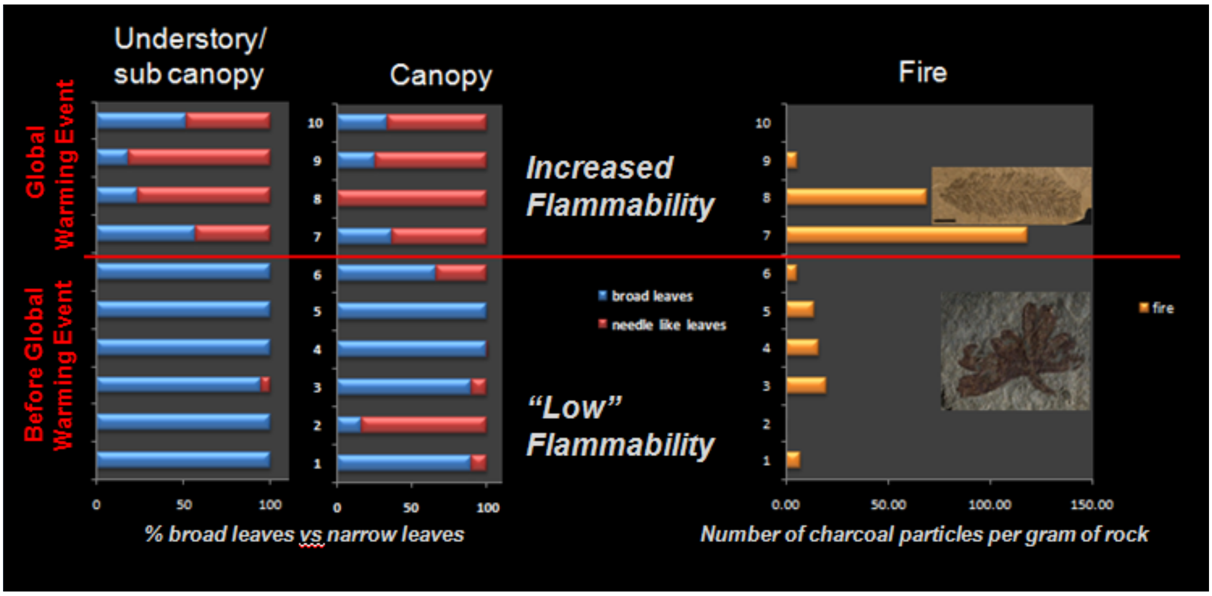

Figure 1. Abundance of broad and narrow fossil leaves and the abundance of charcoal before and after the 200 Ma global warming event. Data from Belcher et al., 2010.

Experimental Flammability Analyses of Analogue Plants

Is the theory that narrow leaves are more flammable than broad leaves supported by experimental evidence? We selected 6 modern plant types (genera) that are morphologically and ecologically similar to the plants that were growing in East Greenland 200 Ma for flammability analysis. All are from coniferous trees. Two narrow leaved genera were selected, two broad leaved genera and two slim-broad leaved genera. The plants were tested for their flammability using the state of the art FM Global fire propagation apparatus (FPA) housed at BRE Centre for Fire Safety Engineering at the University of Edinburgh. The operation of the apparatus (as used for synthetic materials) is detailed in the Standard ASTM-E 2058. The plant samples were placed into a basket 400cm^3 volume, and open at the top with porous walls. Plant architecture was maintained as best as possible by leaving leaves attached to their stems. Four infrared heaters (made each of six halogen lamps) set at 120-144 V delivered a radiative flux of 40kWm^{-2} of thermal radiation to the samples. The thermal radiation causes the sample to pyrolyse and generate flammable gases which are ignited by a pilot flame positioned above the samples. The flame ignition of the gases then leads to steady burning of the fuel until burn out. The FPA measured the mass lost by each sample, the time to ignition, the average heat of combustion and the contents of the exhaust gases. Each plant genera was tested 3 times.

The results of the experiments are shown in figure 2. It can be seen that the narrow leaved genera ignited more rapidly than the broad leaved genera (figure 2a) ($p = 0.0248$). The narrow leaves were also seen to attain higher average heat of combustion than the broader leaved forms (figure 2b). This taken with the time to ignition suggests that narrow leaves burn hotter more quickly. Interestingly the narrow leaves appear to have a higher flux rate of total hydrocarbons at the point of ignition (figure 2c), suggesting that the narrow leaves likely release volatiles more rapidly than the broad leaves and that this enhances their flammability.

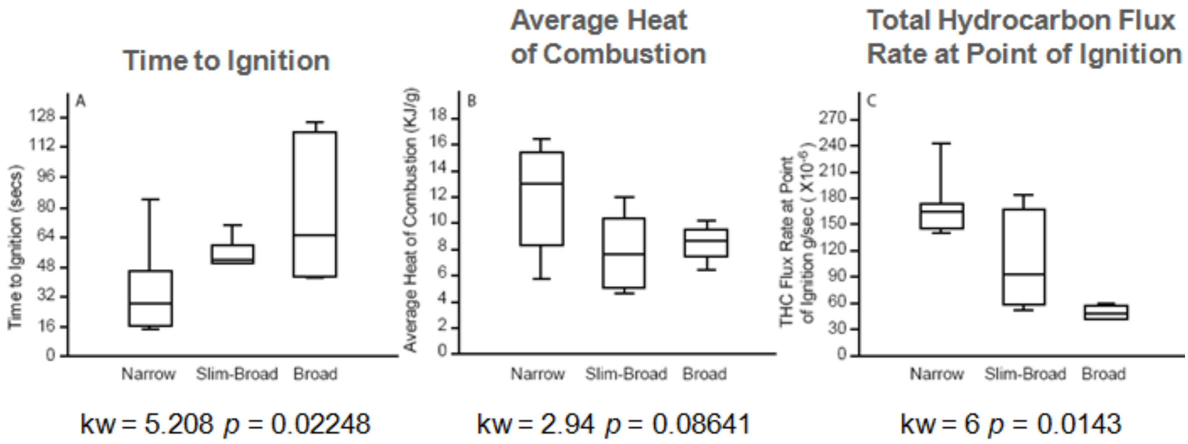

Figure 2. Results of the flammability analyses. Modified from Belcher et al., 2010.

CONCLUSIONS

We have analysed changes in vegetation across an ancient global warming event that occurred 200 Ma. We have assessed this ancient forest for its flammability and compared this to the record of fossil charcoal preserved in the rocks deposited at this time.

- We find a five fold increase in the abundance of fossil charcoal in association with estimated increases in carbon dioxide levels.
- We attribute this increase in fire activity to a climate-driven shift from a prevalence of broad leaved plants to a forest dominated by narrow leaved plants.
- Our flammability experiments show that narrow leaf morphologies are more flammable than broad leaved morphologies.

We suggest that the warming associated with increased atmospheric carbon dioxide levels favoured a dominance of narrow leaved plants, which led to an increase in fire activity. This reveals that Earth has experienced increased fire activity in response to global warming in the past and that we can use this information to begin to make more informed predictions about future forest fire threats based on current climate predictions.

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