Charcoal reflectance: A quantitative approach to understanding the impact of fire on an ecosystem

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

This thesis develops the charcoal reflectance method into a novel metric with which to assess fire severity and begin to explore the relationship between this and the amount of energy that has been delivered across a burned area.
The ability to better understand the effects of fires on ecosystems is critical for future policy and management strategies especially as in some regions of the Earth fire is predicted to become a more prevalent and catastrophic disturbance.

Charcoal is a key product of wildfire, resulting from the incomplete combustion of fuel. During the creation of charcoal, the energy from the fire alters the atomic structure of the plant material and it is eventually re-ordered to a more graphite-like structure. This re-ordering of cells alters the reflective properties of the charcoal i.e. there is an increase in the quantifiable amount of light reflected from the surface of the charcoal thus allowing researchers to study the reflectance properties of charcoal. It has been suggested that the properties of charcoal may be capable of capturing evidence of the heat distribution throughout a wildfire. As such charcoal may be able to provide a means with which to assess fire severity and the amount of energy that has been applied to fuel to create charcoal.

At present, there are two main tools by which fire severity is assessed: Qualitative fire severity scores taken at the ground-level, and quantitative satellite-based approaches. In this thesis, I examine how well charcoal reflectance compares to existing fire severity metrics whilst developing it into a post-fire assessment tool that has the potential to assist in future policy and management decisions, and in predictions of carbon budgeting for ecosystems.

Acknowledgments

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Last but not least, to my family, Chris, and my furry companions (Pixie, Ollie, Bean and Alby). Words cannot express how grateful I am to have had your support and love throughout my PhD. It has not been the smoothest of journeys but the support from all of the above has got me through and help me to achieve my dream.

"Happiness can be found in the darkest of times, if one only remembers to turn on the light." **(J.K.Rowling)**

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Abbreviations and definitions

The following abbreviations are used in this thesis and have been listed below for reference purposes.

C	Carbon
CWD	Coarse Woody Debris
dNBR	Difference Normalized Burn Ratio
Gt	Gigatonne
Ha	Hectare
JP	Jack Pine
PHRR	Peak Heat Release Rate
PNR	Pinelands National Reserve
PyC	Pyrogenic Carbon
RH	Relative Humidity
Ro%	Charcoal Reflectance
Tg	Teragram
THR	Total Heat Release
WRC	Western Red Cedar
WUI	Wildland Urban Interface

Fire behaviour	The manner in which fuel ignites, flame develops, and fire spreads and exhibits other related phenomena as determined by the interaction of fuel, weather, and topography (Merrill and Alexander, 1987).
Fire intensity	A measure of fire behaviour relating to the rate of heat release (Davies, 2013).
Fire regime	The expression of multiple fire events within a spatial and temporal domain; the type of fire, mean and variance in fire frequency, intensity, severity, season, and areal extent of a burn in an ecosystem (Bond and Keane, 2017).
Fire severity	The loss of or change in organic matter aboveground and belowground (Keeley, 2009).
Managed fires	Prescribed burns and experimental fires ignited for management and research purposes.
Prescribed burning	Fires intentionally lit for management purposes (Bond and Keane, 2017).
Unmanaged fires	Fires that are naturally, accidently or maliciously ignited; uncontrolled fires.
Wildfires	Uncontrolled wildland fires (Bond and Keane, 2017).

Chapter 1

Introduction

This chapter provides a review and critical discussion of the existing literature on fire effects and charcoal reflectance.

1.1 The importance of studying fire and its effects on ecosystems

As a natural process, and driver of major shifts in ecosystem dynamics, fire can be both essential, and harmful to the preservation of biodiversity, as well as nutrient and carbon cycles across the globe (Belcher, 2013; Conedera *et al.,* 2009; Shlisky *et al.,* 2007; van der Werf *et al.,* 2010). Fire has been an important aspect in ecosystems for 350-400 million years; a key driver of the distribution and ecological processes of several ecosystems and biomes across the globe e.g. savannas, boreal forests and shrublands (Bond *et al.,* 2005). Fire’s influence on Earth’s ecosystems is increasing due to anthropogenic activity and climate change (Doerr and Santin, 2016; Bond and Keane, 2017). Anthropogenic fire regimes at this present moment are at risk of resulting in catastrophic wildfires (Pausas and Keeley, 2019). The occurrence and risk of fire is increasing in some regions of the earth, affecting a greater area than ever before. Those ecosystems that have not previously been at risk from such high fire activity are vulnerable, and face an uncertain, fiery future (Shlisky *et al.,* 2007; Waddington *et al.*, 2015).

An investigation of the relationship between climate change and wildfire over the period 1979-2013 found that climate-induced changes to the global fire regime has resulted in a lengthening of the fire season by 18.7% across approximately 25% of the Earth’s vegetated surface (Jolly *et al.,* 2015). However, this increase was not evenly distributed across all ecosystems, with the strongest trends being observed in tropical and subtropical grasslands, savannas and shrublands (Jolly *et al.,* 2015). It is important to note that unprecedented catastrophic wildfire events were included in the research, e.g. the drought induced Indonesian fires of 1997–98. Those 1997-1998 peatland fires resulted in 0.19-0.23 gigatonnes (Gt) of carbon being released into the atmosphere (Page *et al.,* 2002). Also included were the 2010 Russian wildfires which were the result of an unprecedented heatwave resulting in Russia's worst fire season ever documented (Konovalov *et al.,* 2011; Jolly *et al.,* 2015). It has been estimated that these record breaking wildfires in Russia released approximately 10 teragrams (Tg) of carbon into the atmosphere (Konovalov *et al.,* 2011; Jolly *et al.,* 2015).

It is important to note that even though it has been found that fire season length in some regions of the Earth have increased (along with an increase in burned area), especially in some locations in North America (Jolly *et al.,* 2015; Doerr and Santin, 2016), quantitative analysis of the global trends in wildfire found that over the past few decades the amount of global area burned has actually declined (Doerr and Santin, 2016; Andela *et al.,* 2017). Andela *et al.,* (2017) for example report that the global burned area declined by approximately 24.3 ± 8.8% between 1998 and 2015. The number of catastrophic wildfires that have occurred recently and the increased number of communities that are at risk from wildfires have perhaps led to misconceptions regarding wildfire behaviour across the globe (Doerr and Santin, 2016). However, the intensity and severity of fires are predicted to increase in the future, along with increases in the percentage of burned area for many regions on the Earth due to climate change and anthropogenic activity (Doerr and Santin, 2016). In boreal forests fire is a natural disturbance, before the arrival of humans, being controlled by the fuel moisture and weather (Chapin *et al.,* 2006). Human induced climate change is predicted to lengthen the fire season which could result in a positive feedback through the release of carbon into the atmosphere (Kasischke, 2010; Randerson *et al.,* 2006; Bowman *et al.,* 2011). Therefore, it is important to better understand the effects of fires occurring at present and in recent history so that researchers can better predict the impact of these fires on the Earth's biomes.

Fires are multifaceted and no fire is exactly the same (Archibald *et al.,* 2013). Looking solely at certain aspects of fire e.g. fire frequency or size of burned areas, does not provide the whole story as to how fires affect ecosystems (Archibald *et al.,* 2013). The effects of fire such as fire severity and fire intensity must be studied at the local to global scale in order to fully understand the impact of wildfires across a range of ecosystems. In order to do this, the appropriate metrics must be developed so that researchers can quantify the damage that is caused to an ecosystem. In this thesis I focus on fire severity. However, it will become clear that the method that I have developed in order to quantitatively assess fire severity could provide researchers with more information about the fire which created the charcoal than initially expected.

1.2 The importance of fire regimes

Fire is a key component of the global carbon cycle, shaping and affecting many ecosystem processes and services in regions across the globe (Bowman *et al.,* 2011; Pausas and Keeley, 2019). The regime of a fire is critical to determining the landscape pattern of vegetation and fuel structure of an ecosystem, therefore any change to the fire regime could have major consequences to an ecosystem (Bond and Keeley, 2005). Bond and Keane (2017) have provided a simple definition of fire regime:

> **“The expression of multiple fire events within a spatial and temporal domain; the type of fire, mean and variance in fire frequency, intensity, severity, season, and areal extent of a burn in an ecosystem”.**

Fire regimes are spatially variable and are influenced by the climate and by anthropogenic action (Bowman *et al.,* 2011). Humans are continually affecting fire regimes through multiple activities such as clearing land for farming and changing vegetation structures, setting fires outside of the natural fire season and supressing fires that would have occurred naturally in an ecosystem (Bowman *et al.,* 2011). Figure 1.1 shows how historical fire regimes and those influenced by society are linked and their effects on ecological processes (Pausas and Keeley, 2019).

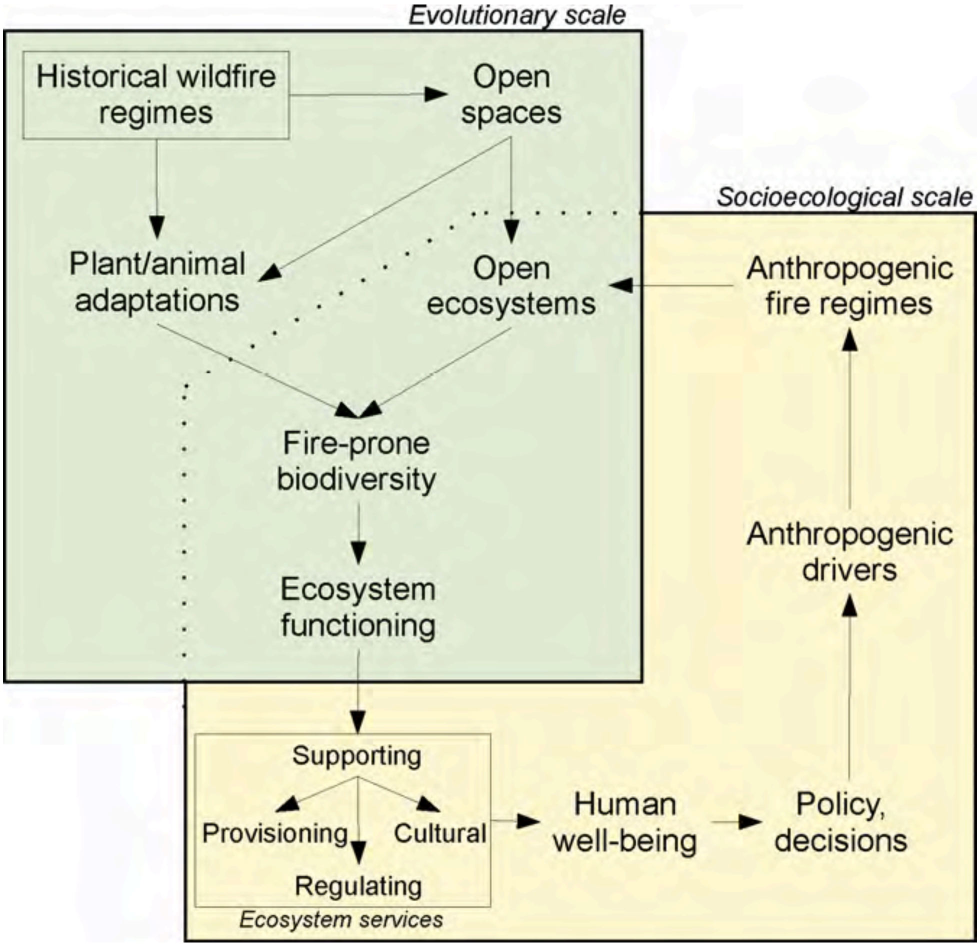

Figure 1.1: Diagram taken from Pausas and Keeley (2019) showing a schematic representation of the links between the evolutionary and socioecological scales and their impacts on fire regimes. Natural (historical) wildfire regimes create open habitats that can promote specific adaptations, biodiversity, and overall functioning in fire-prone ecosystems. Anthropogenic activity such as the implementation of policies may modify fire regimes i.e. policy decisions may switch between maintaining ecosystem services and generating unsustainable fire regimes. Source: Pausas and Keeley (2019:290).

Fire management is one human activity that has a large influence on the fire regime, particularly in North America (Parisien *et al.,* 2016). Management practices have shaped many North American ecosystems and their associated fire regimes and continue to do so today (Ryan et al., 2013). Fire is an increasing threat in the Eastern US as a result of the rise in urban infrastructure in rural environments (Peters *et al*., 2013). Whilst, an estimated > 10 million hectares of coniferous forests in the Western US are vulnerable; in moderate or high fire hazard condition (Stephens and Ruth, 2005; Stephens *et al*., 2009). Prescribed burning is increasingly being used successfully to reduce fuels and restore fire disturbance to landscapes that historically would have experienced wildfire. However, wildfire management in the USA is a widely debated topic (Foereid *et al.,* 2015). Despite the debate fire suppression costs are predicted to reach ~$1.8 billion by 2025 (United States Forest Service, 2015), which will have further effects on the fire regimes of the ecosystems this type of management is implemented in.

Fire regimes are also being shaped by anthropogenic action other than management alongside climate change, this is particularly evident in South America (Uhl and Kauffman, 1990). Previously non-flammable, tropical rainforests are now being transformed into flammable ecosystems, and previously infrequent low-intensity surface fires are being converted to high-intensity more frequently occurring fires that are potentially high-severity, resulting in huge amounts of damage to the ecosystem (Uhl and Kaufmann, 1990).

1.3 Fire intensity, fire severity and fire behaviour

It is important to clarify what is intended when certain fire terminology is used when referring to the different fire effects that will be discussed in this research. Due to the diversification of the study of fire and collaboration between various fields of science and policymakers, definitions of terminology are often different (Davies, 2013). Figure 1.2 by Keeley (2009) clearly shows the key differences between fire intensity and fire severity, two of the main terms that will be used throughout this thesis.

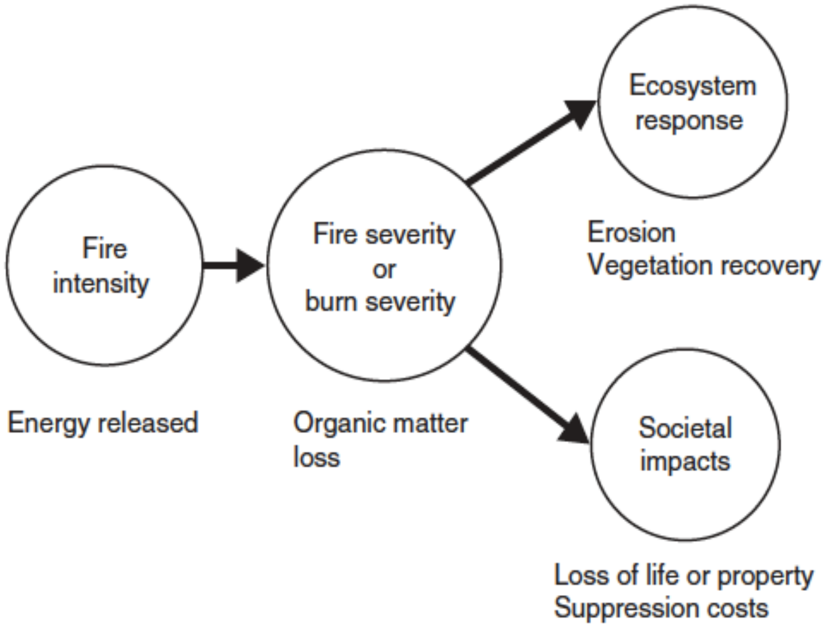

Figure 1.2: A schematic diagram showing the differences between the fire terminology used, a key aim of this diagram is to reiterate the difference between fire severity and environmental effects (ecosystem response) (Keeley, 2009). Source: Keeley (2009:117).

1.3.1 Fire intensity

Fire intensity as defined by Davies (2013) is:

"A measure of fire behaviour relating to the rate of heat release".

It is noted that different types of fire, smouldering and flaming, crown, surface and ground fires, produce varied fire intensities, and that different environmental factors play a major role in determining these intensities (Stocks *et al.,* 2003; Davis, 2013; Rogers *et al.,* 2015). Fuel structure, weather, climate and the physical environment (soil type, elevation, etc.) have been noted by many researchers as having a profound effect on fire behaviour and the relationships between them defined as being complex (Bradstock *et al.,* 2010; Davis, 2013; Penman *et al.,* 2013; Collins *et al.,* 2019).

1.3.2 Fire severity

The definition of fire severity is variable, researchers often have different interpretations of the meaning of severity and this translates into how they measure it in the field. In this thesis the definition by Keeley (2009) will be used:

"The loss of or change in organic matter aboveground and belowground".

Ecologists tend to refer to fire severity in terms of the environmental damage caused by fire. However, Davis (2013) discusses how the environmental effects of fire and fire severity itself should be considered as different entities e.g. severity would include fire-induced tree mortality, and an environmental effect would be post-mortality of a tree due to fire effects on the hydrology of the ecosystem for example (Keeley, 2009; Davis *et al.,* 2013).

There are two main existing methods which have been used in the past to assess fire severity, these are qualitative assessments and remote sensing. Measuring fire severity can easily be conducted in the field by using a fire severity matrix providing a qualitative measurement of the fire. There are different matrices in use many of which are based on the first matrix developed by Ryan and Noste (1985) that relate the impacts of fire on vegetation and soil to the severity of the fire (Keeley, 2009). Table 1.1 provides one example of a fire severity matrix that has been adapted by researchers over time and that will be used in the studies presented in this thesis (Keeley, 2009).

Table 1.1: A simplified fire severity matrix that relates the impact of fire on vegetation and soil to the severity of the fire. Source: Keeley (2009:119).

Fire severity	Description
Unburned	Plant parts green and unaltered, no direct effect from heat
Scorched	Unburned but plants exhibit leaf loss from radiated heat
Light	Canopy trees with green needles although stems scorched
	Surface litter, mosses, and herbs charred or consumed
	Soil organic layer largely intact and charring limited to a few mm depth
Moderate or severe surface burn	Trees with some canopy cover killed, but needles not consumed
	All understorey plants charred or consumed
	Fine dead twigs on soil surface consumed and logs charred
	Pre-fire soil organic layer largely consumed
Deep burning or crown fire	Canopy trees killed and needles consumed
	Surface litter of all sizes and soil organic layer largely consumed
	White ash deposition and charred organic matter to several cm depth

When assessing fire severity in different ecosystems, the metrics in the matrix must be altered to accommodate for the differing vegetation types (Keeley, 2009). Fire size and location must also be taken into account when measuring fire severity i.e. large fires and those in inaccessible locations (Escuin *et al.,* 2008). In these circumstances remote sensing e.g. Landsat, rather than directly mapping fire severity using the matrix, is a technique which can be used (Escuin *et al.,* 2008). The satellite-based method of Difference Normalized Burn Ratio (dNBR) (equation $_{(1)}$) has been increasingly utilized over recent years, particularly in the USA (Picotte and Robertson, 2011).

$$\textbf{dNBR} = \textbf{(NBR)}_{\textbf{pre-fire}} - \textbf{(NBR)}_{\textbf{post-fire}} \quad \textbf{(1)}$$

dNBR uses normalized burn ratio (NBR) images in its equation providing a measure of absolute change in pre- and post- burn NBR indices (and Benson, 2006; Casady *et al.,* 2010). NBR is similar to the normalized vegetation index (NDVI) as they are both used to assess vegetation condition. However, instead of the red band being used like in NDVI, NBR uses the short-wave infrared band alongside the near infrared band (NIR) (equation$_{(2)}$). NIR is used as vegetation reflects strongly in this part of the electromagnetic spectrum and SWIR is used as it reflects burned areas (bare soil) strongly, therefore making NBR and dNBR a useful tool for measuring the effect of fire on the environment (Earth Lab, 2019).

$$\mathbf{NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)}} \quad \mathbf{(2)}$$

This increased use of dNBR is due to its effectiveness for mapping burn severity in forested ecosystems, providing users with a measurable index of change post fire that can be related to ecological change (Picotte and Robertson, 2011; Warner *et al.,* 2017). However, similar to the fire severity matrix discussed previously, dNBR can also be susceptible to subjectivity when being stratified into severity classes (Lentile *et al.,* 2006). Also, in ecosystems with dense canopies dNBR will find it difficult to pick up fire severity on the ground (Hudak *et al.,* 2004; Lentile *et al.,* 2006). Research has found that the optimal ecosystem type for dNBR is open forests and woodlands with a low-moderate canopy cover, whereas when analysing fire severity in closed canopies dNBR did not perform well (Tran *et al.,* 2018).

1.3.3 Fire behaviour

In this thesis, the term fire behaviour will be used (Figure 1.3). Like the terms fire intensity and severity, fire behaviour has variable definitions. For the purpose of this research fire behaviour is defined as:

"**The manner in which fuel ignites, flame develops, and fire spreads and exhibits other related phenomena as determined by the interaction of fuel, weather, and topography**" (Merrill and Alexander, 1987).

Figure 1.3: A visualisation of the definition of fire behaviour represented as the fire triangle. Weather, topography and fuel create the triangle and the three key aspects that contribute to the definition of fire behaviour. Source: Government of Alberta (2015).

Examining the environmental changes that occur due to fire is important for the future of all ecosystems across the Earth. How the different aspects of fire behaviour affect these environmental changes must first be better understood. Methods used to assess such changes are primarily done post-fire i.e. soil and vegetation measurements. This data may provide scientists with an idea of fire severity but how intense the fire was in that location cannot be established at present unless directly measured at the time of occurrence. By studying the charred remains of vegetation, we may be able to build on the understanding of past fires, gaining some idea of their characteristics with the hope of one day being able to quantitatively measure the influence of fire severity on an ecosystem (Belcher and Hudspith, 2016).

1.4 Managed and unmanaged fires

For the purpose of thesis, I will refer to prescribed and experimental fires as ‘managed fires’. I will use the term ‘unmanaged wildfires’ in reference to fires that have not been ignited for management or research purposes, but fires that have either been ignited naturally, accidently or maliciously.

Prescribed burning plays a crucial role in protecting environments, especially those that humans are inhabiting (Davies *et al.,* 2019). In the UK for example, managed burns are used to manage shrublands for game-hunting and conservation purposes (Davies *et al.,* 2019). This management of fuels in ecosystems such as shrublands and boreal forests can also have positive effects on the potential losses of carbon from the environment as the risk of a large wildfire occurring is reduced (Davies *et al.,* 2019). In the US fire management and policies have also been put in place to reduce the risk, and number of, catastrophic wildfires occurring (Pausas and Keeley, 2019). Two policies that are in place in the USA are the ‘natural burn’ policy (which allows wildfires to burn naturally with minimal management interference) and prescribed burns, both of which are in place to reduce the frequency of large wildfires (Pausas and Keeley, 2019). Fire managers and policy-makers need reliable and scientifically proven information regarding fire behaviour and the effects that a fire will have on an ecosystem to ensure that fires are implemented in a safe and effective way (Davies *et al.,* 2019).

Not all fires that occur are the result of management practices. Arson and accidental fires are common in heathlands and moorlands, recent examples of these types of fire include Saddleworth Moor and Winter Hill (New *et al.,* 2018). As wildfires are a natural process in boreal forests and a common occurrence in the USA, the policies and management actions are well established. However, countries where wildfire has been an intermittent threat to ecosystems such as in tropical rainforests and in the UK for example, policies regarding management of fire are not yet in place to deal with the increased frequency and severity of fires that may occur in the future. In the UK for instance wildfire has been overlooked by policy makers in the past, as their extent and impact on UK ecosystems has not been well documented. Unlike the USA, England does not have a specific national wildfire agency or strategy in place (Gazzard *et al.,* 2016). Therefore, it is important to study the impact of both unmanaged and managed fires on ecosystems across the Earth. Fires that occur both in countries where fire is a common threat and those where it is a new disturbance must be studied, in order to help countries put in place polices and management strategies to tackle the predicted increase in the number and severity of wildfires in the future.

1.5 The formation and nature of charcoal

Charcoal is a key product of wildfires that remains in abundance after wildfire events. It is relatively chemically inert; resistant to oxidation, and can remain in soils, sediments and rocks for tens to millions of years (Mooney and Tinner, 2011; Hudspith *et al.,* 2015).

Fire refers to the process of combustion (Michaletz and Johnson, 2007). Combustion consists of two key phases; pyrolysis and oxidation. In order for oxidation to begin, pyrolysis must occur during which organic polymers such as cellulose are broken down (Michaletz and Johnson, 2007). Once volatile gases are released the oxidation phase occurs (Michaletz and Johnson, 2007). In wildfires charcoal is created during the pyrolysis stage of combustion where there is a void of oxygen (Oyedun *et al.,* 2012; Belcher and Hudspith, 2016) as the flame above the surface of the fuel, is using the oxygen. The fuel that is undergoing the combustion process is reduced to a form of carbon during the pyrolysis stage due to the release of volatile gases from within the piece of wood (Oyedun *et al.,* 2012).

1.5.1 The development of charcoal reflectance in fire severity assessments

Charcoal's ability to retain information about the fire which has formed it makes it a valuable resource in wildfire research (Jones *et al.,* 1991; Belcher and Hudspith, 2016). The full extent of the information about fire retained by charcoal is not yet fully known, however reflected light microscopy i.e. charcoal reflectance (Ro%) is able to provide researchers with a method with which to access some of this information (Belcher and Hudspith, 2016).

Researchers have already established that the structure of charcoal varies during creation due to a number of differing factors e.g. wood species and heating (Cohen-Ofri *et al.,* 2006; Lowden and Hull, 2013). As we know through experimental work, during the combustion process charcoal undergoes various phases in which cells are eventually re-ordered to a more graphite-like structure (Figure 1.4) (Cohen-Ofri *et al.,* 2006; Belcher and Hudspith, 2016). This re-ordering of cells alters the reflective properties of the charcoal i.e. there is an increase in the quantifiable amount of light reflected from the surface of the charcoal as the structure becomes more ordered (more graphite-like) thus allowing researchers to study the reflectance properties of charcoal (Belcher, New *et al*., 2018).

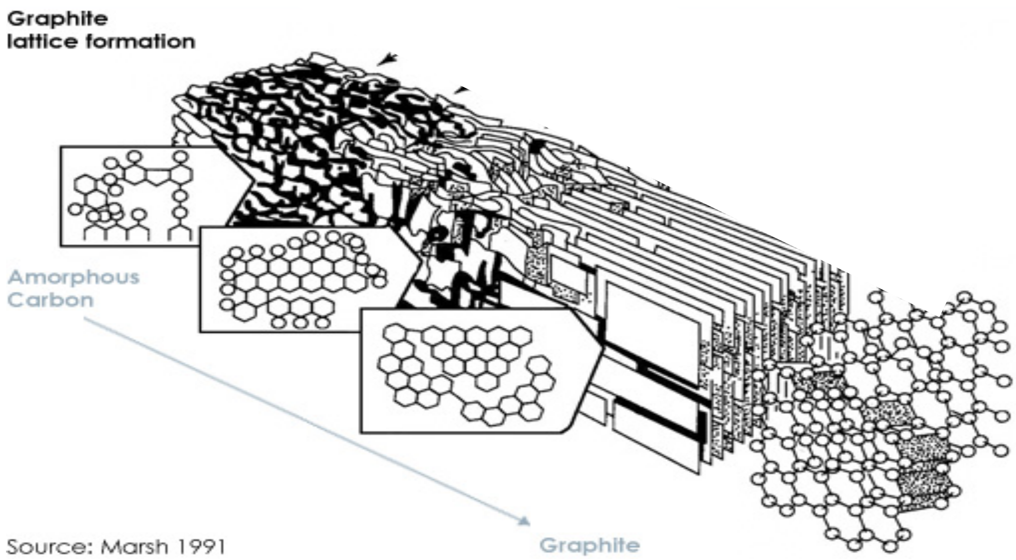

Figure 1.4: A visualisation of the re-ordering of wood cells during the combustion process. Source: Adapted from Marsh (1991 in SGLGroup, 2016).

In wildfire research charcoal is generally used as a tool to ascertain past fire activity in an ecosystem. This is done through charcoal quantification where the size and shape of the pieces are noted (Mooney and Tinner, 2011). This may be able to tell researchers whether this charcoal was from an in-situ/ local fire (macroscopic charcoal), or from a fire elsewhere/ windblown (microscopic) (Scott, 2010; Umbanhowar Jr and Mcgrath, 1998), but this does not provide researchers with any details about fire behaviour or the effects of fire i.e. fire severity. Reflected light microscopy is a technique that can be used to go beyond simply quantifying charcoal, this method is being developed to provide scientists with more information about the effects of a fire (Belcher and Hudspith, 2016). Most recently, researchers have begun to develop the use of charcoal reflectance in post fire assessments, ultimately building toward a quantitative fire severity metric (e.g. Belcher and Hudspith, 2016).

Charcoal reflectance has long been studied in the mining industry to determine the rank of coals (Jones *et al.,* 1997; Scott *et al.,* 2000). Therefore, with the knowledge that reflectance microscopy is a method that works when analysing coal, researchers investigating wildfires have adopted this method to analyse charcoal (Jones *et al.,* 1997; Scott *et al.,* 2000; Belcher and Hudspith, 2016). Measuring the reflectance of charcoal that has been embedded in resin and polished, using a reflectance microscope has been a method that has been implemented to provide researchers with the means to establish the relationship between formation temperature of charcoal and reflectance values of charcoal (Ascough *et al.,* 2010). However, in much of the existing research, oven formed charcoal was used which is not necessarily the best method in which to replicate natural wildfires (Belcher and Hudspith, 2016). Recent research has shown that this method of forming char does not capture the full range of combustion processes (Belcher and Hudspith, 2016). One process in particular is the heat flux generated by the fire which creates charcoal. During a natural wildfire the temperature field and therefore the distribution of heat is variable, in an oven or furnace the temperature is set at a constant heat flux (Alexander 1982; Finney *et al.,* 2015; Belcher and Hudspith, 2016). Therefore, the relationship between temperature/heat flux and reflectance values may be correct for those experiments which have used oven based methods to create charcoal, but this does not represent real-world wildfire conditions and the charcoal which is naturally created. Because of this, oven created charcoal cannot be compared to chars produced by real-world wildfires.

In contrast to oven-based methods, cone calorimetry better replicates the conditions of the combustion processes that occur in the natural environment (Belcher and Hudspith*,* 2016; Belcher, New *et al.,* 2018). Oven-based charcoal is produced in oxygen-depleted conditions thought to represent the effect of a flame on the surface of the fuel (Belcher and Hudspith, 2016). However, in a wildfire, as flaming ceases, both pyrolysis and oxidation of the fuel can occur as the flaming phase of the fire transitions to a smouldering fire (Rein 2013). Oven-based experiments therefore do not capture this phase in the formation of charcoal. Cone calorimetry, unlike a furnace or oven, does not operate under restricted atmospheric conditions (Belcher and Hudspith, 2016). The calorimeter exposes the fuel to a prescribed heat flux, ignites the fuel typically using a spark igniter, and then allows it to burn in a representative fire-environment (Belcher and Hudspith 2016).

Cone calorimetry is a well-established method which better replicates wildfire conditions closely and has recently been used by Belcher and Hudspith (2016). Belcher and Hudspith (2016) have shown that the highest reflectance values are achieved not according to temperature but when fires switch from flaming to smouldering, the transition between pyrolysis and char oxidation. This means that charcoal reflectance more likely captures the amount of heating experienced by plant material and not the temperature of the fire or flame. The preliminary findings by Belcher and Hudspith (2016) indicate that reflectance cannot provide information on certain fire behaviours such as fire/flame temperature or fire intensity, however they do suggest that reflectance measurements may be of use in providing a quantitative measurement to fire severity surveys.

It has been shown that charcoal reflectance is in a state of constant change throughout the combustion process (Belcher and Hudspith, 2016). Belcher and Hudspith (2016) showed that reflectance constantly changes during the different stages of combustion, samples of different moistures and different species all experienced lower reflectance values when extracted at peak heat release rate (PHRR) and higher values at the latter stage of the combustion process when flaming ceases (Figure 1.5). Recent research has also revealed that increasing charcoal reflectance is positively correlated with increasing total energy release, as measured in laboratory experiments and with total energy flux (as represented by the area under thermocouple curves) in an experimental wildfire, and with the duration of heating in both laboratory and field studies (Belcher, New *et al*., 2018).

This is important because the duration of surface heating, for example, has been found to relate to post-fire ecosystem recovery (Gagnon *et al.,* 2015) and to tree mortality (Keeley and McGinnis, 2007) which is useful information that can be used by policy-makers and land managers when deciding upon fire management strategies.

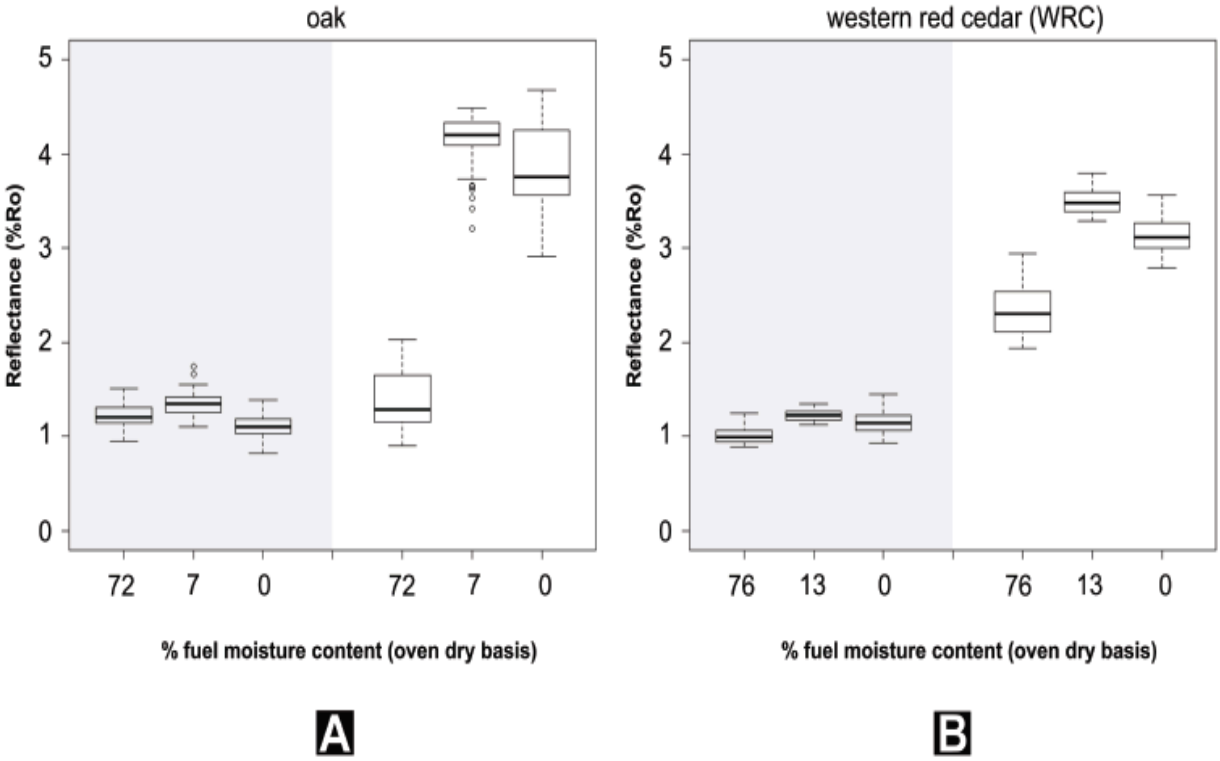

Figure 1.5: Boxplots showing charcoal reflectance values in relation to fuel moisture for Western Red Cedar and oak samples. The grey shaded area of each box represents samples removed at PHRR and the white area (right hand side) of the boxplot represents samples removed when flaming ceased (Belcher and Hudspith, 2016). Samples were burned at three different moisture conditions, represented by the three boxplots for each species. Source: Belcher and Hudspith (2016:16).

1.5.2 Fuel type, reflectance and fire severity

Building on the laboratory experiments of Belcher *et al.,* (2016 and 2018), in this thesis I have expanded this data to field scale fires and their effects, both unmanaged and managed. In this thesis I will look at the spatial distribution of charcoal reflectance across burned areas, charcoal reflectance in respect to fuel type and the likely range of charcoal reflectance values across a burned area, and how these relate to post-fire effects. The spatial distribution of fire severity should relate to alterations in forest structure and degradation.

The reflectance of charcoal has been shown to be influenced by fuel type (Hudspith *et al*., 2014). Hudspith *et al*., (2014) demonstrated though experimental methods the effect of different species on reflectance values across a peatland ecosystem. The main finding of their assessment was that fuel type was the main driver of pyrolysis intensity, for example different vegetation species/fuel type produced differing reflectance values even though they were burnt during the same fire (Figure 1.6) (Hudspith *et al.,* 2014). This is the first study looking at the reflectance of charcoal which has looked at, and successfully showed that fuel type has an influence on reflectance measurements (Hudspith *et al.,* 2014). This study by Hudspith et al., (2014) highlights the importance of starting the development of the charcoal reflectance method in a relatively simple ecosystem in order to gain an understanding of how reflectance values vary before moving on to more ecologically diverse ecosystems such as tropical rainforests.

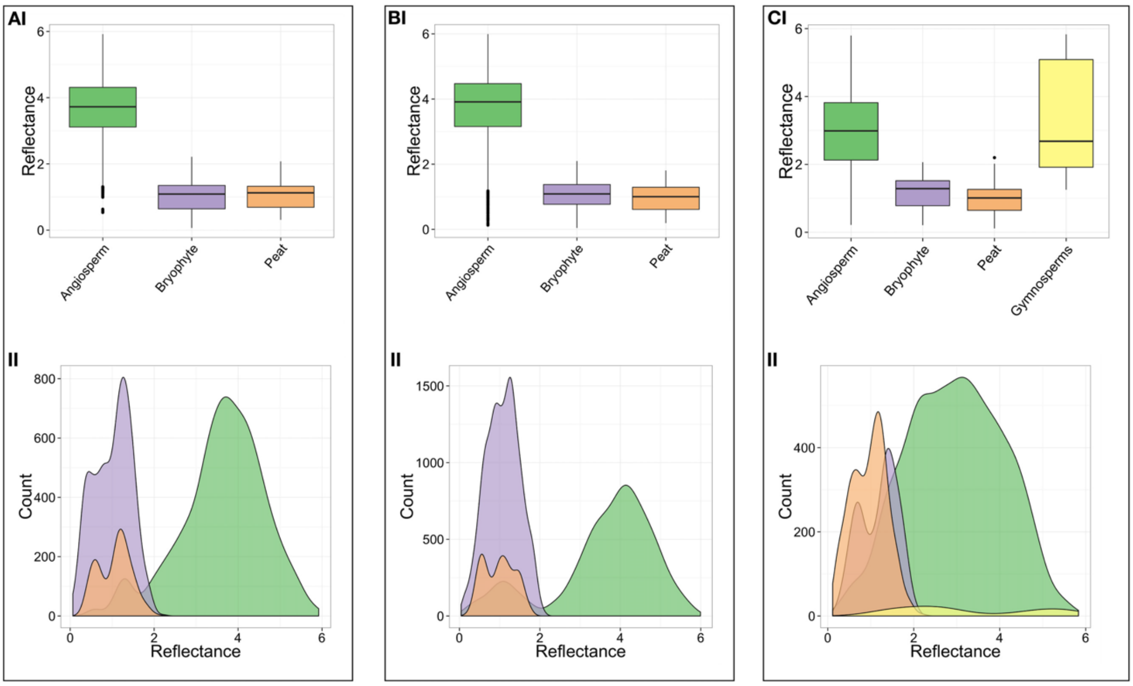

Figure 1.6: Boxplots from Hudspith *et al*. (2014) show charcoal reflectance from different species of vegetation and different fire severities: a) presents results from a light burn, fire severity 3, b) a moderate burn, fire severity 4, and c) a deep burn, fire severity 5. Source: Hudspith *et al.,* (2014:8).

Recent research in the Brazilian Amazon has shown that fuel type has an influence on fire behaviour. Flame height and flaming duration were two features of fire that were affected by fuel composition (Parsons *et al.,* 2015). This research has also gone further than just looking at species level interaction with fire, Parsons *et al.,* (2015) have investigated how species-specific traits, in particular leaves, are influencing flammability in the Brazilian Amazon. Those leaves that were thin and lightweight resulted in the most rapid and intense fires compared to those leaves that were larger and thicker (Parsons *et al.,* 2015). The researchers highlight the fact that in diverse forests such as those in Amazonia the relationship between species, their specific traits, and fire must be investigated allowing us to better understand fire behaviour in a structurally changing and more fire prone Amazon rainforest (Parsons *et al.,* 2015). However, Parsons *et al.,* (2015) have not looked at woody fuels and their influence on fire behaviour, reflectance has also not been looked at in this research.

In order to explore this, this thesis will build an understanding of reflectance distributions across burned areas in respect to vegetation distributions and map the fuel consumption (fire severity) of the same areas. This work began in relatively simple ecosystems of low diversity e.g. temperate UK moorland, and mapped the ecological regrowth according to fire severity and reflectance distributions. Once charcoal reflectance was developed into a metric with which to assess fire severity, i.e. an understanding has been gained regarding the relationship between charcoal reflectance and the effects of fire, charcoal samples collected across a number of ecosystems including the Amazon were investigated using the charcoal reflectance metric. During the analysis of different ecosystems, different fire types were also investigated.

1.5.3 The importance of fire type

The type of fire that has occurred is important to consider when assessing fire effects in an ecosystem. Fire intensity often varies between fire types (Davies, 2013) and we can therefore assume that fire severity is also variable. There are three generally accepted types of fire: (1) crown: high intensity fires that burn through tree and shrub canopies, (2) surface: variable intensity fires that burn litter on the ground surface, and shrubs beneath a forest canopy mainly fine and coarse fuels, (3) ground: low intensity fires that often smoulder through deep layers of decomposing organic matter e.g. peat (Davies, 2013). Fire intensity varies between fire types due to the type of fuel that dominates. Crown fires are fuelled by both leaf and woody material. In the most intense canopy fires, all woody biomass is consumed, whereas surface fires are generally driven by non-woody fuels such as grasses or at least fine 1 hr fuels (Bond and Keeley, 2005; Pausas, 2015).

Fire type varies across different ecosystems. These different fire types are being driven by climate and vegetation structure (Archibald *et al.,* 2018) (Figure 1.7). Fire in the boreal forests of North America for example are predominantly high-intensity crown fires which result in stand-replacing fire events (Archibald *et al.,* 2018). Fires in Europe on the other hand, are dominated by slow-spreading, low-intensity surface fires e.g. wildfires events in heathland and moorlands (Archibald *et al.,* 2018; Davies and Legg, 2008). Boreal forests in Canada and North America are dominated by flammable vegetation such as Spruce trees (*Picea)* which promote crown fires through their low lying branches (de Groot *et al.,* 2013). Eurasian boreal forests in comparison comprise of trees such as Larch (*Larix* spp.) which are deciduous and shed their dead lower branches reducing the threat of crown fires (Archibald *et al.,* 2018).

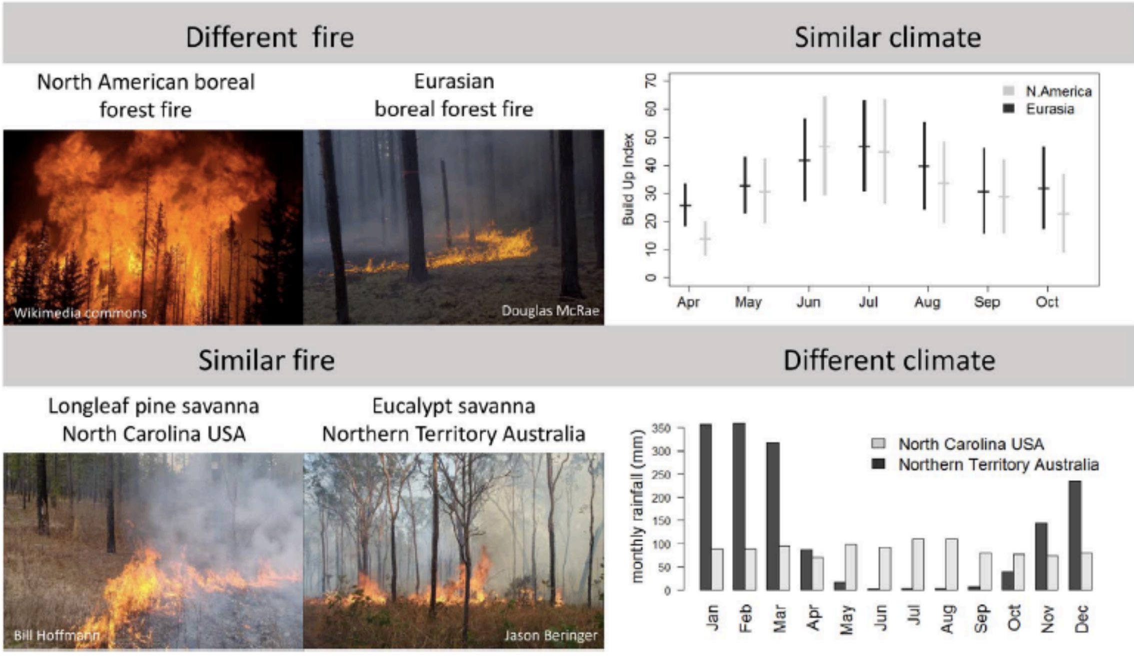

Figure 1.7: Figure taken from Archibald *et al.,* (2018) showing examples of how climate and vegetation structure can influence fire regimes in different regions across the globe. The first set of examples show how different vegetation structure in boreal forests in North America compared to boreal forests in Europe can produce different fire types (crown and surface, respectively) even though the two forests are experiencing the same climate. The second pair of images shows how a different climate can produce the same fire type i.e. crown fires in Longleaf savanna in North America and Eucalypt savanna in Australia (Archibald *et al.,* 2018). Source: Archibald *et al.,* (2018:5).

Crown fires receive much of the publicity in media as they are far more detectable than surface fires, leaving a greater fire scar on the landscape especially in ecosystems such as tropical rainforests where much of the ground/surface is blocked from view by the wide dense canopy of the rainforest (Peres, 1999; Haugaasen *et al.,* 2003). However, it is surface fires that are emerging in the scientific community as one of the greatest threats to the forest structure in ecosystems such as those in Amazonia (Cochrane and Laurance, 2008).

Reaching heights of only around 10-30cm and burning the fine and coarse surface litter on the forest floor surface fires could be thought of as causing little damage to the vegetation of the Amazon rainforest (Haugaasen *et al.,* 2003; Cochrane, 2003). However, major changes in forest structure occur due to surface fires especially in ecosystems such as tropical rainforests where species are less adapted and more vulnerable to the effects of fire i.e. thin barked trees and vegetation that grows on the base of trees e.g. lianas (Haugaasen *et al.,* 2003). The slow-moving spread of surface fires is the greatest threat to the surface vegetation and thin barked trees in the Amazon. The slow advance of the fire front means that fires linger in one area for a relatively long period of time (seconds-minutes) often resulting in severe damage and mortality of vegetation including trees (Cochrane and Laurance, 2008).

Surface fires are most common in tropical rainforests and also in ecosystems such as moorlands and peatlands where there is an extensive layer of surface fuel available (Cochrane, 2003). In these ecosystems where there are also deep layers of belowground organic matter there is also the threat of ground fires accompanying those occurring on the surface (Cochrane, 2003). One of the main differences between these two fire types in the tropical rainforest ecosystem is that surface fires that burn the litter layer are relatively easy to extinguish if discovered, ground fires on the other hand are almost impossible to extinguish and can result in major changes to forest structure i.e. complete destruction of seedbanks (Cochrane, 2003).

Surface fires are increasing in both frequency and severity in the Amazon rainforest for example. The increasing amount of dead and dying trees that gather on the forest floor after previous fires, deforestation etc. increase the amount of fuel on the ground and potentially increase the severity of subsequent fires in the area (Haugaasen *et al.,* 2003). The disruption to the carbon cycle and the increased likelihood of fire becoming a common occurrence in ecosystems is noted as being surface fires greatest ecological effect (Haugaasen *et al.,* 2003; Cochrane and Laurance, 2008).

1.5.4 Fire severity and vegetation regeneration

Fire severity can also be looked at in terms of how it affects seedling recruitment and seed banks. This is important to investigate, as how a forest responds after a fire has a major influence on carbon cycling and biodiversity. Seedlings are often mentioned in conjunction with nutrient availability and fire intensity (Balch *et al.,* 2008; Kennard *et al.,* 2002), but heat damage to the ground is also important. Increased fire severity for example has been found to have an indirect effect on seedling regeneration across a range of ecosystems including tropical forests and UK heathlands (Nepstad *et al.,* 1995, Haugaasen *et al.,* 2003; Davies *et al.,* 2010).

Prescribed burning in the UK is a recognised tool especially in regards to assisting with regeneration projects relating to conservation and ecological management (Davies *et al.,* 2008). It can be used to develop diverse forest habitats such as pine wood regeneration and the expansion of woodlands (Hancock *et al.,* 2005; Davies *et al.,* 2008). Post-fire regeneration in moorland and heathland ecosystems has been well documented in the literature (e.g. Gimingham *et al.,* 1981; Maltby et al. 1990; Bullock and Webb 1995; Legg

1995; Davies *et al.,* 2008). Vegetation age for example has been shown to be an important factor when deciding where to burn in moorlands/heathlands (Davies *et al.,* 2008). Post-fire regeneration may be poor in these older stands of vegetation resulting in a vegetation shift in the ecosystem, fire behaviour has also been shown to be more variable and less predictable in areas of mature growth (Davies *et al.,* 2006; Davies *et al.,* 2008; Davies *et al.,* 2010).

The post-fire environment, increased nutrient availability and increased light penetration, is one which favours the establishment of grasses and shrubs. This in turn has a negative impact on tree regrowth as they are outcompeted for water and nutrients by grasses (Balch *et al.,* 2008). A study by Kauffman (1991) for example found that in eastern Amazonia only half of the tree species in a study site were able to resprout after fire activity. The degree of change in post-fire nutrient availability can be attributed to differing fire intensities. Although the majority of these changes have a short-term impact on the system the addition/removal of nutrients to the system does affect seedling regeneration (Balch *et al.,* 2008). Those fires that are more intense i.e. higher amounts of energy release, and those that are more frequent have been found to cause a greater loss of nitrogen from the environment, whereas lower intensity fires can result in additions of inorganic nitrogen encouraging seedling germination and establishment (Balch *et al.,* 2008; Certini, 2005). Ultimately a feedback cycle is created (Figure 1.8) whereby the increase in fine fuels and light penetration, due to a reduction in the number of trees (canopy), increase the flammability of the forest and so on, this creates what is known by researchers as the ‘Gulliver effect’ (Bond and van Wilgen, 1996; Balch *et al.,* 2008). The ‘Gulliver effect’ is where larger species of vegetation are prevented from establishing in an ecosystem due to frequent fires, which result from the increase in fine fuels (Bond and van Wilgen, 1996; Balch *et al.,* 2008).

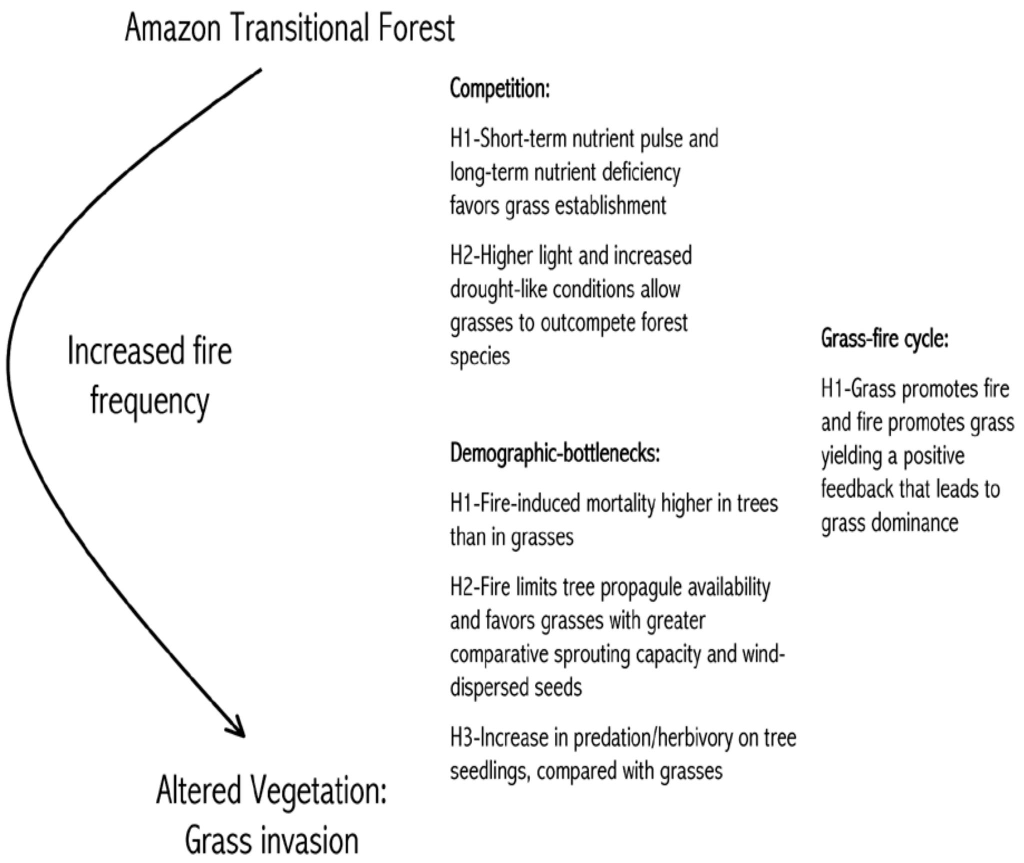

Figure 1.8: A diagram showing 'potential mechanisms of fire-induced grass invasion and establishment' (Balch *et al.,* 2008:495). Source: Balch *et al.,* (2008:495).

Vegetation regeneration and fire severity has recently been studied in the Brazilian Amazon (Flores *et al.,* 2016). The study took place along the floodplains of the Negro river, a different study site and environment than the tropical rainforest this thesis will be studying. However, similar to upland forest environments, floodplain forests burn severely during drought, and the mechanisms controlling forest regeneration after fire in both environments remains poorly understood (Flores *et al.,* 2016). Results show that in the forest floodplains repeated fires resulted in the complete destruction of tree seedbanks and a 100% increase in the amount of herbaceous cover on the forest floor (Flores *et al.,* 2016). After an initial fire where forest structure recovered slowly subsequent fires resulted in the floodplain forest becoming fragile, unable to recover and causing the loss of the forest structure and the persistence of a non-forested state (Figure 1.9) (Flores *et al.,* 2016).

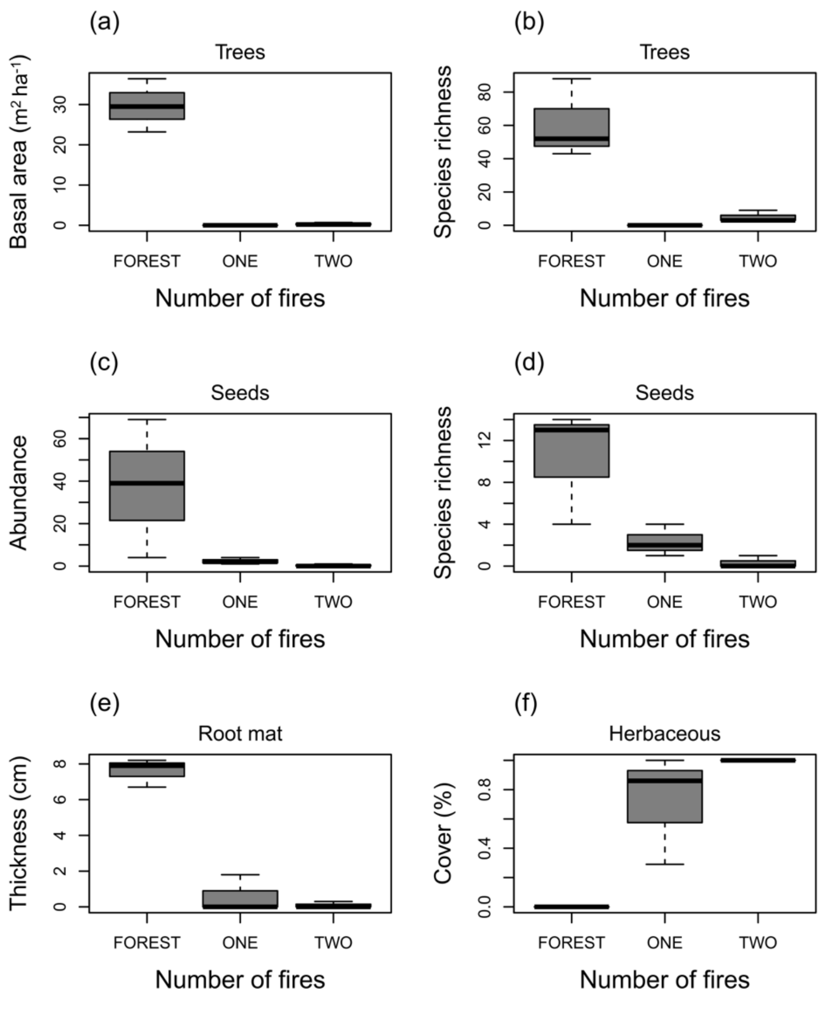

Figure 1.9: Recently burnt floodplain forest plots (3 years after last fire), boxplots show the vegetation state of forests with no burning, burnt once and burnt twice (Flores *et al.,* 2016). Source: Flores *et al., (*2016:20).

This fragility of the forest structure has also been seen in the upland forest environment where fires increasing due to human presence and changing climates are increasing fire severity resulting in forests losing up to 98% of their seedbanks (Nepstad *et al.,* 1995; Kennard *et al.,* 2002; Haugassen *et al.,* 2003; Bush *et al.,* 2008; Alencar *et al.,* 2011; Silvério *et al.,* 2013; Flores *et al.,* 2016).

Therefore, it is reasonable to suggest that fire severity and frequency of fires should be considered as two of the most important factors influencing regeneration in ecosystems, especially those not adapted to the effects of fire e.g. in the tropics. The fate of the Amazon in one sense depends on the resilience of vegetation to fire and the regeneration of seedlings, and re-establishment of species after fire activity (Brando *et al.,* 2014). One of the aims of this thesis is to determine how well, if possible, charcoal reflectance can inform researchers about regrowth potential, this will be discussed in the first data chapter, Chapter 3.

1.6 Thesis overview and aims

The research presented in this thesis addresses the issue regarding fire severity and the lack of quantitative methods that currently exist that can be used to analyse and assess this aspect of fire. Existing methods have caveats that charcoal reflectance can overcome whilst also providing advantages for its user. Those methods used in the past to assess fire severity are primarily qualitative and subjective, or, rely on good weather and cloud-free days as most satellites require. Charcoal reflectance provides its user with quantitative data free from subjectivity, and, as long as the charcoal can be collected from the burned area, the weather is not a limiting factor for this method. Ultimately, this research aims to develop charcoal reflectance into a fire severity metric. In the course of this development I will demonstrate through the analysis of charcoal from a number of different locations from around the world, that this metric can be used as a quantitative tool which researchers can use to gain information about the fire that has formed the charcoal, information that could not have been gained from existing fire severity metrics.

The following are more specific aims of this thesis:

1) **To ascertain how well charcoal reflectance compares to existing fire severity metrics**

   This will be achieved by comparing charcoal reflectance values to existing metrics including satellite derived severity data and qualitative severity assessments.

2) **To determine if charcoal reflectance can record the spatial distribution of heat across a burned area**

   Through the analysis of charcoal from across burn scars can the dynamic nature of fire be recorded in the charcoal that is formed, and what information regarding the fire can be retrieved using charcoal reflectance.

3) **To use the analysis of charcoal reflectance results to address real-world problems i.e. management of fires**.

   This will be done through analysing unmanaged fires in the form of wildfires (ignition undeterminable) and comparing these results to managed fires which are experimental or prescribed burns;

those fires that have been ignited by firefighters and researchers in order to achieve an objective.

4) **To establish the key drivers of charcoal reflectance**

This will enable researchers to the use charcoal reflectance as a metric with which to assess fire severity post-fire whilst being able to take into account any underlying factors which may have affected the measurements. This will be done by obtaining a range of charcoal samples from a variety of ecosystem types, fuel types and fire regimes in order to be able to better understand what factors may be driving the establishment of charcoal reflectance.

1.7 Thesis structure and chapter overviews

Chapter 2 will discuss in detail the charcoal reflectance method. The methodology will include the preparation of samples and the process of obtaining the measurements using the reflectance microscope. A short synthesis of charcoal reflectance has been provided in each of the data chapters, with Chapter 2 presented in this thesis as a full methodology for reference.

The first data collection chapter will be Chapter 3. This chapter begins the development of charcoal reflectance as a fire severity assessment metric by analysing charcoal collected from heathland fire in Carn Brea, Cornwall. The link between reflectance and regrowth potential is explored whilst comparing charcoal reflectance to a qualitative fire severity assessment. This qualitative assessment is based on Ryan and Noste's (1985) original matrix which related fire severity to changes in soil organic matter and aboveground vegetation.

Chapter 4 discusses the use of several metrics with which to assess fire severity across two burn scars in the Pinelands National Reserve (PNR). A mixture of qualitative and quantitative techniques, including charcoal reflectance, are described and compared to one another. Satellite derived data in the form of Difference Normalized Burn Ratio (dNBR) are also included, of which the data sets and maps were obtained from Professor Timothy Warner (2017, personal communication) (Warner *et al.,* 2017).

Chapter 5 analyses the fire severity of an unmanaged wildfire in the PNR, Breeches Branch, and then compares the results of this analysis to that of managed fires, which have been discussed individually in more detail in Chapter 4.

Chapter 6 is the final data collection chapter and compares the reflectance values of a variety of ecosystems and fire regimes, whilst evaluating the ability of charcoal reflectance to act as a metric to use in the analysis of fire severity. Charcoal from the Brazilian Amazon, UK moorland and heathland ecosystems, Canadian boreal forests and an Australian tropical forest have been analysed as part of the investigation of the use of reflectance in assessing the fires which created the charcoal collected from these sites.

Chapter 7 provides a synthesis of the main discussion and conclusions points from the four data chapters. Research implications and future directions for the charcoal reflectance metric have also been ascertained and are included at the end of this chapter.

1.8 Contributions to co-authored papers

Chapter 3 has been published in the International Journal of Wildland Fire (New *et al.,* 2018). The charcoal used in the analysis was collected by Dr Victoria Hudspith, whom also embedded the charcoal in the resin. I conducted the rest of the laboratory work which included polishing the blocks and obtaining the measurements of charcoal reflectance using the reflectance microscope. The paper was written by me with some suggestions to the manuscript provided by Professor Claire Belcher who was a co-author on the paper.

Work undertaken as part of this PhD has also been published in Belcher, New *et al.,* (2018). The work that I conducted and that was included in the paper included laboratory testing of different density woods using the iCone calorimeter in the wildFIRE Lab at the University of Exeter. The analysis of the reflectance data from these charring experiments and aspects of this research have been discussed in the Chapter 6.

Chapter 2

Charcoal reflectance methodology: sample preparation and data gathering

For the majority of the charcoal samples analysed as part of this thesis, the charcoal was removed straight from the ground surface after the fire, or the charcoal was removed from the vegetation itself, i.e. tree bark and branches from heather or bracken (Figure 2.1a) and this meant that the charcoal was therefore relatively clean, free from dried in soil and organic material. However, for the Amazonian soil samples (Feliz Natal) the charcoal was very dirty; covered in dried-in sediments that were difficult to remove (Figure 2.1b). This was more than likely due to the fact that these samples were collected from the soil, which may have had a higher clay content, and had been in situ for longer than the freshly recovered charcoal samples from the other study locations. Therefore, before the samples were embedded in the resin they were first cleaned, and any organic material or soil was removed from the particles using the hydrogen peroxide (H_2O_2) digestion method.

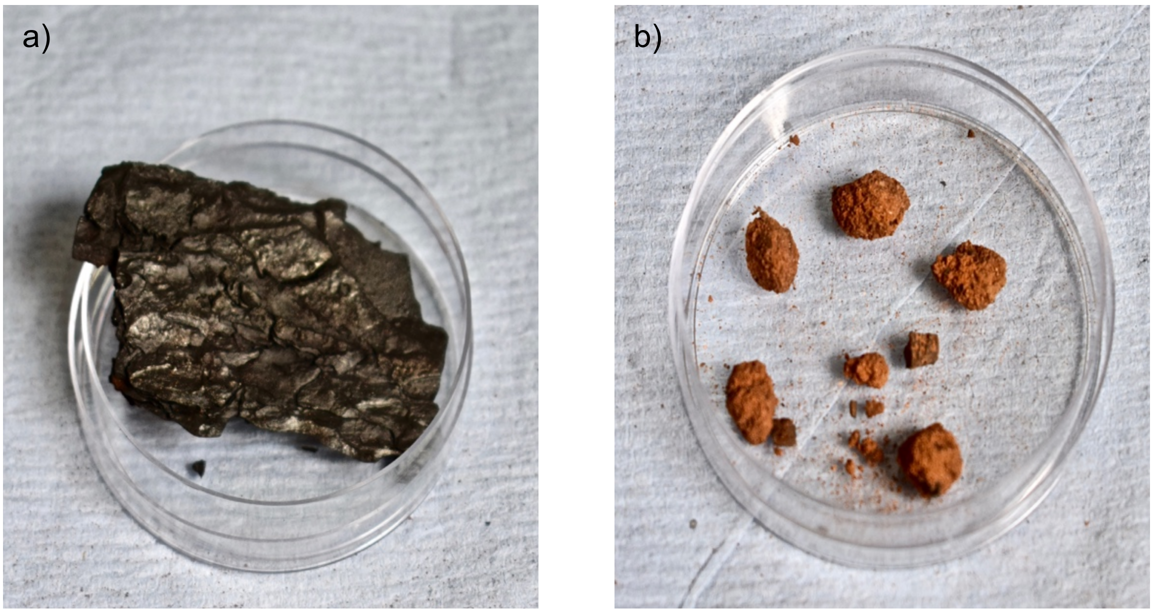

Figure 2.1: Images of a) bark charcoal from *Pinus rigida* in the New Jersey Pinelands National Reserve, b) soil charcoal from Feliz Natal in the Brazilian Amazon.

This method was used as it bleaches and loosens organic material and sediment and leaves the charcoal clean. Charcoals from field samples were collected or provided from the locations listed in Table 2.1.

Table 2.1: Table showing information regarding the charcoal samples analysed in this thesis.

Site	Charcoal Type	Described in Chapter	Plant family
Carn Brea, Cornwall, UK	Charred branches of heather and gorse	3 & 6	Angiosperms
Lost Lane, NJ, USA	Bark from charred Pitch Pine trees	4 & 5	Gymnosperms
Chatsworth Road, NJ, USA	Bark from charred Pitch Pine trees	4 & 5	Gymnosperms
Breeches Branch, NJ, USA	Bark from charred Pitch Pine trees	5	Gymnosperms
Triangle plot, Northwest Territories, Canada	Western Red Cedar blocks	6	Gymnosperms
Pine Point, Northwest Territories, Canada	Western Red Cedar blocks	6	Gymnosperms
Britannia fire, VIC, Australia	Western Red Cedar blocks	6	Gymnosperms
Feliz Natal, Mato Grosso, Brazil	Charcoal from soil	6	Angiosperms
Winter Hill, Greater Manchester, UK	Charcoal from grass and bracken	6	Angiosperms and Bryophytes

Similar protocols to clean charcoal particles have been used to analyse the macroscopic charcoal fraction by researchers such as Rhodes (1998) and Schlachter and Horn (2010). These methodologies used concentrations of hydrogen peroxide (H_2O_2) ranging from 1% to 9%, and lengths of time ranging from 8 hours to 24 hours in which the material has been left to digest. H_2O_2 has been used as charcoal particles, unlike non-charred organic material, are not bleached or digested by H_2O_2 therefore making charcoal identification easier (Rhodes, 1998; Schlachter and Horn, 2010). The charcoal samples from the collected from Feliz Natal did not have much organic material attached to the particles, however, they were covered with a thick layer of red sediment. The soils in the Feliz Natal region are old highly weathered soils with high aluminum content and lower acidity (Quesada *et al.,* 2010). Therefore, for these samples a solution made up of equal parts 6% hydrogen peroxide and 10% sodium metaphosphate was used (Higuera *et al.,* 2014). The charcoal particles were placed in 10ml of the solution for 24-48 hours depending on the amount of material attached to the charcoal particles. After soaking in the solution, a soft paint brush was used to assist with the removal of sediment that was still attached to the charcoal particles as they were decanted from the supernatant liquid into a 250μm sieve using deionized water. As a result of the H_2O_2 digestion the material attached to the charcoal particles came off fairly easily. Once cleaned, the particles were placed into plastic sample containers and left to dry again in the oven at 40°C for 48 hours before commencing the embedding stage. Those charcoal particles that were clean enough to not have to go through the H_2O_2 cleaning stage were oven dried at 40°C for 48 hours before the embedding process began.

All of the charcoal samples analysed as part of this thesis were embedded in polyester resin blocks and subsequently ground and polished (Belcher and Hudspith, 2016). The type of embedding that this research has used is referred to as cold-mounting epoxy resin. This is a relatively simple technique consisting of two components, an adhesive and a hardener (Jones and Rowe, 1999). Resin blocks are created by filling plastic moulds (Figure 2.2a) with a prepared polyester resin mix (polyester resin in styrene) and allowed to set overnight.

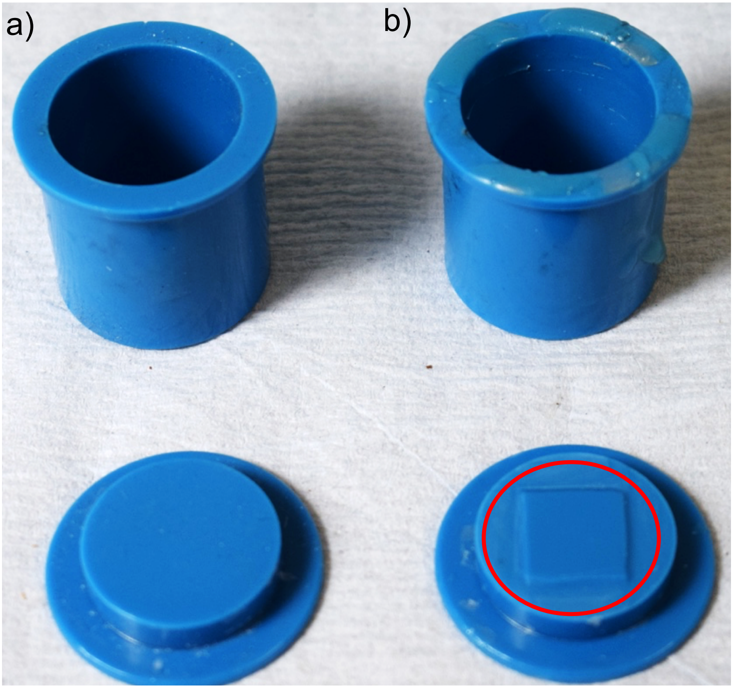

Figure 2.2: Images of a) unmodified resin mould used to create resin blocks that are smooth on both the bottom and the surface of the block, and b) resin mould with ground down square base (circled in red) used to create resin blocks with a square indentation for the ground-up charcoal samples.

Some of the samples were ground and some were not. All bark charcoal samples were prepared in homogenised ground form, whilst all others were imbedded as their respective small sized particles. To create the blocks for the ground-up charcoal the following steps were taken. A selection of the moulds were altered by grinding out a square platform into the base (Figure 2.2b) so that once set the block will have a shallow depression in the surface in which to insert the ground-up charcoal samples. For charcoal taken from the Lost, Chat and Breeches Branch studies, the charcoal samples were ground using a pestle and mortar (Figure 2.3). This was because the field sampling procedure did not allow us to know the way up of the particles. All bark particles were large, therefore a subset was selected and ground to produce a homogenised sample, where the highest reflecting ground particles would be measured. This meant that the parts of the wood that would have faced outwards towards the oncoming flames were measured.

Figure 2.3: Image showing ground-up charcoal in a mortar and on a spoon type implement ready to be placed onto a resin block with square indentation on the surface of the block.

Ground charcoal preparation: Once the blocks were made and had set, the ground-up charcoal was spooned into the depression on the surface of the block, a pipette was then used to drop a small amount of epoxy resin (Struers EpoFix Resin) onto the sample and left to dry for 48 hours. All other charcoal particles (see Table 2.1) were individually placed on the surface of the block and not ground into a powder. This was for several reasons 1) the Amazonian charcoal did not have enough material to grind the sample, in some instances the charcoal was ~1mm in size (Figure 2.1b), and 2) for the Western Red Cedar and Jack Pine samples these were blocks placed into fires and we wanted to be able to retain the upright position of these samples for other studies that were running in parallel to this study.

Before allowing to set the samples were placed in a vacuum pump ensuring that the resin has been drawn down into the cells of the charcoal particles. After the air bubbles have settled on the surface the samples are removed, and more resin added. This process is repeated until no more bubbles appear on the surface of the block. After the resin had fully set the surface of the block was ground using a MetaServ 250 with Vector Power Head grinder-polishing machine (Buehler, Neckar, Germany), with a silicon carbide disc (50μm grain size) (Figure 2.4a). Sample surfaces were then polished using a Kemet synthetic silk polishing pad and a 3μm diamond suspension polishing solution (Figure 2.4b) (Belcher and Hudspith, 2016) which is sprayed onto the surface of the polishing cloth maintaining the moisture of the cloth during the polishing procedure. The surface polish quality of the blocks was checked under a Zeiss Axio-Scope A1 optical microscope, with a TIDAS-MSP 200 microspectrometer (SMCS Ltd, Baldock, UK), for any scratches (Jones, 1999; Hudspith *et al.,* 2014; Belcher and Hudspith, 2016).

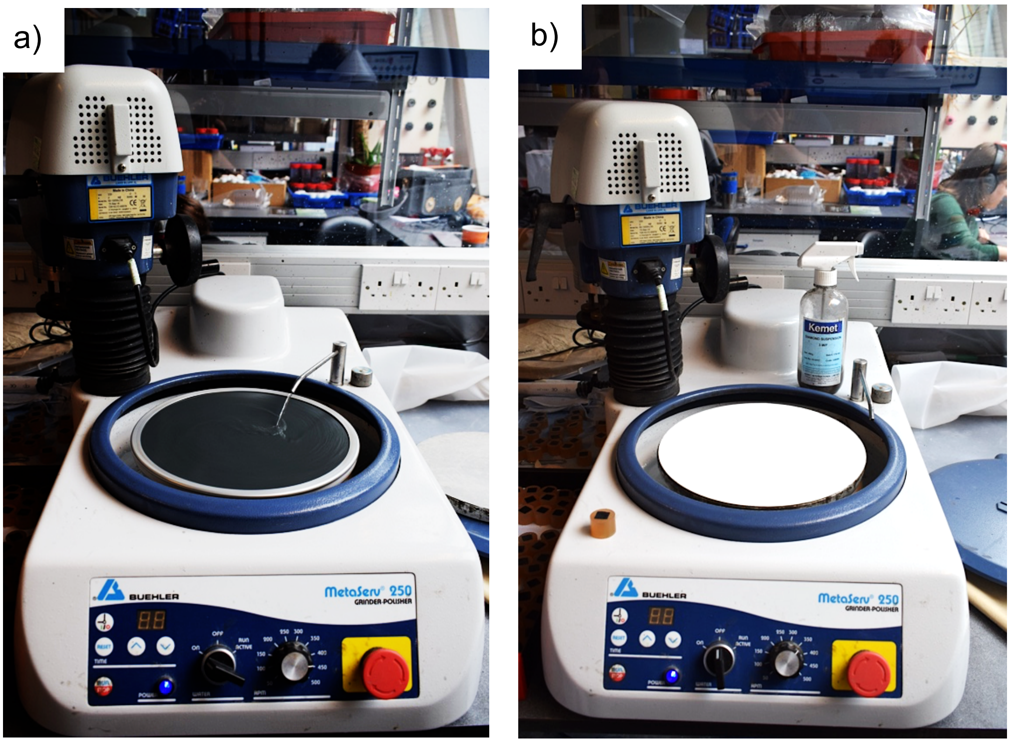

Figure 2.4: Images showing the MetaServ 250 with Vector Power Head grinder-polishing machine (Buehler, Neckar, Germany), with a) a silicon carbide disc (50μm grain size) attached, used to grind the surface of the block, and b) attached to the machine is a Kemet synthetic silk polishing pad and a 3μm diamond suspension polishing solution shown in the spray bottle just behind the disk.

Unground charcoal preparation: For the other charcoals I followed the method of embedding used by past charcoal reflectance methodologies (e.g. Belcher and Hudspith, 2016). In contrast to grinding the charcoal and filling a small depression in the resin block with ground charcoal (Figure 2.5a), the non-ground charcoal samples were embedded as whole pieces onto the resin block (Figure 2.5b). Here the resin moulds were filled approximately ¾ full with the wet resin, and then when dry the particles were attached to the top of the block by placing charcoal pieces (using tweezers if small) on to the surface of the block and using a pipette to add a drop of resin onto the charcoal to hold it in place. When set, the block with charcoal particle attached was placed back into the mould and the mould topped up to the top of the mould so that the charcoal particle was completely covered in resin.

a)

b)

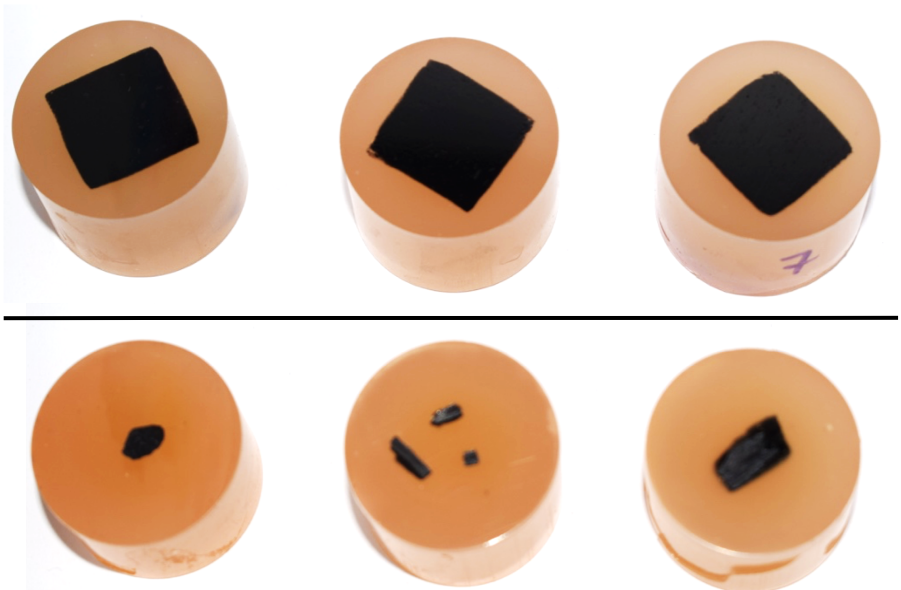

Figure 2.5: Images showing the charcoal particles embedded in the resin blocks. a) Shows the embedded ground charcoal and b) shows the whole particles of charcoal embedded as an unground single piece.

Once the polishing process was complete the resin blocks were attached to a glass slide using a pressure-sensitive adhesive putty and a few drops of immersion oil (RI 1.514 at 23°C) is added to the polished surface and the sample placed under the microscope (Figure 2.6). The oil acts as a bridge between the sample and the microscope lens (Jones, 1999).

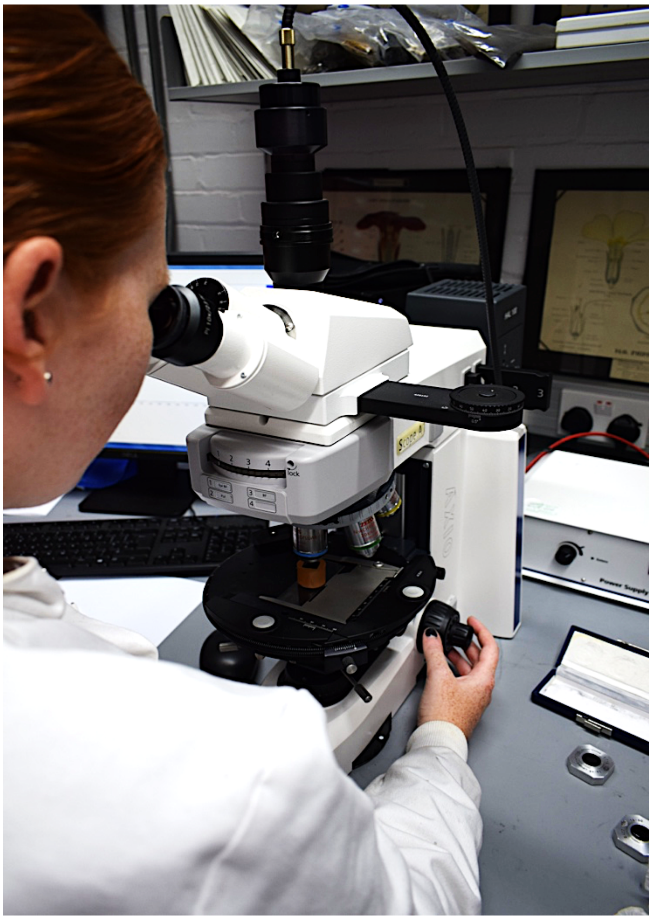

Figure 2.6: Image of the reflectance microscope being used to analyse a resin block.

The TIDAS-MSP 200 system is calibrated using three synthetic reflectance standards, strontium titanite (5.41% reflectance in oil (Reflectance)), gadolinium gallium, garnet (GGG) (1.719% Reflectance) and spinel (0.42% Reflectance) (Belcher and Hudspith, 2016). An x50 objective (with x32 eyepiece magnification) is used and the measurement of reflectance is manually taken at the cell-wall junction (Figure 2.7) using *MSP200 v 3.27* software (Belcher and Hudspith, 2016). Where possible, thirty reflectance measurements were taken per sample, with 3 replicates per tree or sampling location. The whole block was traversed under the microscope, moving from the top of the bock to the bottom in a sweeping pattern to ensure the whole block was covered and measured.

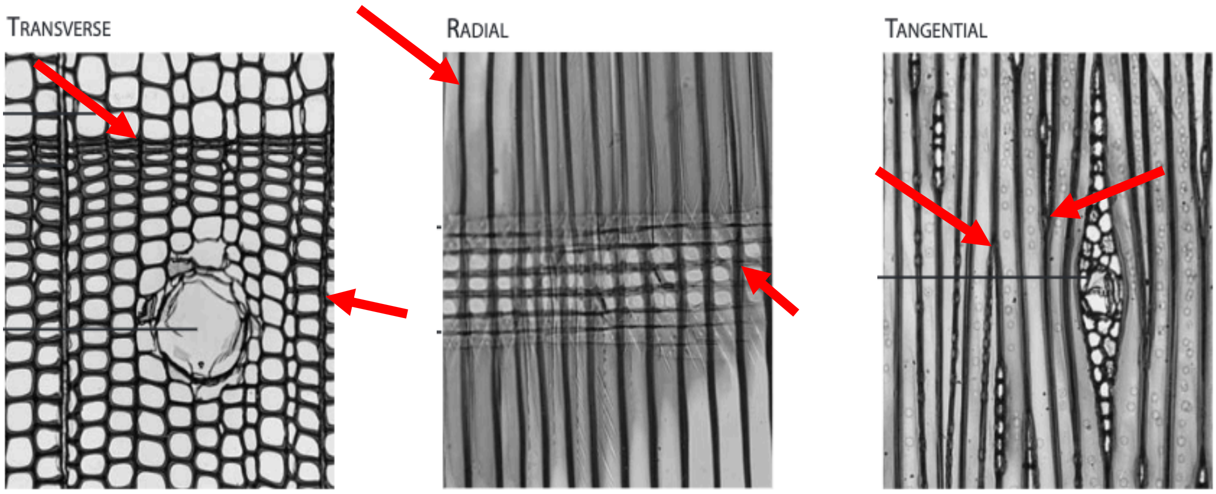

Figure 2.7: Thin sections of wood (pine) magnified x100 showing different views of the tracheids that would be seen under a microscope (Hoadley, 2017). The red arrows point to the sections of the tracheids which would be measured under the reflectance microscope. This is the cell wall, which is shown as black lines in these images, but will be grey/silver/white under the reflectance microscope depending on the how reflective the piece of charcoal is (see Figure 2.8). Source: Hoadley (2017: 20).

The charcoal reflectance values obtained from the analysis of charcoal varied both across and within the various study sites investigated in this thesis. Figure 2.8 shows three different pieces of charcoal with differing reflectance values, these demonstrate the visual differences in the colour/brightness of the charcoal depending on its reflectivity.

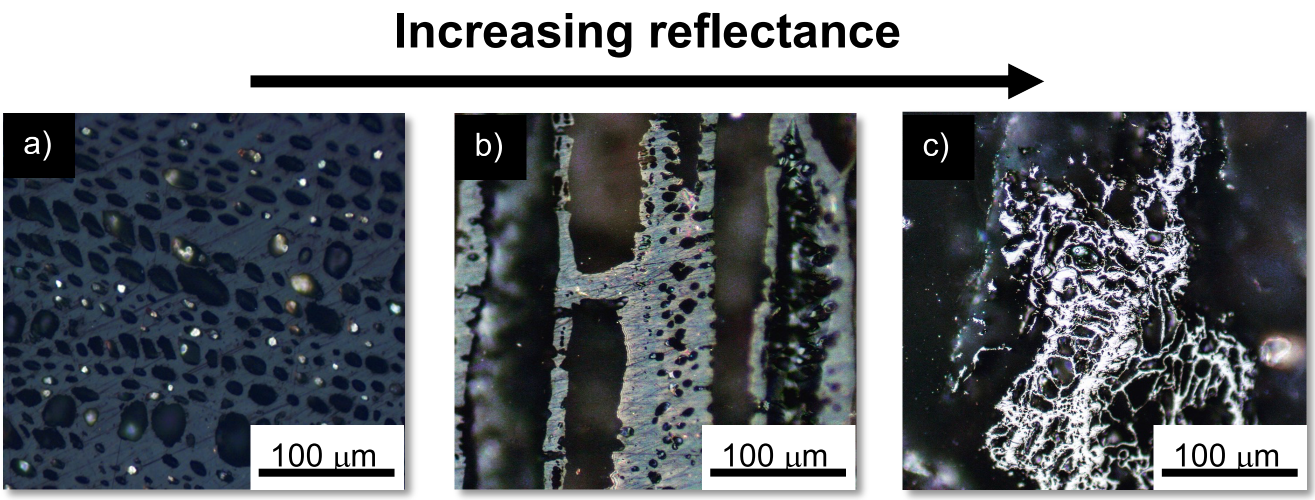

Figure 2.8: Images of charcoal reflectance under the reflectance microscope. The reflectance values for the pieces of charcoal are as follows: a) 0.15%, b) 0.71, c) 2.33%. These charcoal samples were taken from the Carn Brea study site (more information about this study site can be found in chapter 3).

This chapter has provided a detailed description of the charcoal reflectance method, from the preparation of the samples to the gathering of data from the reflectance microscope itself. Shorter summaries of the charcoal reflectance method have been included in each chapter along with the description of the particular way in which the samples were embedded and the number of measurements taken should it vary.

Chapter 3

Quantitative charcoal reflectance measurements better link to regrowth potential than ground-based fire severity assessments following a recent heathland wildfire at Carn Brea, Cornwall, UK

This chapter is based on New, S.N., Belcher, C.M. and Hudspith, V.A. (2018) ‘Quantitative charcoal reflectance measurements better link to regrowth potential than ground-based fire severity assessments following a recent heathland wildfire at Carn Brea, Cornwall, UK’, *International Journal of Wildland Fire*, *7*(12), pp.845-850.

3.1 Abstract

Charcoal has recently been suggested to retain information about the fire that generated it. When looked at under a microscope, charcoals formed by different aspects of fire behaviour indicate different ability to reflect the amount of light when studied using the appropriate technique. It has been suggested that this method, charcoal reflectance (Ro%), might be able to provide a quantitative fire severity metric that can be used in conjunction with or instead of standard qualitative fire severity scores. We studied charcoals from a recent heathland wildfire in Carn Brea, Cornwall, UK, and assessed whether Ro% can be linked to standard qualitative fire severity scores for the burned area. We found that charcoal reflectance was greater at sites along the burned area that had been scored as having a higher qualitative fire severity. However, there were clear instances where the quantitative charcoal reflectance measurements were able to better indicate damage and regrowth potential than qualitative scoring alone. We suggest measuring the reflectance of charcoals may not only be able to provide quantitative information about the spatial distribution of heat across a burned area post fire but that this approach is able to provide improvement to fire severity assessment approaches.

3.2 Introduction

Fire has been suggested to have a complex role in the ecology of moorlands and heathlands (Davies *et al.,* 2016). Recent debates regarding this role have focused on the use of fire as an ecological management tool (Davies *et al.,* 2016). Such debates have centred around arguments based on the long-term historical use of fire in these settings versus building an understanding of how different fire disturbance regimes might influence the dynamic equilibrium that exists in moorland and heathland ecosystems (Davies *et al.,* 2016). Some research has suggested that the presence of burning in these landscapes may have negative impacts (Brown *et al.,* 2015) or argues that we lack the understanding that fire effects have on long-term carbon storage in these ecosystems (Douglas *et al.,* 2015). Most moorland and heathland vegetation is, however, highly flammable and ignitions are common either via arson or accidental ignition. Recent examples of these types of ignitions include the large fires of summer 2018 on Saddleworth Moor and Winter Hill in the UK. As such, the impact of both managed and unmanaged fires requires building an additional understanding of the impact of different fire types on these ecosystems.

It has been suggested that the combination of the duration, degree and depth of heating at and below ground level will govern the impact of managed and unmanaged wildfires on moorlands or heathlands (under conditions where any peat beneath does not ignite) (Neary *et al.,* 1999). For example, extended periods of heating above 50°C are likely to induce cambial kill in *Calluna* species, limiting resprouting (Davies *et al.,* 2010).

Instrumented prescribed burns have been undertaken in such ecosystems and have provided valuable insight indicating that *Calluna* stand age and soil heating are both linked to the success of post-fire recovery (e.g. Davies *et al.,* 2010). However, if we are to understand a range of management approaches and particularly compare them with unmanaged fires, post-fire methods are required because it is not easily practicable to fully instrument managed areas before a burn and even more difficult to achieve this in unmanaged fires. Novel tools that enable post-fire assessments of energy regimes are needed so that linkages between energy release and fire effects can be monitored.

Researchers have established that the structure of charcoal varies during creation owing to several different factors such as wood species, wood density and heating regime (Cohen-Ofri *et al.,* 2006; Lowden and Hull 2013; Belcher *et al.,* 2018). Experimental research has indicated that during the combustion process, charcoal transitions through various phases in which cells are eventually re-ordered to a more graphite-like structure (Cohen-Ofri *et al.,* 2006; Belcher and Hudspith 2016). This re-ordering of cells alters the reflective properties of the charcoal, i.e. there is an increase in the quantifiable amount of light reflected from the surface of the charcoal as heating continues (Jones *et al.*, 1991; Belcher and Hudspith 2016).

Research has shown that reflectance is in a state of constant change throughout the combustion process, where maximum charcoal reflectance is reached at the end of flaming combustion and the end of exposure to heating (Belcher and Hudspith 2016), where a strong positive relationship between increased total heat released during combustion and increased charcoal reflectance has been observed (Belcher *et al*., 2018). This seems highly relevant with respect to findings that the total energy released from fires can be linked to its impacts in this ecosystem type (Hamilton 2000). As such, charcoal's ability to retain information about the fire has the potential to make the study of charcoals a valuable resource in heathland and moorland fire research.

Many existing post-fire studies include qualitative approaches that assess fire or burn severity on the ground via qualitative visual evaluation of organic matter loss above ground and below ground (Keeley 2009). More recently, quantitative satellite-based burn severity assessment approaches are being used with varying results on such ecosystem types (e.g. Schepers *et al.,* 2014). These approaches have been shown to be able to characterise burned compared with unburned areas of moorland and heathland, to remotely assess burn severity among the different vegetation types with confidence, some understanding of pre-fire vegetation distributions is required. However, neither of these approaches yield information that is inherently linked to the energy regime that formed them. For this reason, the present research has studied the potential use of charcoal reflectance in post-fire assessments as a tool to explore the variation in energy delivered by fires in moorlands and heathlands. Here, we suggest that areas that have burned and experienced a higher total energy release will produce charcoal that is more highly reflecting. We present findings of reflectance measurements in combination with a qualitative ground-based fire severity survey from a recent wildfire in a heathland fire at Carn Brea, Cornwall, UK. Our aim is to consider whether measuring charcoal reflectance may provide a useful tool for disentangling the effects of managed and unmanaged fires on moorland and heathland ecosystems.

3.3 Methods

3.3.1 Study site, sampling and monitoring

An unmanaged heathland fire in a region dominated by heather (*Calluna sp.*) and gorse (*Ulex europaeus*) occurred on 26 May 2015, burning 7 ha in Carn Brea, Cornwall, UK (50.2141°N, 5.2551°W) (BBC 2015) (Figure 3.1). The heathland (maximum elevation of 252 m) is dominated by peat and gravelly acidic soils, and gorse and heather are the main fuel constituents; this mixed vegetation structure is homogeneous across the heathland (Natural England 2014). The patches of gorse and heather are intersected by several small streams and exposed granite outcrops (Natural England 2014). Charcoal samples and fire severity scores were taken 2 days post fire. A transect was taken across the axis of the fire scar, and the charcoal sampling locations documented using a Global Positioning System (GPS) device and photographs taken at each site. Samples were collected every ~1 m using a 1m x 1m quadrat and collecting charcoal within that area. The fire started at the bottom of the heathland and travelled uphill to where a footpath intersected the heathland, which appeared to have acted as a ‘natural’ fire break. Twelve sampling locations were identified along the transect and scored for fire severity following the descriptions shown in Table 3.1.

Nine months later, the ecological response to the 2015 fire at Carn Brea was assessed (March 2016). The vegetation regrowth was visually assessed and photographs taken at the 12 sampling locations at which the charcoal samples had been previously collected (Figure 3.2).

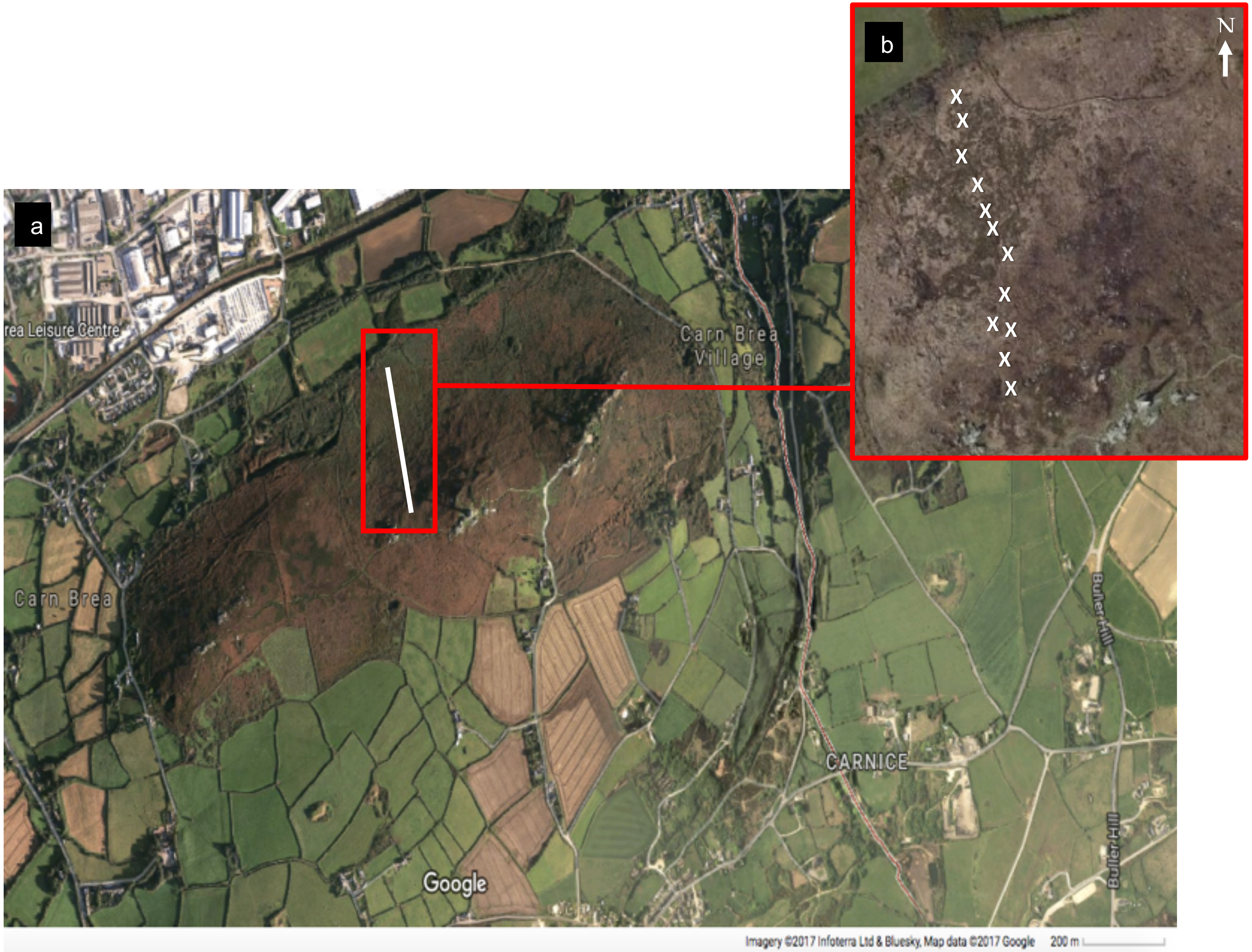

Figure 3.1: Map of Carn Brea. (a) Overview map of site including transect (white line), inset map (b) sampling locations (white crosses) along the transect (Google Maps, 2017).

Table 3.1: Fire severity field classification and severity scores; a simplified version of Ryan and Noste's (1985) original matrix that related fire severity to changes in soil organic matter and aboveground vegetation. This table has been modified for Carn Brea, after Keeley (2009). Source: Keeley (2009:119).

Fire severity	Fire severity score	Description, modified for Carn Brea
Unburned	1	Plant parts green and unaltered, no direct effect from heat
Scorched	2	Unburned but heather and gorse exhibit leaf loss from radiated heat, fine fuels on ground charred
Light	3	Grass tussocks charred by radiated heat. Surface litter, mosses and herbs charred or consumed. Soil organic layer largely intact and charring limited to a few millimetre depth
Moderate or severe surface burn	4	Shrubs charred or consumed, base of tussock remaining. Fine dead twigs on soil surface consumed. Pre-fire soil organic layer largely consumed
Deep burning or crown fire	5	Exposed heather and gorse roots. Surface litter of all sizes and soil organic layer largely consumed. White ash deposition and charred organic matter to several centimetre depth

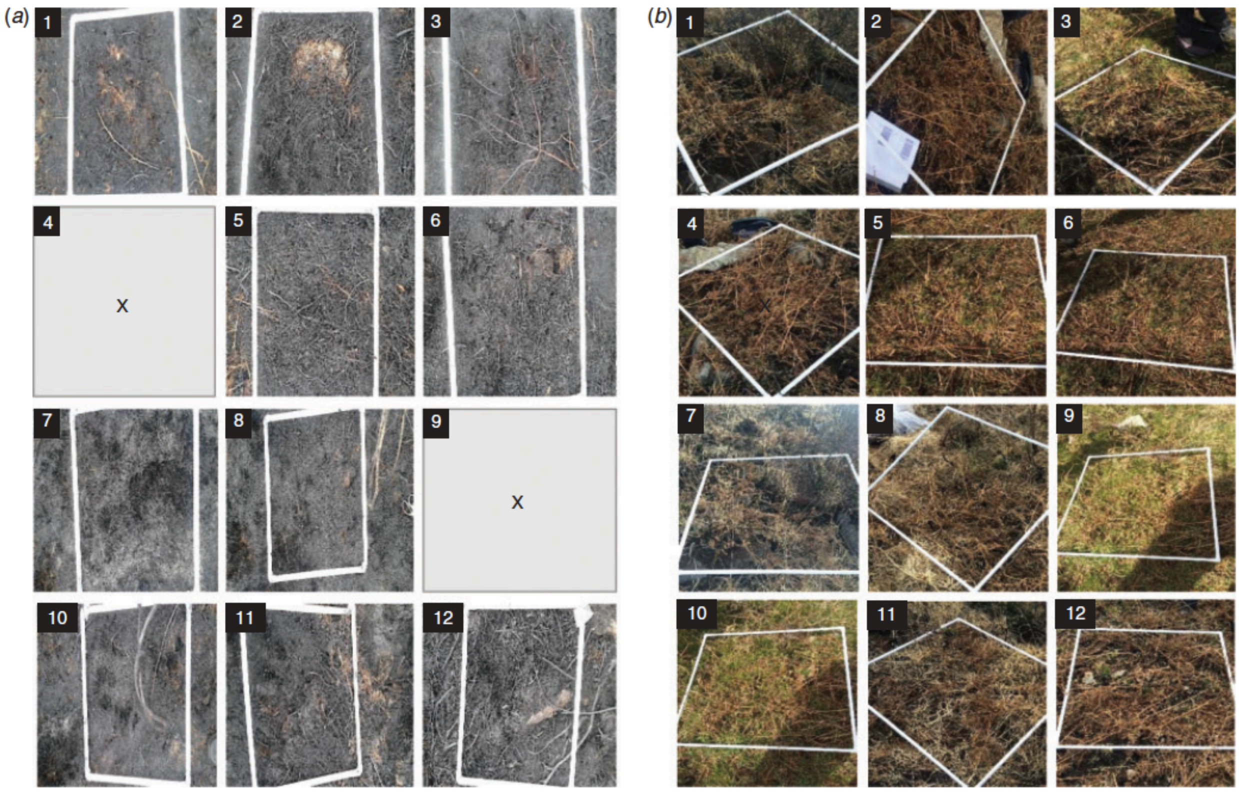

Figure 3.2: Photographs of the sampling locations along the transect of the burn scar at Carn Brea. The left images *a*) show the site 2 days after the wildfire; the right images are of the same locations 9 months later *b*). Regrowth of grasses and mosses is evident in the images on the right with little bare soil visible. This is in contrast to the images on the left where the surface vegetation has evidently been consumed by the fire, leaving only roots and bare soil. There are no images available for Sites 4 and 9 in *a*). (For scale the quadrat shown in the photographs is 1m x 1m).

3.3.2 Charcoal analyses

Charcoal was collected 2 days after the wildfire and dried in an oven at 40°C. The charcoal was embedded in cold-mounting epoxy resin following the approach of Belcher and Hudspith (2016). The charcoal blocks were studied in reflected light under a reflectance microscope, a Zeiss Axio-Scope A1 optical microscope, with a TIDAS-MSP 200 microspectrometer (SMCS Ltd, Baldock, UK), under oil with a refractive index of 1.514. In order to quantify the amount of light reflected back from the charcoal particles, the system was calibrated using three synthetic reflectance standards (cf. Belcher and Hudspith 2016). Samples were studied using an ×50 objective (with ×32 eyepiece magnification). A mixture of gorse and heather charcoal fragments were embedded in each block, ensuring a fair representation of the fuel types in the analysis; 100 measurements of the cell wall reflectance were taken per resin block and five charcoal blocks analysed per site (see Chapter 2 for a more detailed explanation of the methodology).

3.4 Results

Fire severity was found to be similar across the entire transect but was slightly higher in the area where a high fuel load of gorse dominated. Ten locations were classified as having a low fire severity (fire severity score 3), 'surface litter, mosses and herbs charred or consumed' (Keeley, 2009), the two remaining sampling locations were given a moderate or severe fire severity description (fire severity score 4), which includes 'all understorey plants charred or consumed, fine dead twigs on soil surface consumed, pre-fire soil organic layer largely consumed' (Keeley 2009) (Table 3.1). The locations along the burn scar that experienced higher fire severity were also found to yield charcoal with considerably higher reflectance when compared with the lower-severity sites, with median Ro% (measurement of charcoal reflectance) being >2% whereas all other sites (except site 12) yielded median reflectance of <1% (Figure 3.3a). Figure 3.3b plots the density distributions of the charcoal reflectance values for each site compared with one another. It can be seen that the majority of sites have similar density distributions in reflectance values, with median reflectance values lower than 1. However, Site 12 can be seen to have higher density distributions with a large fraction >1 Ro% and Sites 7 and 8 have a large proportion of values >2 Ro%.

The lowest levels of regrowth were observed at Sites 7, 8 and 12 (compare Figure 3.2a with 3.2b). Sites 7 and 8 were given qualitative severity scores of 4 whereas 12 was scored as 3. All three sites were found to exhibit median charcoal reflectance values of >1% (Figure 3.3). Site 7 had experienced the lowest amount of regrowth after 9 months and yielded the highest reflectance of all sites. Median reflectance was 0.4 Ro% greater than the next most highly reflecting site (Site 8), which indicates Site 7 shows a 26% increase in median reflectance compared with Site 8. Both Sites 7 and 8 were given the same qualitative fire severity score despite this difference. The greatest regrowth was observed at Sites 9 and 10, followed by Sites 3, 5 and 6, all of which had median charcoal reflectance values of <1%. Site 1, despite having one of the lowest median charcoal reflectance values, appears to have experienced much slower regrowth. This site is at the base of the hill and is considerably rockier than the other sites; we anticipate that this has slowed its regrowth.

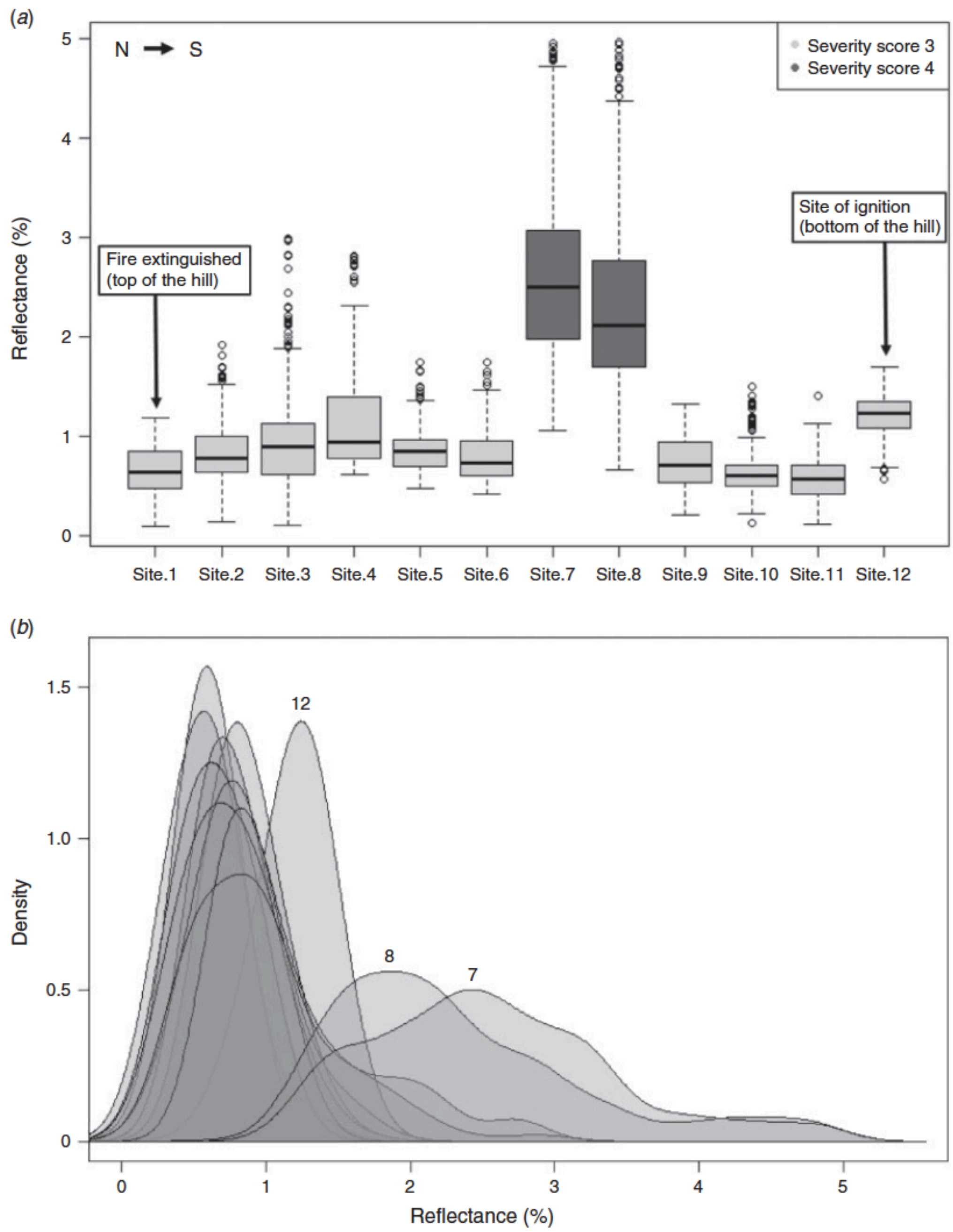

Figure 3.3: Boxplots a), and density distribution plot b) of the charcoal reflectance values for each site along the Carn Brea burn scar compared with one another. Sites 12, 8 and 7 are labelled as they are referred to in the text.

3.5 Discussion

Our analysis reveals that two sites (7 and 8) along the transect exhibited greater than double the measurable median charcoal reflectance of the average of all other sites and produced different reflectance distributions than all other sites (Figure 3.3b). These two sites also had the highest qualitative fire severity score (4), and experienced significant shrub fuel consumption and loss of the soil organic layer. On revisiting Carn Brea the following year, regrowth at Sites 7 and 8 appeared to be slower than at the majority of the other sites, as would be expected from both the qualitative approach and reflectance-based quantitative approach. However, despite Sites 7 and 8 having the same qualitative score of 4, Site 7 exhibited a lower amount of regrowth than Site 8 and maintained several patches of exposed soil (compare Figure 3.2b 7–8). Similarly, the regrowth at Site 12 appeared visually less dense than at Sites 2–6 and 9–11, which were all given the same qualitative score of severity 3. These observations would not have been predictable based on the qualitative fire severity assessment.

Sites 7 and 8 were qualitatively assessed as falling in the score of severity 4, however, Site 7 was observed to yield charcoals that are 26% more reflective than Site 8. Site 12 was the third highest-reflecting site, and like Sites 7 and 8, exhibited a different distribution in reflectance values when compared with Sites 1–6 and 9–11 (Figure 3.3b). Again, despite this difference, Site 12 is qualitatively assessed as falling in the same severity score as Sites 1–6 and 9–11 (score 3). At Sites 7 and 12, the charcoal reflectance approach is shown to provide more information than qualitative scoring alone and has been able to successfully indicate enhanced impact by the fire at these sites when compared with the qualitative scoring categories.

Ecosystem impact has been linked with total energy output (Hamilton 2000) and the duration over which a site experienced high temperature (Gimeno-García *et al*., 2004), although others have suggested that it is variations in fire intensity that will link to consumption of aboveground biomass (and therefore link to fire severity) (Keeley 2009). Charcoal reflectance has been shown to positively correlate with total energy release in laboratory and field-scale wildland fire experiments (Belcher *et al.*, 2018) and shows little relation to maximum fire intensity (Belcher and Hudspith 2016). This has led to the suggestion that studies of charcoal reflectance may have utility in determining the distribution of energy delivery across a burned area (Belcher *et al.*, 2018). Although we do not have direct measurements of the fire itself, the two sites that experienced the highest pyrolysis intensity were observed to be areas of overgrown gorse that we suggest likely burned with a higher total energy release than the other areas along the transect. For example, the high fuel load may have resulted in the fire burning for a significant duration, such that increased total energy release in this area led to higher fire severity and generated higher charcoal reflectance. As such, our study of charcoal reflectance at Carn Brea implies that some sites along the transect experienced high total energy release and that these appeared to have been slower to start regrowth than sites with lower charcoal reflectances.

Owing to the linkage between charcoal reflectance and total energy release from fires, we suggest that reflectance measurements taken across transects of managed and unmanaged heathland and moorland fires may provide a useful post-burn metric for better assessing variations in the impact of managed burns compared with either natural or accidental fires in these ecosystems. Charcoal reflectance, therefore, may be able to provide information for developing appropriate prescribed fire actions to best manage these ecosystems to produce structurally diverse UK heathland and upland landscapes, as well as providing mitigation against the likelihood of extreme unmanaged fires occurring in the future.

Our findings also likely have consequences for understanding the influence of heathland fires on the carbon balance of these ecosystems, where both survival and regrowth of biomass influence the carbon balance through carbon accumulation following fire (Clay and Worrall 2011) and because charcoal itself can influence this balance (Santín *et al.,* 2016). Recent research has been able to link the recalcitrance of charcoal to variations in charcoal reflectance (Belcher *et al.*, 2018; Doerr *et al.*, 2018) in both laboratory-generated charcoal and those formed by wildfires. Belcher *et al.,* (2018) have suggested that more highly reflecting charcoal could be more resistant to degradation and therefore able to add to longer-term carbon burial than less-reflecting charcoal. Therefore, although Sites 7 and 8 at Carn Brea may show slower regrowth, the higher reflectance measured at the sites suggest that these charcoals may be less biodegradable; potentially assisting in mitigating carbon losses. More research is required to consider the balance of carbon losses and gains (e.g. Santín *et al.*, 2016).

In summary, the findings of this proof-of-concept study suggest that by taking measurements of charcoal reflectance, it may be possible to improve the resolution of fire severity assessments by providing quantitative data that is better able to indicate regrowth potential than broad qualitative fire severity scoring approaches alone. Additional studies should seek to undertake charcoal reflectance studies from wildland fires in a range of ecosystems and for larger sample sizes than presented here to fully determine if charcoal reflectance has the ability to move the discipline towards more quantitative fire severity assessment approaches.

Chapter 4

An assessment of fire severity metrics from experimental burns in the New Jersey Pinelands National Reserve (PNR)

4.1 Abstract

The ability to understand better the effects of fires on ecosystems is critical for future management strategies. Charcoal is a key product of wildfire, and it has been suggested that the properties of charcoal may be capable of capturing evidence of the heat distribution throughout a wildfire. As such charcoal may be able to provide a means with which to assess fire severity. At present, there are two main tools by which fire severity is assessed: qualitative fire severity scores taken at the ground-level, and quantitative satellite-based approaches that have a more restricted resolution. Here I have developed the measurement of charcoal reflectance to study charred bark from trees burnt in two full-scale field experimental fires at two sites in the New Jersey Pinelands National Reserve. The results are able to indicate that changes in charcoal reflectance across the burn scar correlate with variations in fire severity obtained from the WorldView-3 sensor and standard qualitative ground assessments. At both sites, a positive correlation and statistically significant relationship is found between fire severity and charcoal reflectance. Ultimately, the results indicate that measurements of charcoal reflectance could be used as a post-fire ground-based quantitative method by which to assess fire severity across a range of spatial resolutions.

4.2 Introduction

Fire is the greatest global threat to forest carbon stocks, contributing an estimated 3431 million tonnes of CO_2 into the atmosphere every year (FAO, 2006; Bowman *et al.,* 2009; North and Hurteau, 2011). It is important to note that CO_2 uptake through regeneration and regrowth following a fire may reduce the estimated contribution of CO_2 from fires into the atmosphere (Keith *et al.,* 2014).

Fire is an increasing threat in the Eastern US as a result of the rise in urban infrastructure in rural environments (Peters *et al.,* 2013). Whilst, an estimated > 10 million hectares of coniferous forests in the Western US are vulnerable; in moderate or high fire hazard condition (Stephens and Ruth, 2005; Stephens *et al.,* 2009). This clash between fire with urban and rural infrastructure expansion makes management of these ecosystems difficult (Stephens and Ruth, 2005; Stephens *et al.,* 2009). Prescribed burning is increasingly being used successfully to reduce fuels and restore fire disturbance to landscapes that historically would have experienced wildfire. However, wildfire management in the US is a widely debated topic (Foereid *et al.,* 2015). Despite the debate an expanding wildland-urban interface (WUI) (Radeloff *et al*., 2005) and increasing fire suppression costs that are predicted to reach ~$1.8 billion by 2025 (United States Forest Service, 2015) provide new challenges for managing ecosystems both for ecosystem health and also for safe living in areas that support flammable ecosystems. Particularly because the rise in the Wildland Urban Interface (WUI) in the area and the subsequent creation of transportation corridors adjacent to these flammable forests have meant that these upland forests have become a major concern to fire managers

(Skowronski *et al.,* 2007). The management of fire is not a new phenomenon to the US, and management practices have shaped many North American ecosystems and their associated fire regimes (Ryan *et al.,* 2013). However, past fire suppression practices in the twentieth century have led to excessive fuel availability in some regions in North America which have resulted in various effects in ecosystem (Ryan *et al.,* 2013). In the Western US, a greater fuel load on the ground surface, including influxes of conifer seedlings, led to an increase in the probability of crown fires and increased fire severity (Agee and Skinner, 2005). However, in the Eastern US the frequency of fires decreased due to the invasion of fire-sensitive vegetation which bring a moister and more shaded environment along with a less flammable litter layer (Ryan *et al.,* 2013).

Improvements in scientific knowledge regarding prescribed fires has led to the expansion of the use of prescribed fires (Ryan *et al.,* 2013). Therefore, new efforts to improve the understanding of fire severity and the impact of fire on the ecology of an ecosystem using well designed prescribed burns are being undertaken.

Research has been able to link increased wildfire-induced carbon losses and tree mortality in forests across the US to fire severity (Swezy and Agee, 1991; Turetsky *et al.,* 2011). As an indicator of ecosystem impact, fire severity is useful to policymakers and resource managers when deciding prescribed fire strategies (Keeley *et al.,* 2008). Unlike fire intensity which is the measure of energy release from the combustion of organic matter (Keeley, 2009), fire severity is the visual evaluation of organic matter lost from aboveground and belowground, and can be measured post-fire (Keeley, 2009). Such approaches have been developed as a solution to the long-standing need to generate predictive tools that allow the linkage of fire behaviour to post-fire ecosystems effects (Keeley, 2009). However, these metrics tend to focus on assessing organic matter loss or changes after fire via qualitative descriptive categories (e.g. Ryan and Noste, 1985) or by utilising quantitative but lower resolution approaches such as satellite difference normalised burn ratio (dNBR). Neither of these approaches are able to link quantitatively to the energy flux delivered by the fire with biomass loss, regrowth or ecosystem shifts.

The two contrasting approaches are qualitative fire severity scores taken at the ground-level, and quantitative satellite-based approaches that have a larger spatial scale but a more restricted resolution in detail. The first of these methods allows the assessment of fire severity to be easily conducted in the field by using a fire severity matrix that enables qualitative description of the loss of material/carbon due to the fire. Ryan and Noste (1985) developed a matrix that related the impacts of heat pulses from fire on vegetation and soil to the fire's severity (Keeley, 2009). Using such ground-based approaches of fire severity provides researchers with a high-resolution data set, but, the method by which the categorical fire severity scores are assigned is qualitative i.e. values are assigned based on a table of descriptions (see Keeley, 2009). Field surveys can also be labour intensive and therefore also costly.

The satellite-based method of difference normalized burn ratio (dNBR) (equation $_{(1)}$) has been increasingly utilized over recent years in the US (Picotte and Robertson, 2011).

$$\mathbf{dNBR = (NBR)_{pre\text{-}fire} - (NBR)_{post\text{-}fire}} \quad (1)$$

This increased use of dNBR is due to its effectiveness for mapping burn severity in forested ecosystems; providing users with a measurable index of change post fire that can be related to ecological change (Picotte and Robertson, 2011; Warner *et al.,* 2017). However, like with many methods there are certain caveats associated with dNBR, which include issues of the adequacy of the satellite to acquire images of the study site that are clear enough and of a sufficient resolution. It has been suggested that the pairing of dNBR with additional quantitative measures of fire severity would allow improved assessment of fire severity and its potential to link to ecosystem impacts (Hoy *et al.,* 2008). Therefore, a method that incorporates the spatial resolution of the ground-based methods but measures severity quantitatively, as remote sensing does, would be a strong solution.

Charcoal is considered indirectly as part of qualitative assessments of fires at the ground level, where descriptions of the degree of charring are made across a burn scar post-fire. This is included in fire severity scoring approaches such as those that focus on organic matter loss (e.g. Ryan and Noste, 1985), semi-quantitative approaches that consider char height such a Composite Burn Index (CBI) (Key and Benson, 2006) and the bark char code assessment (Hood *et al.,* 2008). However, charcoal has yet to be used as a tool from which to extract quantitative data. Here I propose that charcoal may provide a form of forensic evidence that might be used to quantitatively capture fire severity.

Researchers have established that the structure of charcoal varies during creation due to a number of differing factors e.g. plant species, wood density and the amount of heating the material undergoes (Cohen-Ofri *et al.,* 2006; Lowden and Hull, 2013; Belcher, New *et al.,* 2018). Experimental research has indicated that during the combustion process charcoal transitions through various phases in which cells are eventually re-ordered to a more graphite-like structure (Cohen-Ofri *et al.,* 2006; Belcher and Hudspith, 2016). This re-ordering of cells alters the reflective properties of the charcoal i.e. there is an increase in the quantifiable amount of light reflected from the surface of the charcoal as the structure becomes more ordered (more graphite-like) thus allowing researchers to study the reflectance properties of charcoal (Belcher, New *et al.,* 2018). It has been shown that charcoal reflectance is in a state of constant change throughout the combustion process (Belcher and Hudspith, 2016) whilst, recent research has revealed that increasing charcoal reflectance is positively correlated with increasing total energy release as measured in laboratory experiments and with total energy flux (as represented by the area under thermocouple curves) in an experimental wildfire (Belcher, New *et al.,* 2018) and with the duration of heating in both laboratory and fields studies (Belcher, New *et al.,* 2018). This is important because the duration of surface heating, for example, has been found to relate to post-fire ecosystem recovery (Gagnon *et al.,* 2015) and to tree mortality (Keeley and McGinnis, 2007) which is high-value information for the development wildfire management strategies in ecologically important areas, including the design of prescriptions for burns. These suggest that charcoal reflectance may make a novel descriptor of the energy flux across a burned area that might serve as truly quantitative ground-based fire severity metric.

Here I compare two qualitative fire severity scoring approaches (Ryan and Noste, 1985; Hood *et al*., 2008) and dNBR data obtained from the WorldView-3 sensor satellite (Warner *et al.,* 2017) to charcoal reflectance measurements. Satellite images, qualitative information and charcoal from the bark of pitch pine (*Pinus rigida* Mill.) trees that were burnt in two experimental burn sites in the New Jersey, Pineland National Reserve, USA, have been analysed and assessed in order to develop a new quantitative fire severity metric that can be used to shape future management strategies and policy.

4.3 Materials and methods

4.3.1 Study sites

This chapter focuses on two burned sites located in the New Jersey Pinelands National Reserve (PNR) (Figure 4.1). One site located along Lost Lane Road, Chatsworth Township, New Jersey, USA and the other along Chatsworth Road, Chatsworth Township, New Jersey, USA; from here on the sites will be referred to as Lost and Chat (Figure 4.1).

The climate in the region is cool temperate, mean annual precipitation is 1123 ± 182 mm and mean monthly temperatures range between 0.3°C and 23.8°C in January and June, respectively (1930–2004; NJ State Climatologist, Skowronski *et al.,* 2007). Upland forests dominate the Pinelands, 62% of forests are classified as upland, and despite the poor soil quality; sandy, acidic soils low in nutrients, there is high fuel accumulation and moderate to dense shrub layers in the understorey (Tedrow, 1986; Pan *et al.,* 2006; Skowronski *et al.,* 2007). There are three dominant upland forest communities in the PNR ‘pine-oak forests’, ‘pine-scrub forests’ and ‘pine plains’, all three forest types contain pitch pine (*Pinus rigida* Mill.), oak trees (*Quercus* spp.) and have an understorey dominated by ericaceous shrubs such as huckleberry (*Gaylussacia* bacata) and blueberry (*Vaccinium* spp.) (Skowronski *et al.,* 2007; Warner *et al.,* 2017). Two experimental prescribed fires were undertaken between the 29th February to the 18th March 2016. The ignition patterns used in the 2016 prescribed burns varied, these included backing, heading and plastic sphere aerial ignition, meteorological conditions and fuel moistures also varied throughout the burn period (Warner *et al.,* 2017). The charcoal samples and locations analysed in this study were collected/assessed from the Lost and Chat sites in March 2017.

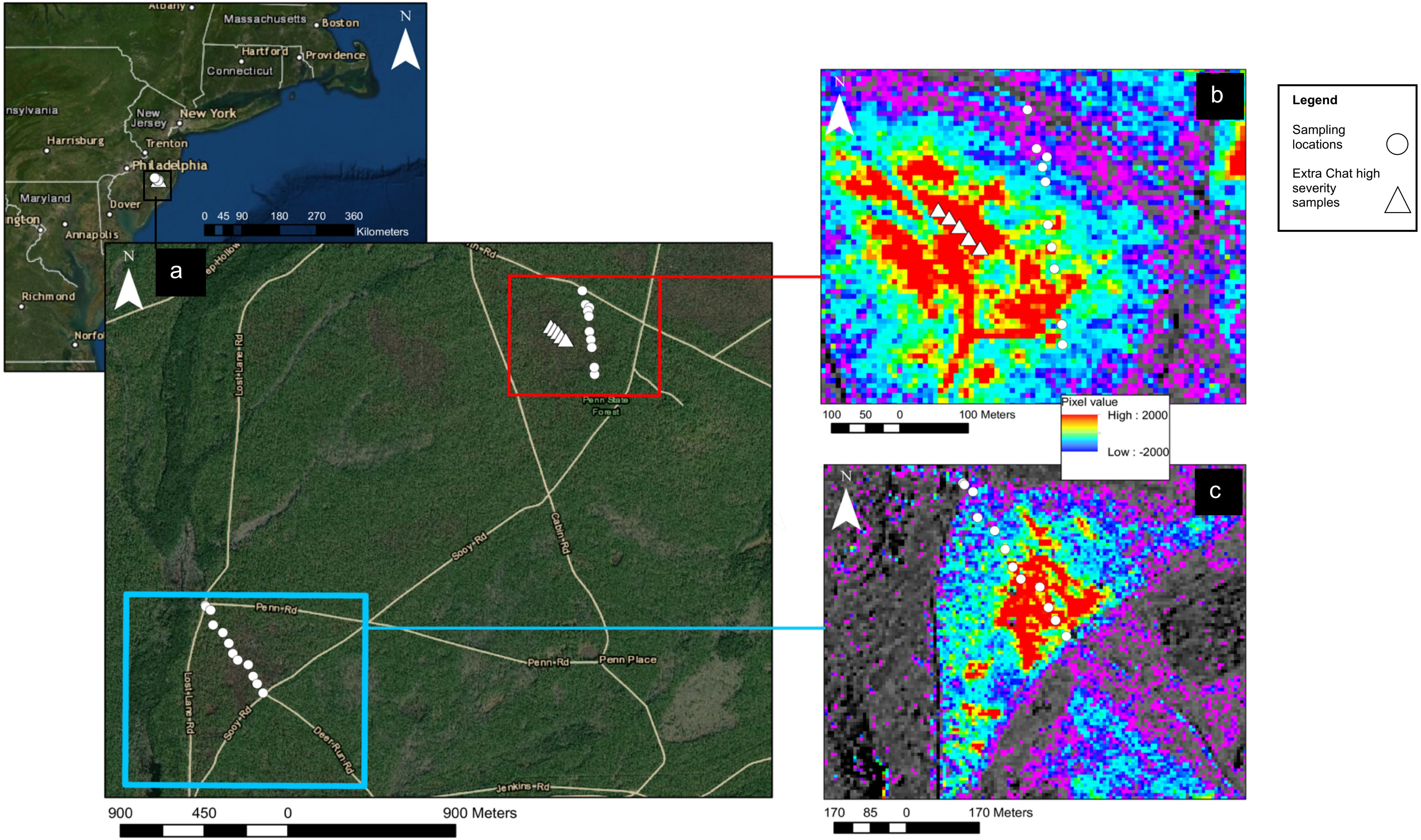

Figure 4.1: ArcGIS maps showing the Chat and Lost study sites. a) Shows the study area post-fire, b) and c) show the dNBR images used to extract fire severity data obtained from the WV-3 satellite. A colour ramp has been used to highlight the difference in severity across the site. The burns were conducted within the boundaries of the roads within which the transects are located, highlight blue (Lost) and red (Chat) boxes. Base-map source: Esri (2019).

4.3.2 Qualitative field severity observations

Two qualitative approaches to assess fire severity have been used in this study. The first considers overall carbon loss based severity from the sites, following Ryan and Noste (1985) and the second that considers the degree of charring of bark, following that of Hood *et al.,* (2008).

Carbon loss based severity (Ryan and Noste, 1985)

At each sampling location, a qualitative assessment of the burn was conducted and given a fire severity description of either low, medium, or high severity based on the charring of the tree (Figure 4.2) based on the carbon loss based fire severity scheme of Ryan and Noste (1985) Table 4.1.

Bark char code based severity (Hood et al., 2008)

The damage inflicted by the fires to the bark of the trees at both Lost and Chat were visually assessed by qualitatively describing the degree of bark charring according to the schema set out by Hood *et al*., (2008) (Table 4.2).

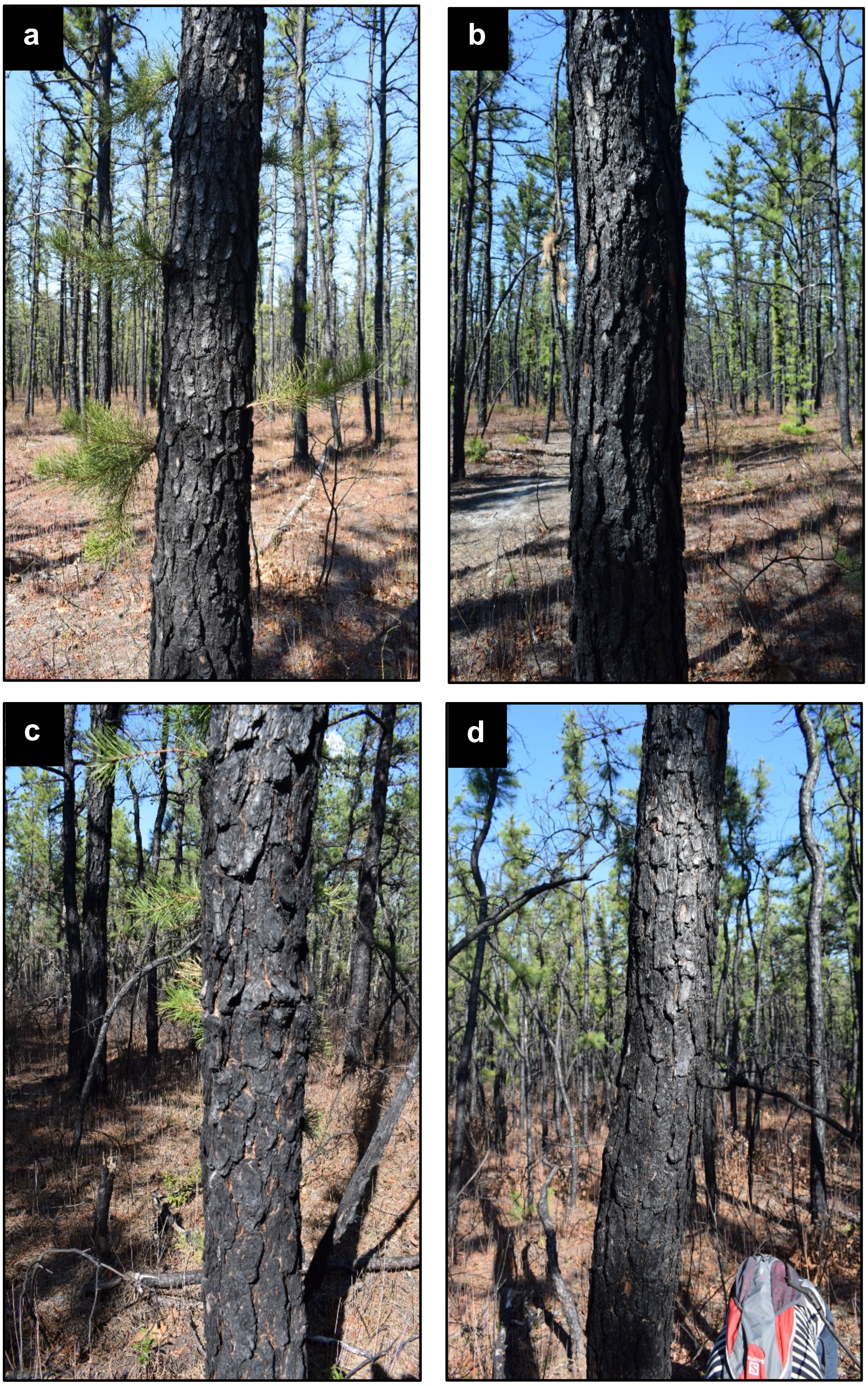

Figure 4.2: Examples of the trees sampled in 2017. a) Lost sampling location 9, b) Lost sampling location 11, c) Chat sampling location 4 and d) Chat sampling location 7. Similar circumference trees were selected.

Table 4.1: Fire severity scoring criteria; a simplified version of Ryan and Noste's (1985) original matrix which related fire severity to changes in soil organic matter and aboveground vegetation; adapted from Ryan (2002) and Turner *et al.*, (1994). Source: Keeley (2009:119).

Fire Severity	**Severity Score**	**Description**	**Alternative term used in this thesis**
Unburned	1	Plant parts green and unaltered, no direct effect from heat	
Scorched	2	Unburned but plants exhibit leaf loss from radiated heat	
Light	3	Canopy trees with green needles although stems scorched Surface litter, mosses, and herbs charred or consumed Soil organic layer largely intact and charring limited to a few mm depth	Low
Moderate or severe surface burn	4	Trees with some canopy cover killed, but needles not consumed All understorey plants charred or consumed Fine dead twigs on soil surface consumed and logs charred Pre-fire soil organic layer largely consumed	Medium
Deep burning or crown fire	5	Canopy trees killed and needles consumed Surface litter of all sizes and soil organic layer largely consumed White ash deposition and charred organic matter to several cm depth	High

Table 4.2: Bark char code table used classify the charcoal collected from Lost and Chat. Source: Hood *et al.,* (2008:63).

Bark char code	**Bark appearance**	**Alternative term used in this thesis**
Unburned	No char	
Light	Evidence of light scorching; can still identify species based on bark characteristics; bark is not completely blackened; edges of bark plates charred	Low
Moderate	Bark is uniformly black except possibly some inner fissures; species bark characteristics still discernible	Medium
Deep	Bark has been burned into, but not necessarily to the wood; outer bark species characteristics are lost	High

4.3.3 Quantitative approaches: Charcoal reflectance

Charred bark from the surface of pitch pine (*Pinus rigida* Mill.) trees was collected at locations along a ~450m transect across both of the sites, a total of 11 sampling locations for Lost and 10 locations for Chat. Bark charcoal from five extra trees were sampled in Chatsworth, these were chosen due to their location in an area of high fire severity according to known dNBR pixel values from the WorldView-3 satellite. A single tree was sampled at each location, removing the surface bark by inserting a knife and prising off the charred bark (Figure 4.2). Trees were selected based on their resemblance to the majority of the trees in that particular area of the study site so as to gain a good representative sample. Individual charcoal samples were placed in small labelled sealed bags and then all bagged samples placed in a larger sealed bag. The charcoal samples were transported in suitcases and were packed in such a way to ensure damage was limited. Each selected tree from across the transects was of a similar circumference (95cm mean) (Figure 4.2). Each tree's location was logged by GPS and photographs were taken of each sampling location. A Garmin handheld Global Positioning System (GPS) was used, there is an error of ~3m associated with this device. A single species was sampled based on the suggestion of Belcher *et al.,* (2016) that charcoal from the same species should be used for reflectance analysis, through their research exploring the relationship between fuel and fire properties.

All charcoal samples were oven dried at 40°C before preparing for analysis under the reflectance microscope. Charcoal samples were embedded in polyester resin blocks and subsequently ground and polished (Belcher and Hudspith, 2016). Once the polishing process is complete the resin blocks are attached to a glass slide using a pressure-sensitive adhesive putty and a few drops of immersion oil (RI 1.514 at 23°C) is added to the polished surface and the sample placed under the microscope. The oil acts as a bridge between the sample and the microscope lens (Jones, 1999). The TIDAS-MSP 200 system is calibrated using three synthetic reflectance standards, strontium titanite (5.41% reflectance in oil (Ro)), gadolinium gallium, garnet (GGG) (1.719% Ro) and spinel (0.42% Ro) (Belcher and Hudspith, 2016). An x50 objective (with x32 eyepiece magnification) is used and the measurement of reflectance is manually taken at the cell-wall junction using *MSP200 v 3.27* software (Belcher and Hudspith, 2016). Thirty reflectance measurements were taken per sample, with 3 replicates per tree, in all cases the points across the block showing the highest reflectance were measured to ensure that the surface of the bark was being captured. The full methodology can be found in Chapter 2.

4.3.4 Quantitative approaches: Computing dNBR satellite burn severity index

Past research has found a correlation between ground-based fire severity surveys (e.g. Table 4.1) and dNBR Landsat satellite-derived fire severity measurements (Keeley, 2008). In this thesis ArcGIS has been used to extract the fire severity data acquired by the WorldView-3 satellite. This satellite provides a finer spatial resolution than previously used remote sensing instruments such as Landsat, with the WorldView-3 satellite providing a 7.5m resolution opposed to Landsat's 30m resolution (Warner *et al.,* 2017). Post-fire differenced normalised burn ratio (dNBR) images of the study site have been used; obtained from Warner et al. (2017) (a full methodology for this can be found in Warner *et al.,* 2017). A black and white dNBR satellite image containing the straight index data (combination of Bands 7 and 14) was used to obtain fire severity data for comparison with the qualitative fire severity descriptions taken in the field and the charcoal reflectance data from the charred pitch pine bark. A single pixel value was selected and the data extracted; the GPS points that were taken in the field during charred bark sample collection were inserted onto the satellite image and where the pixel that the GPS point covered was selected for data extraction.

4.4 Results

In total 90 charcoal reflectance measurements were taken, per location in each site. Figure 4.3 shows boxplots for both Chat and Lost coloured to represent the qualitative descriptions given to each sampling site in the field; ground-based fire severity descriptions assigned to the sampling locations were: low, medium and high severity.

Both sites followed the same trend in qualitative fire severity (Ryan and Noste, 1985) through the transects, beginning with low severity, moving to medium and ending with high fire severity. Reflectance measurements for both sites also follow similar trends to one another and as the ground-based severity descriptions; low reflectance values can be found in those areas deemed as having a qualitatively low fire severity at ground-level and vice versa for the highest reflectance values. However, when comparing the charcoal reflectance values to the qualitative severity categories of Ryan and Noste (1985) the mid values of qualitative severity do not appear to well link to measured reflectance (Figure 4.3). For example, sites 5, 6, 8 and 9 have been given a severity score of high at Chat whilst, sites 6, 7, 8 have been given a severity score of medium despite both of these having similar charcoal reflectance ranges (Figure 4.3). A logistic regression of these data (Figure 4.4) indicates that there is little rationale for the 'medium' qualitative severity category in terms of reflectance because nearly all of those scored as medium severity at both Lost and Chat can be explained by reflectance distributions that also fall in either the low or high qualitative category. The regression analysis suggests that charcoal reflectance values <1.6% should be scored as low whilst, those that are >1.6% are better described as high severity (p <0.001).

Table 4.3 compares the bark char code, the Ryan and Noste (1985) severity table and reflectance (along with other notes). In general, the bark char code scores are similar to those given by the Ryan and Noste (1985) scheme, with the exception that Chat 10 is scored as medium severity but deep\high bark charring and Chat 6 has been scored as high severity but with moderate/medium bark charring. A logistic regression of the bark char code qualitative scores and their relationship to reflectance is shown in Figure 4.4, this also indicates that there seems to be little rationale for the moderate/medium bark char code descriptor because there is no clear delineation of the moderate/medium category according to reflectance. Light/low charring could be considered from <1.6 Ro%, whilst deep charring is apparent from > 1.6 Ro% ($p < 0.001$).

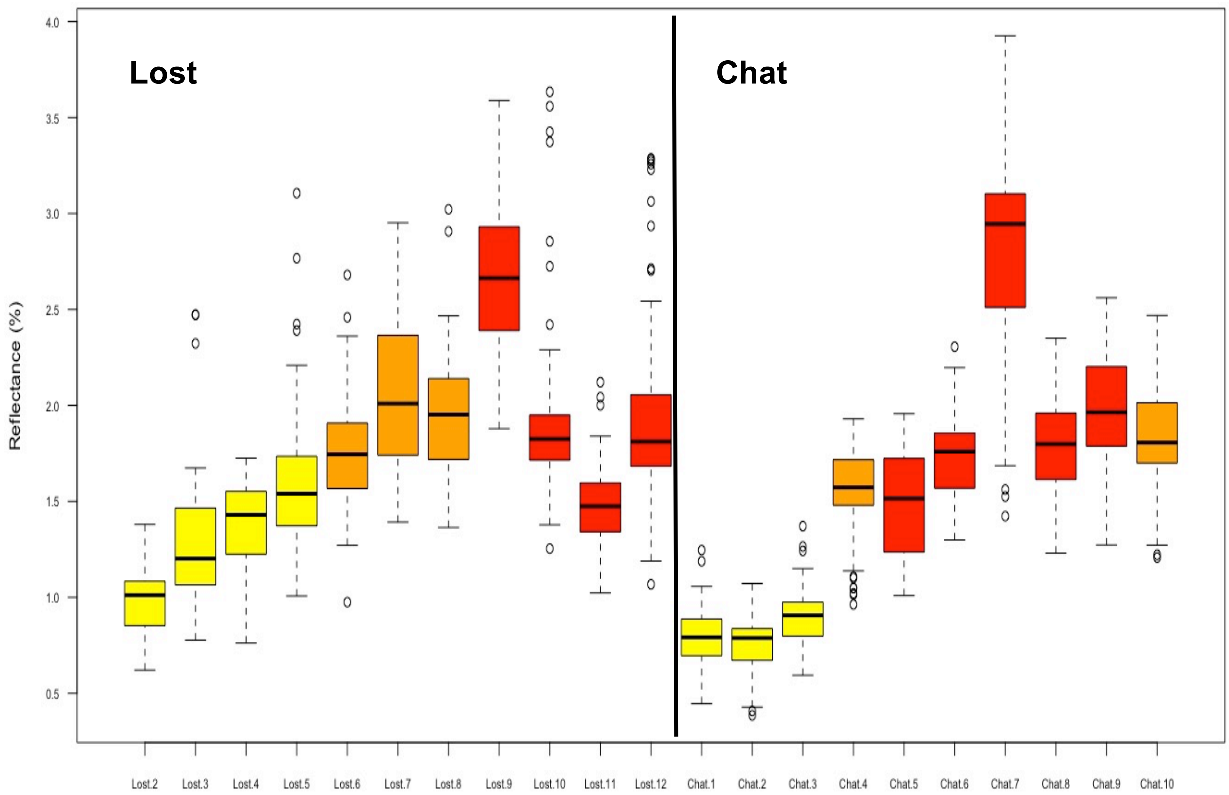

Figure 4.3: Boxplots of the Lost and Chat charcoal reflectance data. Boxes are coloured according to the fire severity score assigned to them through qualitative assessment in the field; yellow = low-severity, orange = medium-severity and red = high-severity.

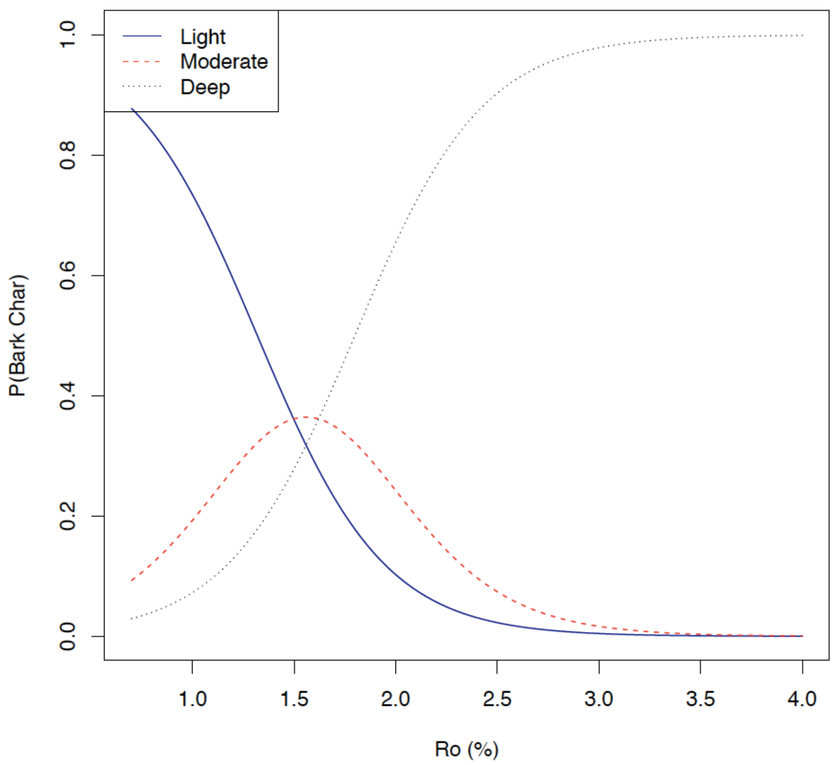

Figure 4.4: Ordinal logistic regression plot of the charcoal reflectance results from lost and chat and the bark char codes that have been assigned a numerical value: 1 = light damage, 2 = moderate damage and 3 = deep damage.

Table 4.3: Information about the sites and the individual trees from which the bark charcoal was taken, along with the reflectance (%) and dNBR data for each site.

Site	Fire severity score	Bark char code	Average Ro%	Height of tree (m)	DBH (cm)	dNBR pixel value
LOST 2	low	light	0.989	11.921	69	568
LOST 3	low	light	1.263	16.919	101	528
LOST 4	low	light	1.372	17.458	101	591
LOST 5	low	light	1.565	14.649	94	613
LOST 6	med	moderate	1.759	11.795	113	610
LOST 7	med	moderate	2.072	14.339	102	787
LOST 8	med	moderate	1.935	14.837	70	1065
LOST 9	high	deep	2.686	13.511	116	1169
LOST 10	high	deep	1.909	14.718	90	996
LOST 11	high	deep	1.705	13.334	95	1094
LOST 12	high	deep	1.927	13.316	90	852
CHAT 1	low	light	0.796	11.683	74	429
CHAT 2	low	light	0.754	12.182	82	510
CHAT 3	low	light	0.904	9.820	81	583
CHAT 4	med	moderate	1.569	9.264	74	649
CHAT 5	high	deep	1.499	11.706	78	628
CHAT 6	high	moderate	1.743	9.822	82	902
CHAT 7	high	deep	2.823	9.022	73	984
CHAT 8	high	deep	1.786	15.860	65	735
CHAT 9	high	deep	1.981	12.866	77	714
CHAT 10	med	deep	1.810	13.431	89	712
CHAT A	high	deep	2.394	11.095	84	1240
CHAT B	high	deep	3.023	13.044	83	1242
CHAT C	high	deep	2.319	10.881	62	1274
CHAT D	high	deep	2.189	7.737	76	1254
CHAT E	high	deep	2.763	6.689	68	1225

Figure 4.5 compares to the two quantitative approaches used in this chapter. Here I have plotted dNBR pixel values compared to the pitch pine bark charcoal reflectance measurements. Lost and Chat both show a positive linear correlation between dNBR and charcoal reflectance, Lost with an *r* value of 0.768 and Chat producing a higher *r* value of 0.866. Statistical analysis (Spearman's Rank) was conducted using R Studio (Version 0.99.893) and indicates both Lost and Chat produced statistically significant relationships between Ro% and dNBR: ρ = 0.879, *p*-value = 0.002, and ρ = 0.773, *p*-value = 0.008 respectively.

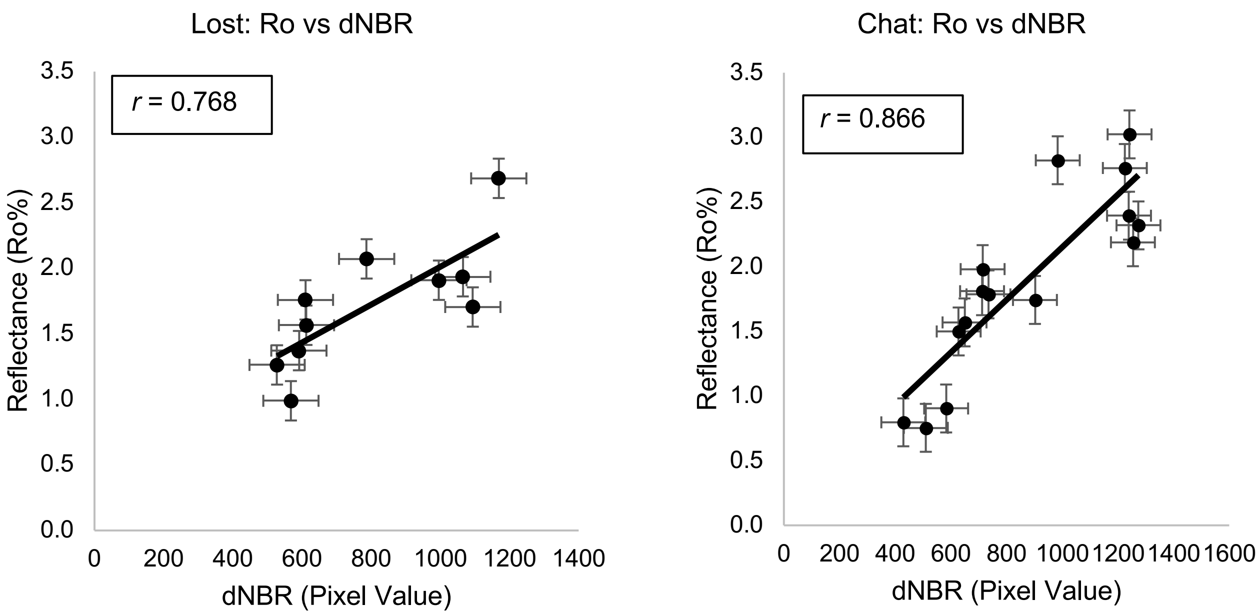

Figure 4.5: Lost and Chat charcoal reflectance data plotted against dNBR pixel values obtained from dNBR WV-3 satellite images from Warner *et al.,* (2017).

4.5 Discussion

In the analysis of the use of charcoal reflectance as a quantitative metric with which to assess fire severity I have compared four different approaches: two quantitative metrics, charcoal reflectance and dNBR, and two qualitative metrics, the bark char code (Hood *et al.,* 2008), and the carbon loss approach (based on Ryan and Noste, 1985). I have been able to indicate that changes in charcoal reflectance across two burn scars correlate with these existing approaches.

Whilst I have shown a link between reflectance and dNBR, I am surprised by the relatively strong relationship that I have found. Although both have been shown to be able to provide a quantitative measure of fire severity (e.g. Keeley *et al.,* 2009; Warner *et al.,* 2017; Belcher, New *et al*., 2018; New *et al.,* 2018), dNBR should perhaps correlate better with metrics that provide information regarding fireline intensity; e.g. flame height, char and scorch height (Ndalila *et al.,* 2018), measures which Ro% does not provide information for. Ndalila *et al.,* (2018) has shown for example that classification by dNBR worked best where crown defoliation, scorch heights and char heights were highest. Ro%, on the other hand, has been shown to provide information regarding the amount and duration of heating (Hudspith *et al.,* 2018; Belcher, New *et al*., 2018).

A similar study by New *et al.,* (2018) (Chapter 3) compared the qualitative table of descriptions against charcoal reflectance in their assessment of fire severity and its impact on regrowth potential. New *et al.,* (2018) were able to show in their assessment that the qualitative scoring system was too broad in its descriptions of the level of damage imparted by the fire on an area and showed that charcoal reflectance was better at indicating the damage and regrowth potential at a site. In this study I have presented similar findings when comparing charcoal reflectance and the qualitative table of descriptions, finding that for Chat in particular a number of sampling locations have been given a high severity score of 4 when sampling locations of similar reflectances at Lost have been given a medium severity score of 3. Both sites were assessed by the same researcher using the same table of descriptions, therefore I suggest that the categories, in particular medium and high, need to be broken down e.g. including low-medium, high-medium categories. This research has also shown that another qualitative severity assessment, the bark char code, is also too broad with its categorisation of fire severity. The need for broader categories for the bark char code is also noted by (Hood *et al.,* 2008), again I suggest that by splitting the category into low-moderate and high-moderate I would be able to better to show the variability of fire severity across a burn site. Whilst I make similar suggestions for the Ryan and Noste (1985) table it is important to be aware that the categories can only be broken down to a certain degree. After a while these tables of assessments will become too complicated if broken down too far, increasing the time taken to use these methods in the field and potentially also increasing their subjective nature. Therefore, in support of New *et al.,* (2018) I have shown that charcoal reflectance not only provides similar results to the qualitative assessments, but that it has been shown in two different ecosystems (heathland (New *et al.,* 2018) and temperate forest) to be able to provide a better more detailed assessment of fire severity.

Hudspith *et al.,* (2017) in their assessment of fire severity also highlight the ability of charcoal reflectance to provide more information than the qualitative metrics, they suggest that charcoal reflectance may be able to provide information about the duration of heating, and not only fire severity. Belcher, New *et al.,* (2018) support these findings, finding that charcoal reflectance also varies with different heating regimes, and suggest that charcoal reflectance may make a useful metric with which to determine the distribution of energy delivery across a burned area. The findings by Belcher, New *et al.,*

(2018) and Hudspith *et al.,* (2018) both lead to the conclusion that charcoal reflectance may have the potential to enable the prediction of longer-term effects of fire on ecosystems e.g. the carbon budget as information about duration which is often critical to mortality of trees (e.g. Keeley and McGinnis, 2007). Taking the findings from these various studies along with the results I have presented in this research, I therefore suggest that charcoal reflectance should be used in place of the qualitative tables.

Whilst research shows that dNBR is a useful metric to assess fire severity there are disadvantages to using remote sensing. Picotte and Robertson (2011) for example discuss how changes in fire severity can be falsely identified by satellites due to their sensitivity to changes on the land surface, these changes which affect vegetation greenness such as deforestation and hydrological changes e.g. drought, can be misclassified as sites of fire activity, therefore this approach is best used when fires are known to have occurred. Imagery acquisition for dNBR can also be limited by frequent cloud cover and seasonality (Fornacca *et al.,* 2018). In this study I have shown, to a certain degree, that charcoal reflectance can replicate fire/burn severity results from remote sensing, and this, along with other advantages of charcoal reflectance, such as the lack of dependency on weather and its potential to provide more information than simply fire severity i.e. the amount and duration of heating (Hudspith *et al.,* 2018; Belcher, New *et al.,* 2018), has led us to make the suggestion that charcoal reflectance should be used in conjunction with remote sensing and in place of qualitative severity scoring systems in future assessments of fire severity.

The importance of this type of research is clear, in the past similar research has helped shape policy and successful management strategies through improving the understanding of the ecology after a prescribed fire (Ryan *et al.,* 2013), something this research can also potentially do. There is the possibility for this new fire severity metric which I have developed to be used as a tool by which to assess post-fire tree mortality, perhaps as a ‘risk rating system’, the ‘risk’ being mortality and the ‘rating’ derived from reflectance measurements (Swezy and Agee, 1991).

Continued improvement of the science behind understanding the effect of wildfire on an ecosystem will help shape future management strategies, with the potential to reduce the cost of these practices and improve the ecological response to a wildfire. Developing fire severity estimates into a metric which can be linked to wildfire impact on an ecosystem will not only help with future management strategies but with potentially forecasting future carbon losses from the global system as well. This is important to take into account when conducting prescribed burns in areas that are both ecologically important and an important carbon sink. Linking science, management and policy are critical when considering the ecological impact of prescribed fire on an ecosystem and continued improvement of the science that shapes management practices will help improve the ecological legacy of management strategies (Ryan *et al.,* 2013).

I have shown in this research how well reflectance has worked when analysing a single species. Belcher, New *et al.,* (2018) also highlight this requirement for Ro% to be used on charcoal from the same species through their research exploring the relationship between fuel and fire properties; of most interest is the variation that they found in reflectance values that were produced by woods of differing densities. This highlights the difficulty that would be faced by researchers if they were to analyse different species; would the reflectance values vary due to fire severity or would the variance be due to the differing bulk density of the wood or bark of the species (Belcher, New *et al.,* 2018). I suggest that if fire severity were to be assessed using charcoal reflectance analysing multiple species that some kind of correction factor would need to be included to account for this variation in bulk density. However, bulk density is just one aspect of the fuel that may be affecting the reflective properties of the charcoal, more research is needed to explore this, but ultimately I suggest that the relationship between charcoal reflectance and fire severity should be analysed within species and not between species.

4.6 Conclusion

The results from this study indicate that measurements of charcoal reflectance could be used as a post-fire ground-based quantitative method with which to assess fire severity across a range of spatial resolutions, whilst also having the potential as Hudspith *et al.,* (2018) and Belcher, New *et al*., (2018) show, as being able to provide us with an improved measure of fire severity by providing information on the amount of heating and its duration. Ultimately, reflectance has the possibility to provide quantitative information about fire behaviour that cannot be discovered using existing techniques. However, to better understand the potential of Ro%, future work must include full scale fire experiments to conclusively prove this approach (Belcher, New *et al.,* 2018).

Chapter 5

An investigation of fire severity using charcoal reflectance of an unmanaged wildfire, and the comparison to managed burns in the New Jersey Pineland National Reserve, USA

5.1 Abstract

Fire severity is an important aspect of fire behaviour that can have implications for long-term carbon storage in an ecosystem. How well ‘natural’ fire severity is replicated by prescribed burns is important to consider in wildfire science. Here, I use charcoal reflectance to quantitatively assess fire severity across an unmanaged fires’ burn site in the Pinelands National Reserve, USA, and compare this to managed burns in the same area of forest to assess how well prescribed burns mimic unmanaged or ‘natural’ wildfires. I also assess how fire severity is affected with distance from a fire break in all three burns and investigate if the quantitative approach of charcoal reflectance was able to better detect differences in fire severity than qualitative metrics in an unmanaged wildfire in a forest ecosystem. Charcoal reflectance has been used as a quantitative metric to assess the fire severity across three sites in the same pine forest (2 prescribed burns and 1 unmanaged fire). Charcoal reflectance was found to outperform qualitative assessments when assessing fire severity and significantly positive relationships were largely found between distance from a fire break and fires severity across the three sites. The results show that prescribed burns resulted in lower severity fires than the unmanaged wildfire. This is an important finding as it could have implications for long-term carbon storage due to the susceptibility of lower-energy formed charcoal to degradation. Notably, the results indicate that currently prescribed wildfires do not replicate fire severity to same degree as unmanaged wildfires.

5.2 Introduction

Wildfire is an increasingly common threat to the world's forests (McMorrow *et al*., 2009; Turetsky *et al.,* 2015; Roos *et al.,*2016). It is now a global challenge in which ecosystems that have not previously had fire as part of its natural functioning, and therefore are not adapted to it, are now at risk of being affected by its destructive nature. In the USA, where fire is already common on both the east and west coasts, the management of the forests and fires are increasingly important in order to reduce the effect fire has on all aspects of ecosystem functioning i.e. social, ecological and economic functions.

Scientists attending and implementing experimental equipment in prescribed burns help managers to better understand the role of fire in these ecosystems and the behaviour of fire under different conditions. Prescribed burning helps to reduce the forest fuel on the ground, i.e. shrubs and woody debris from surrounding trees, so that if a wildfire were to occur, the intensity or severity should be less, and thus the impact on ecological services reduced (Schwilk *et al.,* 2009: Stephens *et al.,* 2012). However, if fire was not supressed, as it has been in the past due to the threat of an ever-increasing human presence in and around forests, prescribed burns would perhaps not be needed as the natural occurrence of fire in these ecosystems would reduce the fuel on the ground and therefore the threat of a high severity and high intensity fire in the future. This is unfortunately the 'legacy of fire suppression' in the USA (Thompson *et al.,* 2007). Therefore, as these prescribed burns are on some level replacing the role of natural fire in these ecosystems they should then replicate the effect that 'natural' fire would have had on the ecosystem.

However due to these prescribed burns being by nature ‘managed’, can the results of these fires ever be the same as that of a natural wildfire?

It has been observed that the current goals of prescribed fires do not meet the perceived needs of heterogeneity in burning (Nesmith *et al.,* 2011). A meta-analysis, of the available literature on thinning and burning treatments conducted by Fulé *et al.,* (2012) found that burning treatments result in the replication of low-severity fire behaviour. It is known from various studies on fire severity that unmanaged wildfires are not heterogenous in their severity (e.g. see Hudspith *et al.,* 2014 and New *et al.,* 2018) and that high severity fires are becoming increasingly common across ecosystems (McMorrow *et al.,* 2009). Boisrame *et al.,* (2017), noted that unmanaged fires typically create high-severity burn areas unlike lower intensity prescribed burning. The aim of prescribed burning is to imitate the natural role of fire on the landscape and reproduce the effects that fire has on an ecosystem, effects which have been lost through fire suppression (Nesmith *et al.,* 2011). However, this is somewhat difficult to achieve if the prescribed burns are designed to result in low severity fires, with the perception that these will be less ecologically damaging.

There are a number of reasons why prescribed burns produce low severity fire. Prescribed burns are managed fires controlled by fire crews to stop them from reaching an uncontrollable state. There are various controls in place to stop the impact of the wildfire becoming too great on the ecosystem and surrounding environment. For instance, the time in which a fire can be ignited is restricted due to air quality regulations; short burn times coupled with fast moving fire fronts aim to reduce the amount of smoke released into the environment (Nesmith *et al.,* 2011). This is quite different to those fires that naturally occur, e.g., due to natural ignitions such as lightning strikes, that generally have a longer duration and burn a larger area than those that are managed (van Wagtendonk and Lutz, 2007). Perhaps it is due to their managed nature that prescribed burns therefore produce lower severity fires. However, Gallagher (2017) found that fire severity varied independent of fire size when comparing prescribed and unmanaged burns in the Pineland National Reserve (PNR). In Gallagher (2017) it is found that prescribed burns produced lower severity fires compared to unmanaged wildfires, primarily due to the time of year in which the prescribed burns are conducted i.e. seasonality. Seasonality would affect fuel availability and the weather in which prescribed fires are conducted. Gallagher (2017) notes how the current management strategies in the PNR are limited by the time frame in which burning is conducted and that this is an important reason for why prescribed burns are not fully replicating the severity of unmanaged wildfires. Something for land managers to consider in the future is whether or not there is a way for higher severity burns to be conducted in a safe and controlled manner.

As an indicator of ecosystem impact, fire severity, the visual evaluation of organic matter lost from aboveground and belowground (Keeley, 2009) is useful to policymakers and resource managers when deciding prescribed fire strategies (Keeley *et al.,* 2008). Studies have found that fire severity is linked to pyrogenic carbon stocks (PyC), most importantly it has been found to influence the distribution of PyC in an ecosystem (Maestrini *et al.,* 2017). PyC is considered as having an important role in carbon cycling due to the recalcitrance of the charcoal that is created by fire, but interestingly fire severity has been found to have no effect on the amount of PyC created (Maestrini *et al.,* 2017). PyC stored in the forest floor is susceptible to loss from erosion, whereas when PyC is stored in standing trees and coarse woody debris (CWD) the risk of rapid loss from the system is lower and therefore the carbon stays locked in the environment for longer (Maestrini *et al.,* 2017). This is important to consider when assessing fire severity in an ecosystem. Maestrini *et al.,* (2017) found for example that higher severity fires resulted in 3.3 times more PyC being stored in standing trees than medium-low severity fires which had a 22% higher amount of PyC stored in the forest floor. This is important to consider as prescribed burns are increasing the risk of loss of carbon from the ecosystem as they are lower severity than natural wildfires would have been.

One way to assess fire severity is through the analysis of the charcoal that the fire creates i.e. charcoal reflectance, which I am currently developing as a metric with which to assess fire severity (Hudspith *et al.,* 2014; New *et al.,* 2018, Belcher, New *et al.,* 2018). Research has shown that maximum charcoal reflectance is reached at the end of flaming combustion/ and the end of exposure to heating (Belcher and Hudspith, 2016), where a strong positive relationship between increased total heat released during combustion and increased charcoal reflectance has been observed (Belcher, New *et al.,* 2018). These seem highly relevant with respect to findings that the total energy released from fires can be linked to its impacts (Hamilton, 2000). Moreover, charcoal reflectance and the recalcitrance of PyC has been shown to vary between high intensity crown fires and lower intensity surface fires (Belcher, New *et al*., 2018; Doerr *et al*., 2018), hinting that charcoal reflectance will vary between managed and unmanaged wildfires. Recently, New *et al*., (2018 and Chapter 3 - Carn Brea) has indicated that charcoal reflectance is able to provide better resolution fire severity information than qualitative scores alone. These data were indicated for heathland ecosystems whilst, Chapter 4 (Lost and Chat) has indicated that the charcoal reflectance metric performed similarly for managed wildfires in a conifer forest ecosystem. As yet there have been no assessments made for an unmanaged wildfire and none where charcoal reflectance as a severity metric has been compared between unmanaged and managed wildfires.

In order to assess variations in fire severity between managed and unmanaged fires three recent fires in the Pinelands National Reserve (PNR) in New Jersey, USA where studied. Fire in the PNR is not only important in shaping the forest community structure, but it also has an important ecological role in the forest ecosystem where it impacts nutrient cycling, carbon cycling and seedling release (Gallagher, 2017). The PNR has great societal and ecological value. For example, it is home to 41 threatened or endangered animal species and there are 29 Pineland sites on the National Register of Historic Sites, including restored historic villages and settlements, town historic districts, and historic structures and ruins (New Jersey Pinelands Commission, 2006). It's notoriety for cranberry farming means that it is also of economic value to the area; New Jersey ranks 4th in cranberry production nationally (2004) and 2nd in blueberry production nationally (2004) (Fulé *et al.,* 2012; New Jersey Pinelands Commission, 2006). The PNR, however, is one of the ecosystems in the USA that has adjusted to the presence of fire in its forests by having a forest floor community that has adapted to fire by resprouting quickly after a fire. This was clearly apparent after the Breeches Branch fire that occurred in 2018, a week after the fire tufts of grass were present (New York Times, 2018), and the shrubs and herbaceous plants that dominate the forest community of the PNR were at shin height after 11 weeks (New York Times, 2018).

Extensive wildfires, ~8,000-16,000 ha, are not a new occurrence to the PNR. For example, wildfires in the PNR averaged approximately 40,000 hectares per year at the beginning of the 20th century (Forman and Boerner, 1981, Kümmel 1902). Since then, management in the PNR, primarily fire suppression efforts, have resulted in a decline in the average area burned (La Puma *et al*., 2013, Forman and Boerner 1981, Boyd 2008). Although management in these forests may result in a decline in the number of fires and the amount of annual area burned, they can result in larger than average wildfires that affect huge amounts of the ecosystem due to the uncharacteristic build-up of forest fuel (Brotons *et al.,* 2013; Pinõl *et al.,* 2005). In 1963 for example, a number of large fires resulted in 82,000 ha of the PNR being consumed by fire (Forman and Boerner 1981). Most recently, on the 30th March 2019 a wildfire in the PNR, the Spring Hill wildfire, the largest single fire in recent history, burned over 11,000 acres (State of New Jersey, 2019). 11 of the most recent large wildfires to have been reported in the PNR add up to a total ~ 930,000 ha (Hoover, 2017). Land managers need to consider if the current prescription of burning 6,000-8,000 ha annually is enough in future assessments of prescribed burning in the PNR, as wildfires increase in their occurrence burning more land than in previous years (Gallagher, 2017; New Jersey Department of Treasury, 2012, 2014, 2016; Hoover, 2017).

In this study, I have analysed the variation in fire severity across a burn site that was the result of an unmanaged wildfire in the Pinelands National Reserve (PNR), New Jersey, USA. Here, I compare two different metrics with which fire severity can be assessed; a qualitative scoring metric first developed by Ryan and Noste (1985), and the quantitative charcoal reflectance method. The results from the analysis of the unmanaged wildfire in this chapter have been compared to the fire severity and charcoal reflectance analysis of the two managed wildfires in Chapter 4, the fires from both of these chapters occurred in the same forest region and type. The results of the comparison of fire type in this chapter will not only aid in the development of the charcoal reflectance method, but, it could assist with future management strategies regarding prescribed fires and their short-term and long-term impacts on the ecosystem. Three hypotheses will be assessed in this chapter: 1) charcoal reflectance will perform better at describing fire severity than qualitative metrics in unmanaged wildfires in forest ecosystems. 2) severity will increase with distance from any form of fire break i.e. roads, in both wildfires and managed fires, 3) that fire severity and reflectance values will be lower in managed fires than they are in wildfires in this region.

5.3 Methods and materials

On the 22nd April 2018 a wildfire occurred in the PNR which will be referred to in this chapter and has been referred to in the press as the Breeches Branch fire (New York Times, 2018). The Breeches Branch fire occurred in Penn State Forest, Burlington County, situated close to Oswego Lake (Figure 5.1). The fire started on Lost Lane in the Lost forest unit studied previously in Chapter 4, driven by a northwest wind. As the fire became established there was a major and lasting wind shift to a southeast wind, which caused it to turn and head northwest. The fire spotted (spot fire) to the next block north and across Breeches Branch (M.Gallagher, personal communication, 2019).

Starting on Lost Lane, the Breeches Branch fire also burned the Lost and Chat sites. Lost and Chat has been studied previously in this thesis as they underwent prescribed (experimental) burns in 2016; their fire severity using charcoal reflectance is studied in Chapter 4. The data from Chapter 4 will be used as a comparison against the Breeches Branch fire. Lost and Chat were both managed burns yet behaved differently due to the conditions in which their burns occurred. The Lost burn was conducted on the edge of acceptable conditions for prescribed burns and acted more like a wildfire; the conditions being ‘at the volatile end of acceptability’ (M.Gallagher, personal communication, 2018), and Chat was more typical of a prescribed fire; occurring when the weather was cooler, damper and less windy than the Lost burn (M.Gallagher, personal communication, 2018).

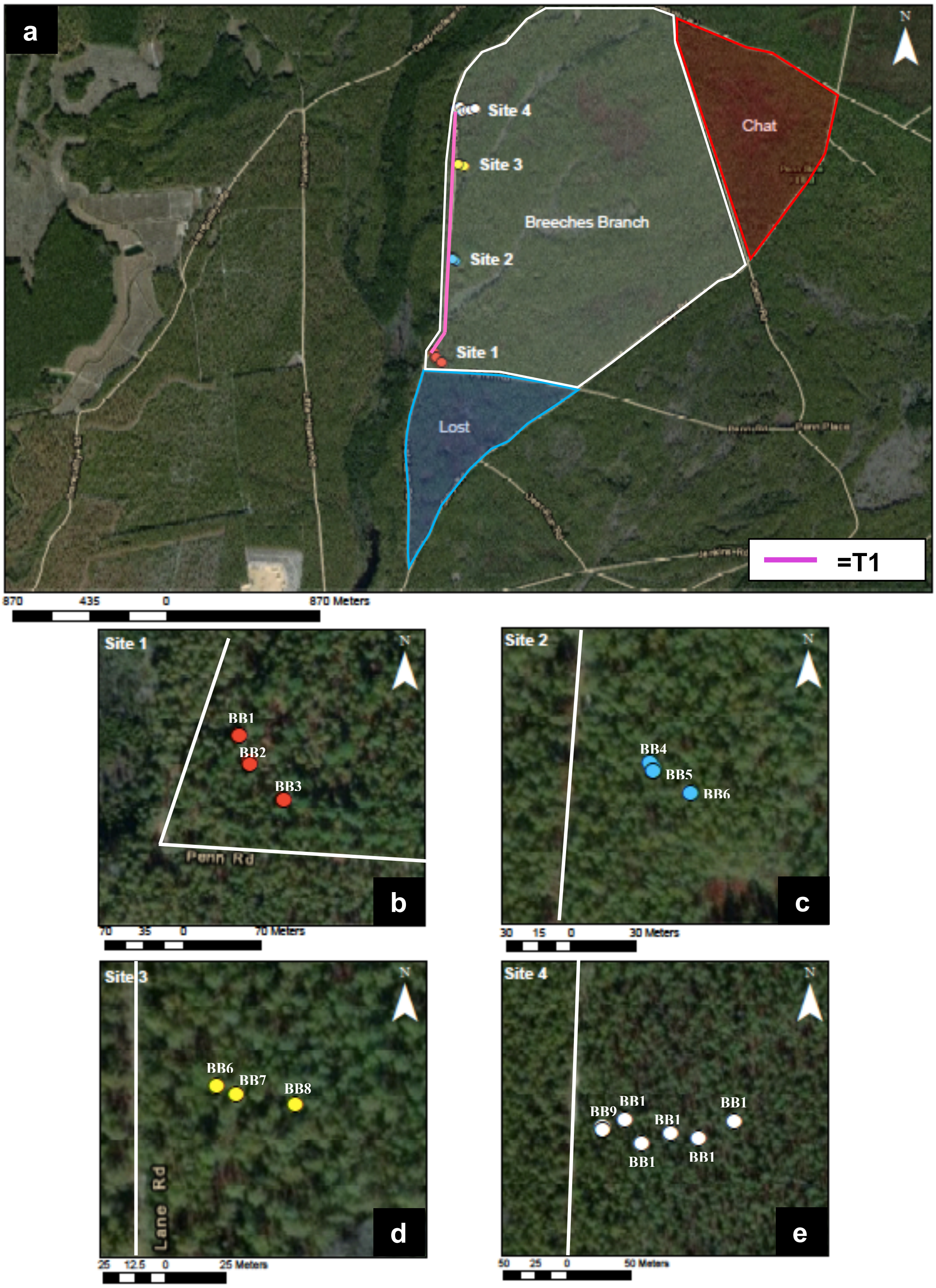

Figure 5.1: Maps showing the locations of the trees used in the analysis of fire severity. Study transect along the road is highlighted in pink in the overview map a) and the road has been highlighted in white in b), c), d) and e). The three study sites analysed in this chapter have also been delineated: Lost (blue), Breeches Branch (white) and Chat (red). Base-map source: Esri (2019).

All study sites, Breeches Branch, Lost and Chat, are located in the Pinelands National Reserve (PNR), and therefore have the same climatic conditions, soil type etc. The climate in the region is cool temperate, mean annual precipitation is 1123 ± 182 mm and mean monthly temperatures range between 0.3°C and 23.8 °C in January and June, respectively (1930–2004; NJ State Climatologist, Skowronski *et al.,* 2007). Upland forests dominate the Pinelands; 62% of forests are classified as upland, and despite the poor soil quality; sandy, acidic soils low in nutrients, there is high fuel accumulation and moderate to dense shrub layers in the understorey (Tedrow, 1986; Pan *et al.,* 2006; Skowronski *et al.,* 2007). There are three dominate upland forest communities in the PNR: 'pine-oak forests', 'pine –scrub forests' and 'pine plains'. All three forest types contain pitch pine (*Pinus rigida* Mill.), oak trees (*Quercus* spp.) and have an understorey dominated by ericaceous shrubs such as huckleberry (*Gaylussacia* bacata) and blueberry (*Vaccinium* spp.) (Skowronski *et al.,* 2007; Warner *et al.,* 2017).

5.3.1 Sampling

Sampling began at the South Eastern corner of the plot at the intersection of Lost Lane Road and Penn Road (See Figure 5.1) and continued northwards along Lost Lane Road until I was confident that I had captured a range of fire severities within the study site. The total transect length was ~1.14 km. Table 5.1 shows the distance between the sampling locations, which are also indicated in Figure 5.1. Charcoal was taken from trees along a transect from the edge of the forest, the side nearest the road, into the forest interior. In total 4 sub-sampling transects were created, sampling 3 trees into the forest interior in each site, I chose to only go a short distance into the forest as I was time limited and confident that the trees had been sampled were representative of the study area being sampled. This sampling strategy continued until I reached the final site, site 4, when I sampled 6 trees in total. This was done to attempt to capture a fuller picture of how fire severity changed moving through the forest by extending the length of the transect compared to the other sites.

Table 5.1: Sampling sites, the distance between the sites and the individual trees having fire severity qualitatively and quantitatively assessed.

Sampling locations	Distance apart (metres)
BB1-BB2	20.60
BB2-BB3	33.44
BB1-BB4 (Site 1 - Site 2)	413.31
BB4-BB5	3.42
BB5-BB6	15.43
BB4-BB7 (Site 2 - Site 3)	401.89
BB7-BB8	6.78
BB8-BB9	19.03
BB7-BB10 (Site 3 - Site 4)	237.96
BB10-BB11	13.74
BB11-BB12	17.41
BB12-BB13	17.53
BB13-BB14	16.91
BB14-BB15	23.80

A single tree was sampled at each location and a single species, pitch pine (*Pinus rigida*), was sampled based on the suggestion of Belcher *et al.,*

(2016) through their research exploring the relationship between fuel and fire properties. Surface bark was removed by inserting a knife and prising off the charred bark, trying to keep the piece as intact as possible. Trees were selected based on their resemblance to the majority of the trees in that particular area of the study site so as to gain a good representative sample. Each selected tree from across the transects was of a similar circumference (95cm mean) (Figure 5.2). Each tree was logged by GPS and photographs were taken of each sampling location. A Garmin handheld Global Positioning System (GPS) was used, there is an error of ~3m associated with this device.

5.3.2 Qualitative field severity observations

Carbon loss based severity (Ryan and Noste, 1985)

I used a single qualitative approach to assess fire severity, this approach follows on from Ryan and Noste's (1985) assessment table and considers overall carbon loss based severity from the sites. At each sampling location, a qualitative assessment of the burn was conducted and given a fire severity description of either low, medium, or high severity based on the charring of the tree and also the quality and state of the pine needles on the tree and on the forest floor (Figure 5.2).

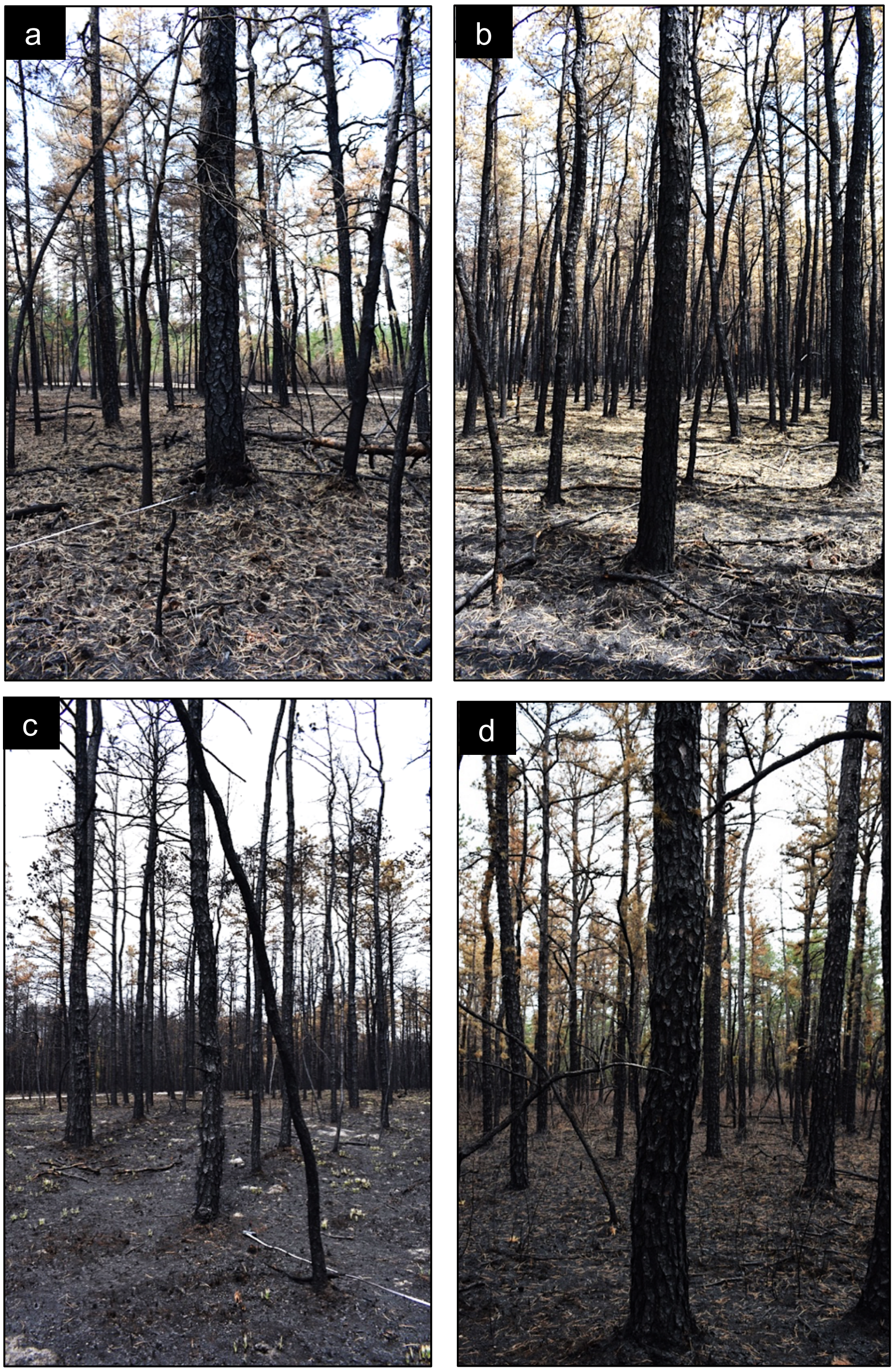

Figure 5.2: Photos of sampling locations a) BB1 (medium severity), b) BB6 (medium-high severity), c) BB8 (high severity) and d) BB13 (med-low severity).

5.3.3 Laboratory work

Chapter 2 provides a more detailed account of the charcoal reflectance methodology, please see this chapter for more detail. All charcoal samples were oven dried at 40°C before preparing for analysis under the reflectance microscope. Charcoal samples were embedded in polyester resin blocks and subsequently ground and polished (Belcher and Hudspith, 2016). The type of embedding that this research has used is referred to as cold-mounting epoxy resin, this is a relatively simple technique consisting of two components, an adhesive and a hardener (Jones and Rowe, 1999). After the resin has fully set the surface of the block was ground and polished using a MetaServ 250 with Vector Power Head grinder-polishing machine (Buehler, Neckar, Germany. The surface polish quality of the blocks was checked under a Zeiss Axio-Scope A1 optical microscope, with a TIDAS-MSP 200 microspectrometer (SMCS Ltd, Baldock, UK), for any scratches (Jones, 1999; Hudspith *et al.,* 2014; Belcher and Hudspith, 2016). Measurements were obtained using a x50 objective (with x32 eyepiece magnification) and the measurement of reflectance manually taken at the cell-wall junction using *MSP200 v 3.27* software (Belcher and Hudspith, 2016). Thirty reflectance measurements were taken per sample, with 3 replicates per tree, in all cases the points across the block showing the highest reflectance were measured to ensure that the surface of the bark was being captured.

5.4 Results and discussion

A range of reflectance values were found across the sites studied which I interpret as differing fire severities experienced throughout the burned area (Figure 5.3) following New *et al*., (2018). The results have been split up into different sections. Breeches Branch will be discussed first, and secondly, the reflectance data from these transects have also been compared to the Lost and Chat reflectance data from the previous chapter in this thesis (Chapter 4).

5.4.1 Is charcoal reflectance able to better detect differences in fire severity than qualitative metrics in unmanaged wildfires in forest ecosystems?

New *et al.'s* (2018) study of a heathland fire in Carn Brea (Chapter 3) indicated that in a many instances quantitative charcoal reflectance measurements were able to better indicate damage and regrowth potential than qualitative scoring alone, and that measurements of charcoal reflectance were able to provide quantitative information about the spatial distribution of heat across a burned area improving fire severity assessments. Whilst, regrowth for Breeches Branch has not been assessed the charcoal reflectance values and the qualitative fire severity scores have been compared. Figure 5.3 shows the qualitative fire severity scores (coloured boxes) and the quantitative charcoal reflectance measurements. The charcoal reflectance measurements appear to more clearly separate the high and medium severity classes (Figure 5.3).

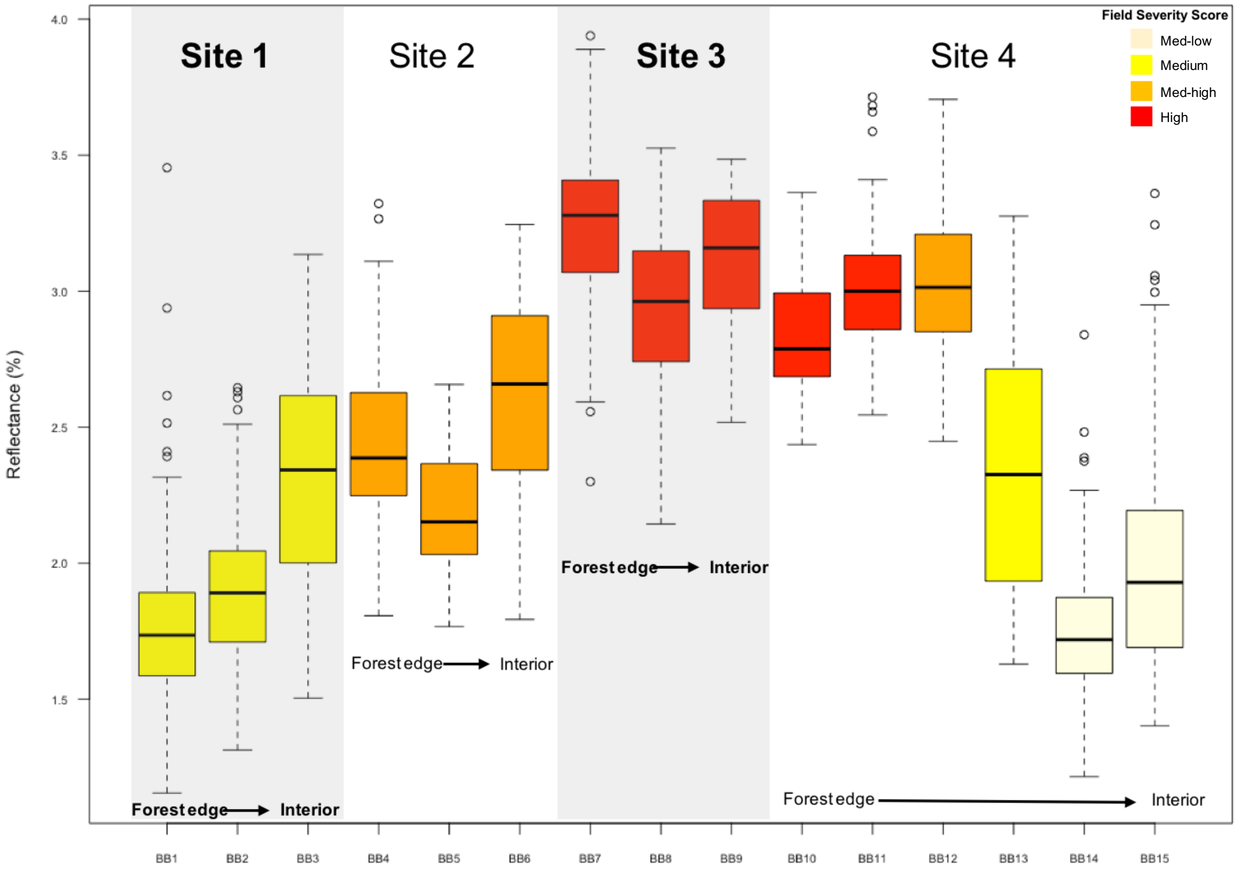

Figure 5.3: Boxplot showing the reflectance measurements for each site and each box is coloured according to the fire severity classification it was given from the qualitative assessment in the field.

For example, in Figure 5.3 BB12 in site 4 has been assigned a severity score of 'medium' by the qualitative assessment conducted in the field. The reflectance data, however, suggests that BB12 may fall into the high severity class as it has a similar reflectance range as those in site 3 which have been assigned a severity score of 'high' by the qualitative assessment. There are similar discrepancies between the medium and med-high classes. BB3 and BB13 (Figure 5.1) have both been assigned as 'medium' severity by the qualitative assessment, the reflectance data suggests that these trees might be better ascribed into the 'med-high' severity class because their range of reflectance values are similar to that of other trees that have been classed as ‘med-high’ severity. As in Chapter 3 (New *et al*., 2018) Breeches Branch reveals that the qualitative method of splitting medium and low, and medium and high severity classes (Figure 5.3) lacks resolution, whereas the reflectance method is better at distinguishing objectively between severity classes and is more effective at placing severities into the medium class. This is in agreement with Hudspith *et al.,* (2018) where they highlight that charcoal reflectance is able to provide more information than the qualitative severity metrics. In their study of four Alaskan tundra fires they suggest that charcoal reflectance is able to provide information about the duration of heating, and not only fire severity. Belcher, New *et al.,* (2018) support these findings by indicating that charcoal reflectance varies with different heating regimes, concluding that charcoal reflectance may make a useful metric with which to determine the distribution of energy delivery across a burned area. The findings by Belcher, New *et al.,* (2018) and Hudspith *et al.,* (2018) both lead to the conclusion that charcoal reflectance may have the potential to better enable the prediction of longer-term effects of fire on ecosystems than qualitative fire severity scores. Here, the Breeches Branch study suggests the same can be observed in a conifer forest ecosystem providing strong evidence as to why reflectance should be taken up as a key tool in fire severity assessments in future work.

It is important to note that the drop to med-low severity seen in site 4 is due to those trees falling into an area of bog, these data points have been removed from later analysis as they skewed the results. This area of bog would resulted in the ground having a higher moisture content and therefore fuel on the surface having a higher moisture content, therefore the severity of the fire would have been lower than the surrounding drier surface fuel as we see in the reflectance measurements

5.4.2 Will severity increase with distance from fire breaks?

Figure 5.3 shows the reflectance values and attributed qualitative severity categories for each of the sampling sites (site 1-site 4). The set of west to east transects attempt to capture the difference in reflectance and severity between the forest edge (e.g. next to the road) and away from the road following what should be a changing fuel load. This is in contrast to the main transect that moves from site 1 to site 4 northwards along Penn Road, and aims to capture the fire behaviour independent of fuel load by only looking at the first tree at each of the study sites.

The boxplot shows how fire severity generally increases as you move northwards along the road (see Figure 5.1, T1), and also shows the variability in the individual sites moving from west to east into the forest. The different transects are discussed in more detail in the following sections. The boxplot also shows the ascribed fire severity score given to each of the trees sampled according to the fire severity descriptions shown in Table 5.2. Interestingly, the fire did not produce any areas that were of low severity, the majority of the sampled trees showing severities of medium or greater.

Site 1 to site 4 (see pink line in overview map a) in Figure 5.1) is the longest transect ~1145 m. This transect follows the road and captures the movement of the fire as it travelled through the forest (the fire spread SE to NW). By only looking at the first tree of each of the sites (sites 1-4) this allowed us to look at how the fire ‘naturally’ varied in terms of fire severity broadly independent of changes in fuel load; in each of these sampling locations the vegetation structure and abundance should be similar as they are all closest to the road. Moving northwards along the road, from sites from one to four, analysing the first tree only, the fire severity can be seen to change from low to high, slightly dropping in reflectance values at the most northerly site (site 4); nonetheless high and medium fire severities are maintained here. This pattern in reflectance measurements also appears to follow the broad direction of spread of the fire (which moved SE to NW) across Breeches Branch.

Out of the 4 west-east study transects, qualitative fire severity was found only to increase into the forest interior at site 4 (Figure 5.3). All other sites have the same within-site level of qualitatively ascribed fire severity (the colour of the boxes in Figure 5.3) as the rest of the trees in their individual sites, however, charcoal reflectance was found to be more variable at each site than qualitative fire severity might suggest.

Site 3 was found to yield much higher reflectance measurements, max 3.13% median 2.34% (Figure 5.3) than all other sites (Mann-Whitney U-test $p < 0.001$). There was no noticeable difference in the density of trees or a change in the topography compared to the rest of the sites, and the whole study site was almost completely flat; no major changes in the topography were noticeable. Therefore, I hypothesise that at this location there must have been a higher density of understory fuels e.g., the shrub layer. Despite the longer transect studied for Site 4 (Figure 5.3) (twice the number of trees were measured stretching 150m into the forest) there appeared to be a decrease in fire severity and reflectance further from the road such that a negative relationship between reflectance and distance away from the road (Spearman's $\rho = -0.652$, $p < 0.001$) was found. This may be due to the fact that this transect is close to the intersection of two roads (Figure 5.1) leading to lower reflectance values when compared to the two middle sites (sites 2 and 3), which are furthest from the roads around the borders of the forest plot. Site 4 also contained three different fire severity scores; those scores given to the sampled trees according to the fire severity table (Table 5.2). This is the only site that varies in its ascribed qualitative fire severity score out of all 4 sites in the study area. Note that site 4 in Breeches Branch has the first three trees plotted in Figure 5.4 and analysed in statistical tests and not the entire 6 trees in the transect, this is due to those trees falling into an area of bog which has skewed the results.

The charcoal reflectance data from trees across Breeches Branch supports the observations that the fire spread (SE to NW); reflectance increases in the study sites across Breeches Branch moving from site 1 in the south east to site 4 in the north west. This pattern in reflectance measurements would mirror the direction and spread of the fire, as the fire moved across the study area it would have gained momentum and energy, and therefore would have produced higher reflecting/ more severe burns to the area, as the results have shown. The middle of the burned area would more than likely of had the greatest density of fuel and is the furthest point away from any of the road edges therefore it is fair to assume this area would have experienced the greatest fire severity, this is also supported by the charcoal reflectance data. Reflectance is greatest at site 3. Site 3 is situated in the mid portion of the forest plot of Breeches Branch and is the furthest site from the four roads that surround the forest plot (Figure 5.1). As such whilst no statistically significant increase in severity or reflectance was found within each site the finding that site 3 has the highest reflectance severity suggests that fire-breaks did play a role in mitigating damage to the forest as well slowing spread. Although roads do not prevent spot fires they act as an important fire break in forest ecosystems, affecting the spread of the fire (Sturtevant *et al.,* 2009) and influence the abundance of fuel availability in proximity to the road edge (Harper *et al.,* 2015). This appears to support my assumption that understory fuel density must have been greatest in the mid region of the plot as evidenced by the high severity and reflectance values found at site 3.

Figure 5.4 shows line plots of reflectance measurements vs distance from road edges (fuel breaks) for Breeches Branch, Lost and Chat. The severity transects through the Lost and Chat sites show an increase in reflectance moving from the road edges into the interior of the forest. When testing the relationship between distance and reflectance measurements Lost and Chat were found to have significant positive relationships (Spearman's $\rho = 0.636$, $p < 0.001$) and (Spearman's $\rho = 0.891$, $p < 0.001$) respectively. This is in contrast to Breeches Branch, that whilst Figure 5.4 indicates apparent slight increases in reflectance away from the road edge into the forest this relationship was non-significant (Spearman's $\rho = 0.383$, $p = 0.313$). Although similarly Breaches Branch ascribed severity and reflectance is highest in the middle transect (site 3).

The statistically non-significant relationship between distance from the roadside and reflectance at each transect at Breeches Branch are not what I would have necessarily of expected to find, as I anticipate that fuel load and therefore fire intensity would have probably been higher in the interior. Although it should be noted that the transects did not extend into the forest as far as was sampled at Lost and Chat and therefore, it could be suggested that the higher severity parts were missed. However, managed fires, like those at Lost and Chat, are lit with the idea to bring the fire together at one point via igniting a backing fire, the flanks and final letting a head fire run towards the centre; this is designed to prevent out of control spread and draw the fire toward itself (Professor Claire Belcher personal communication, 2019). It therefore stands to reason that the highest reflectances and severities were found towards the centres of the plots at Lost and Chat. However, the Breeches Branch fire, being unmanaged, spread as a head fire, crowning with 30m flames and covering half a square mile in 40 mins (The New York Times, 2018) therefore, its behaviour was considerably different to that at Lost and Chat. It therefore seems more likely that this may account for the different distribution in fire severity and reflectance between the unmanaged fire at Breeches Branch and the managed fires at Lost and Chat.

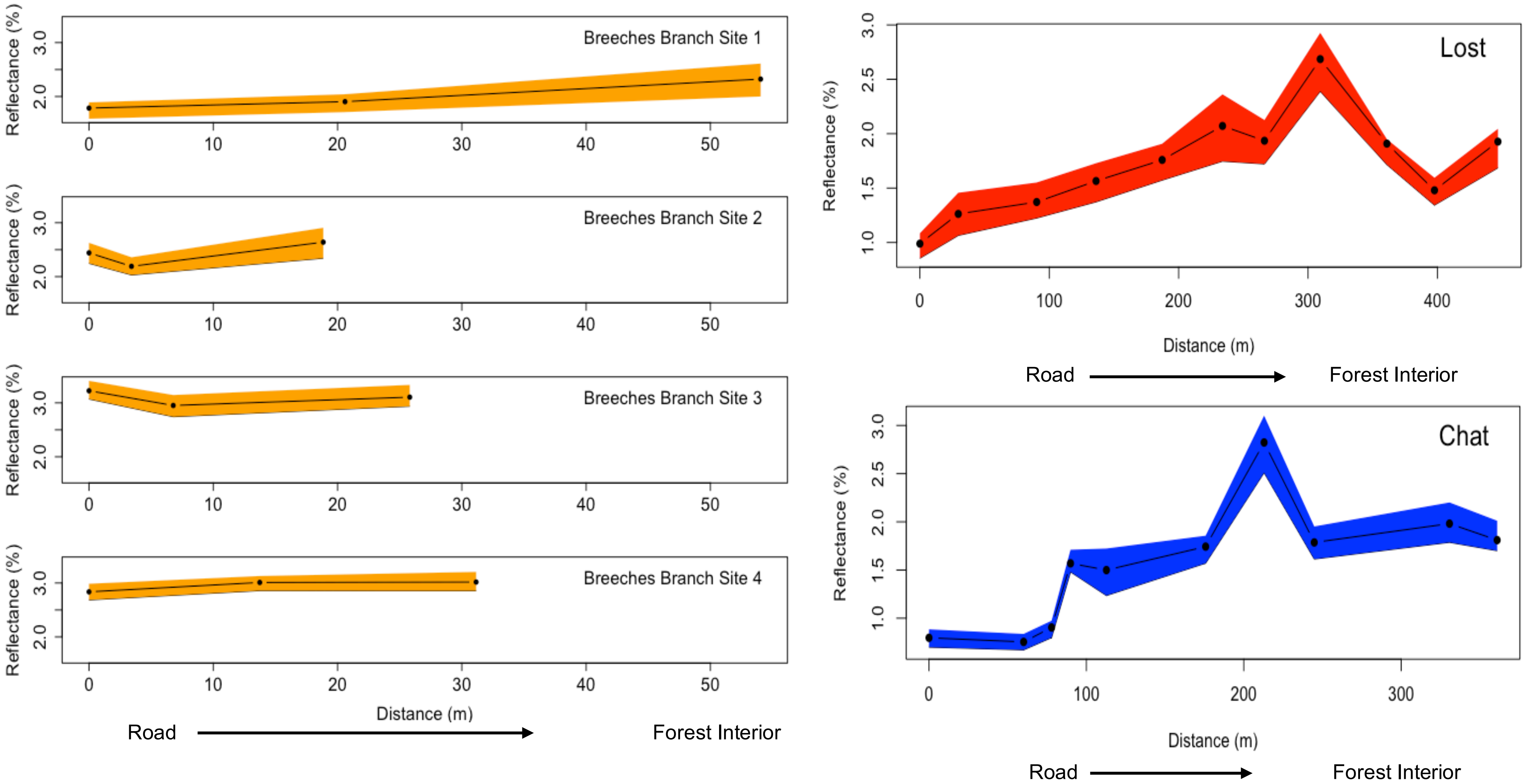

Figure 5.4: Line plots with polygons showing the 25th and 75th quartiles of the reflectance data vs distance, from road edge to forest interior, for Breeches Branch, Lost and Chat. Note that site 4 in Breeches Branch has the first three trees plotted and not the entire 6 trees in the transect, this is due to those trees falling into an area of bog which has skewed the results; for clarity in the figure these data points have been removed.

Table 5.2: Qualitative fire severity table used to assess the Breeches Branch fire scar, based on Ryan and Noste (1985) and adapted for this pineland ecosystem.

Tree	Circumference (cm)	Height of tree (m)	Severity score	Notes
BB1	158	22.0	Med	Brown needles on ground, evidence of smouldering base, crown intact, no ground vegetation remaining, charred up to crown, green needles remain on trunk
BB2	107	18.9	Med	Brown needles on ground, crown intact, no ground vegetation remaining, charred up to crown, some green needles remain on trunk
BB3	98	18.2	Med	Brown needles on ground, larger shrubs surrounding the tree were not fully charred, charred up to crown, some green needles remain on trunk
BB4	92	16.1	Med-High	Brown needles on ground, crown intact, charred approx. 1/3 up the tree not reaching crown, no ground vegetation
BB5	58	14.0	Med-High	Brown needles on ground, crown intact, charred approx. 1/3 up the tree not reaching crown, no ground vegetation
BB6	89	16.6	Med-High	Brown needles on ground, crown intact, charred up to crown, no ground vegetation
BB7	85	12.7	High	Fully charred, no crown, no smaller branches remaining in crown, no needles on ground, trees sappier, pinecones on ground fully charred, some brown and orange needles remain on higher branches
BB8	67	12.0	High	Fully charred, no crown, no smaller branches remaining in crown, no needles on ground, trees sappier, pinecones on ground fully charred, some brown and orange needles remain on higher branches
BB9	101	18.4	High	Fully charred, no crown, no smaller branches remaining in crown, no needles on ground, trees sappier, pinecones on ground fully charred, some brown and orange needles remain on higher branches
BB10	82	13.1	High	Fully charred, no crown, cones partially charred, few brown uncharred needles remain on ground, some brown and orange needles remain on higher branches
BB11	60	9.2	High	Fully charred, no crown, no smaller branches remaining in crown, cones partially charred, few brown uncharred needles remain on ground
BB12	91	13.0	Med-High	Fully charred trunk, some needles in crown remain, few brown uncharred needles on ground
BB13	87	16.7	Med	Fully charred trunk, some needles in crown remain (more than previous tree), more than previous brown uncharred needles on ground
BB14	80	11.4	Med-low	Charred approx. 1/3 up trunk, brown needles on ground, branches with needles remain near base of tree and all of the way up to the canopy, lots more needles remain that previous tree, bigger shrubs surrounding partially charred but no leaves remain, more than previous brown uncharred needles on ground
BB15	111	13.0	Med-low	Needles all along trunk (bog brush) remain, orange and brown needles on floor, more than previous brown uncharred needles on ground

5.4.3 Will fire severity be lower in managed fires than unmanaged fires?

Figure 5.5 shows boxplots and density distributions of the charcoal reflectance values for fires occurring at Breeches Branch, Lost and Chat compared to one another.

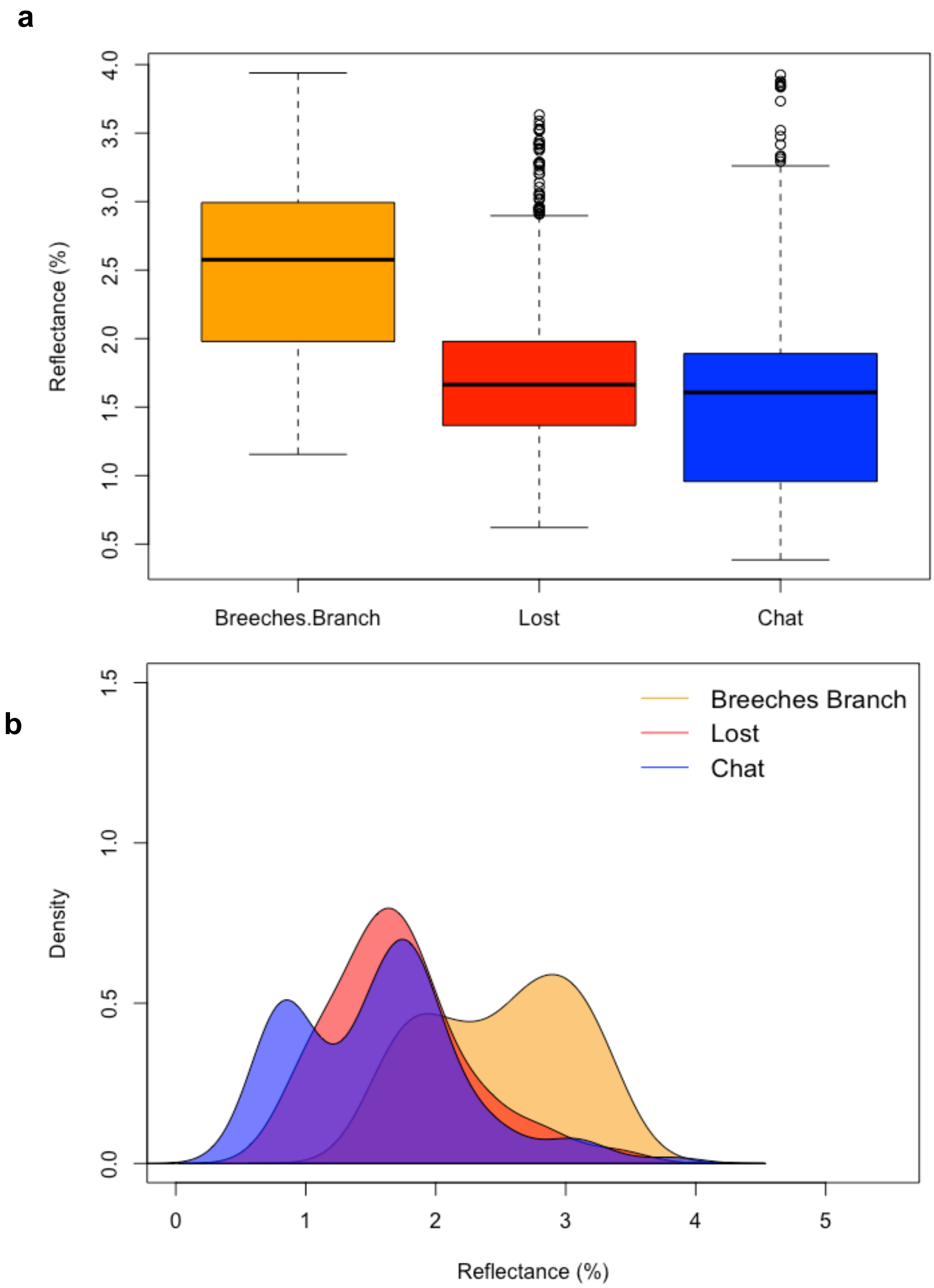

Figure 5.5: Boxplots a) and density distributions b) of the charcoal reflectance values for Breeches Branch and, Lost and Chat. A Welch 2 sample t-test showed a significant difference between the reflectance values of the prescribed burns (Lost and Chat) when compared to the unmanaged fire (Breeches Branch) (p<0.001).

It can be seen that the two prescribed burns, Lost and Chat, have similar density distributions in reflectance values to each other, with median values just below 2%. However, Breeches Branch, the unmanaged fire, can be seen to have a higher density of measurements of >1% reflectance and the highest density of measurements falling in the 2.5-3% range of reflectance values. A Welch 2 sample t-test showed a significant difference between the reflectance values of the prescribed burns (Lost and Chat) when compared to the unmanaged fire (Breeches Branch) ($p < 0.001$). Comparing the two prescribed fires, Lost can be seen to have a slightly higher mean reflectance when compared to Chat and also has a higher density of values > 2% (a full comparison with more information about each site can be found in the Chapter 4).

This is an encouraging finding as it is typically the aim of prescribed fires to have lower severity impacts, therefore the finding that the managed fires of Lost and Chat typically had low severity and reflectance than Breeches Branch is an important observation. These results are supported by Gallagher (2017), whom indicated that in a study of 367 prescribed fires and 80 wildfires in the PNR, that burn severity, using difference normalised burn ratio (dNBR) that the occurrence of low severity fires is much more common in prescribed burns than for unmanaged wildfires, that are generally of higher severity. Chapter 4, which precedes this current chapter, shows a significant relationship between dNBR and charcoal reflectance. Because of this, I can assume that Gallagher's (2017) dNBR results would match the charcoal reflectance derived fire severity scores that I use in this research.

There is considerable debate about the development of true prescription fires and whether or not prescribed fires should mimic natural fires or not (Paton *et al.,* 2015). Ignition patterns will influence fire intensity, severity, and vegetation response to fire where backing fires compared to head fires create different fire behaviour (Martin and Hamman, 2016). Head fires are wind-driven and more flashy, with high rates of spread, longer flame lengths and shorter heat flux residence times. Backing fires, burn into the wind and are primarily fuel-driven, they lower rates of spread and shorter flame lengths but the heating of the ground can have long residence times. These differences are anticipated to have specific first- and second-order impacts on community response (Martin and Hamman, 2016) and therefore also on fire severity. Therefore, the degree of above ground and below ground biomass loss, influences the post fire recovery trajectory of forests (Kelly *et al*., 2013). It is a currently major task for fire managers to begin to attempt to restore natural fire regimes to many ecosystems (Martin and Hamman, 2016), particularly those that are fire adapted or fire dependant. Because of this it is critical to better understand the relationships between fire intensity, severity, ignition patterns and vegetation effects, which is why charcoal reflectance makes an intriguing post-fire metric for quantifying heat exchanges in fires, fire severity and utilising these to estimate ecological damage-recovery.

One key issue in assessing differences between managed and unmanaged fires is in timings of the managed fire season and that of unmanaged fires. The conditions of the weather for example in which they are ignited, is very important to land managers who need to consider the surrounding communities (Nesmith *et al.,* 2011). In the PNR prescribed fire season finishes at the end of March, where burns will be undertaken on high humidity days, low wind days. The managed fire at Lost was conducted on the edge of acceptable conditions for prescribed burns and behaved more like a wildfire, whilst, the fire at Chat was more typical of a prescribed burn (M.Gallagher, personal communication, 2018). This appears to be indicated by the reflectance measurements where Lost was found to have slightly higher mean reflectance compared to Chat and also has a greater density of values higher than 2% reflectance. This illustrates that the conditions in which the burn is conducted relates to the fire's behaviour, which in turn links to the formation of charcoal reflectance (Belcher, New *et al*., 2018).

The Breeches Branch fire occurred shortly after prescribed fire season and as such has made an excellent comparator in terms of the time of year and the state of the fuel; a rare opportunity to almost compare like with like. Indeed conditions for the Breeches Branch and managed fires were very similar: at Breeches Branch mean temperature was ~15°C and RH (relative humidity) ~30% but mean wind speed was ~5m/s, at Lost Lane temperature was ~ 13°C (mean), RH was ~ 22% (mean) but wind speed was slower; mean was ~1.4 m/s with occasional gusts of up to 4.4 m/s. The difference in relative humidity may have affected the moisture of the fuel i.e. at Breeches Branch the 1 hr dead fuels could have potentially been wetter than Lost as the RH of former was 30% and the latter 22%. However, because of the overall similarity in conditions and the same fuel types being involved in the both the managed and the unmanaged fire it can be implied that the difference in reflectance will be most likely to be due to differences in the ignitions patterns between the managed and unmanaged fires and the influence that this has on the fire behaviour.

Previous work has suggested that maximum surface fire temperature is positively correlated with fire severity (Hartford and Frandsen, 1992; Chafer *et al*., 2004; Bradley *et al*., 2006; Martin and Hamman, 2016) across a range of ecosystems. This has been suggested to support the idea that higher temperatures will consume more of the surface fuels (Martin and Hamman, 2016). However, Belcher, New *et al*., (2018) suggest that charcoal reflectance well relates to a combination of total energy flux and the duration of heating. This idea is supported by experimental fires that have indicated that fire residence time is greatly influenced by ignition patterns (Martin and Hamman, 2016).

In this analysis charcoal reflectance varies between the two managed fires and the unmanaged fire in the same ecosystem and in similar weather conditions. The managed fires have typically lower median charcoal reflectance than the unmanaged fire at Breeches Branch. This is despite the fact that slower moving backing fires occurred at Lost and Chat which have been suggested to lead to longer duration of heating of some ecosystem elements (Martin and Hamman, 2016). The formation of charcoal reflectance has been suggested to directly relate to the net heat transfer through the fuels surface and must be equal to the absorbed external radiant flux (the flaming front) (Belcher, New *et al*., 2018). The results presented here imply that the overall energy release from the Breeches Branch fire was more important at transferring energy to the ecosystem elements than the slower spreading and potentially long duration of heating applied to plant parts in the managed fires.

This research indicates therefore that charcoal reflectance may provide a particularly useful in tool for assessing differences between wildfires, managed fires, prescribed fires and the success of prescriptions. Where charcoal reflectance has the potential to provide a more direct link between fire properties and ecosystem damage-recovery than qualitative estimates of fire severity (New *et al*., 2018). As such, development of this as a tool with which to assess fires may have significant value in testing prescriptions and providing evidence as to whether the fire's aim was achieved and where improvements might be made.

5.5 Conclusions and significance to ecosystem management

The development of charcoal reflectance as a method of investigating fire severity, and a metric with which to quantitatively assess the potential impact this has on future forest mortality rates and the release and burial of carbon through the creation of charcoal, is important for a future that is predicted to have higher wildfire occurrence. This addresses the increasingly common global challenge of wildfire, due to climate change and anthropogenic activity in and around the world's forests. In this chapter, and in previous papers New *et al*. (2018) and Belcher, New *et al*., (2018), we suggest the use of reflectance as a quantitative method with which to assess fire severity rather than the qualitative methods which have been relied upon in the past. In this study, I use both the qualitative and quantitative methods to further demonstrate how the reflectance method is superior to the matrix description method and how reflectance should be used in more wildfire studies in the future.

The results of this Chapter show that current prescribed fires or experimental fires in the PNR do not completely represent 'natural' wildfires; even those occurring close to the prescribed fire season. I have shown through my analysis of charcoal reflectance that natural wildfires generate higher reflecting charcoal and therefore have higher fire severity, than managed fires in the same forest type. Previous research has shown that conditions, most notably seasonality, in which prescribed burns are conducted are important in influencing the fire severity of fire in the PNR, however as Gallagher (2017) highlights, prescribed burns are only conducted during the time of year when low fire severity is most likely to be the outcome of the burn. It is important to note that Lost and Chat were conducted in the window of allotted time when prescribed burning can take place in the PNR, Breeches Branch occurred just outside of this window. As such seasonality and a strong variation in conditions is less likely to account for the variations observed in this comparison of managed and unmanaged fires. The results presented here suggest that current fire management practices, that require the use of specific ignition patterns, may be a key cause of lack of replication of the natural effects of an unmanaged wildfire in this ecosystem. This may point to reconsideration of the heavy usage of backing and flanking fires that, whilst easier to control, appear not to well represent the nature of unmanaged fires in the area. This undoubtedly represents a challenge for safety none-the-less.

I suggest future work is needed to investigate how fire severity is replicated in prescribed burns in the PNR. Managed fires are typically designed to be less severe than unmanaged fires, and indeed the results from this thesis supports the success of NJ fire service and the NJ Forest Service at achieving this in the PNR. However, if we seek to mimic natural fires in fire adapted ecosystems such as the PNR then it can be seen that even unmanaged fires at a similar time of year do behave differently to their counterpart; managed fires. Such differences may have an impact on the amount of carbon that would be naturally stored in the soil, and the regeneration time of the forest. This is supported by research conducted Doerr *et al*., (2018) who found that PyC loss in wildfires is strongly linked to differing fire intensities. It has been found that high-intensity wildfires produce PyC that has higher recalcitrance than PyC formed in lower severity fires, therefore having an impact on the global carbon cycle and local- to global-scale carbon budgeting (Belcher, New *et al.,* 2018; Doerr *et al.,* 2018). Taking into account the differing recalcitrance of the PyC produced by varying intensity fires, it could be suggested that Breeches Branch, the higher severity unmanaged wildfire, may sequester more carbon in the long-term in the form of charcoal than Lost and Chat, the lower severity prescribed fires. This is further supported by research by Belcher, New *et al*., (2018) in their investigation of the charcoal reflectance metric they found that higher charcoal reflectance measurements were positively correlated with increases in the total heat released during combustion. Charcoal formed during combustion with higher total heat release rates was also found to be more recalcitrant, meaning that charcoal created during lower energy fires would be more vulnerable to post-fire degradation and higher energy formed charcoal would stay in the ecosystem for longer (Belcher, New *et al.,* 2018). Charcoal production is an important aspect of fire in the ecosystem, driving many ecosystem processes. Through its recalcitrant nature and thus long-term stay in the environment, this could mean that affecting the amount of charcoal produced by say conducting prescribed fires of low severity, will have effects on ecosystems long into the future (DeLuca *et al.,* 2006). Whilst, we may be successful in managing fuel loads using fire in certain ecosystems such as the PNR to prevent future large fires, it is unlikely that the way in which we achieve this is having the same impact on the ecosystem over the long-term that the natural fire regime might have.

Chapter 6

Charcoal reflectance variation across a range of ecosystems, fuel types and fire regimes

6.1 Abstract

The research presented in this thesis thus far has indicated that charcoal reflectance performs well as a potential fire severity metric. This chapter will show that charcoal reflectance values across four different ecosystems, with the aim to evaluate whether reflectance is a useful metric to evaluate variation in fire severity and energy regimes across different ecosystems. Here, using the charcoal reflectance metric to assess fire severity across a range of fire regimes and ecosystems, I have also compared the charcoal reflectance measurements: 1) between fuel types (angiosperm and gymnosperm), 2) different fire types (crown vs surface fires), and 3) different ecosystems as a whole. These ecosystems include Canadian boreal forests, United Kingdom temperate heathland and moorlands (shrubland), and tropical forest ecosystems both forests in Australia and the Brazilian Amazon. These ecosystems have been compared in order to consider what commonalities exists between the reflectance of charcoals in these ecosystems and to what extent fire type and fuel type might influence these factors. I found that tropical, and shrubland ecosystems produced a similar range of charcoal reflectance measurements and therefore exhibit similar fire severities. This is in comparison to the Canadian boreal forests, which produced significantly higher reflectance values in comparison to the other ecosystems. I also found that there was a significant difference between the reflectance values when comparing gymnosperms and angiosperms, with gymnosperms across all of the ecosystems producing higher charcoal reflectance values and therefore higher fire severities than angiosperms. To summarise, this chapter shows that charcoal reflectance measurements vary across ecosystems and within ecosystems and with fuel

type. Ultimately, I found that fuel type was more than likely the key driving factor in determining charcoal reflectance in this study.

6.2 Introduction

Keeley (2008), noted that fire regimes are defined by the combination of: (1) intensity and severity, (2) frequency, (3) size, (4) fuel consumption pattern, and (5) seasonality. Where fire regimes are strongly influenced by the fuel type that is consumed during the fire that will determine whether a fire is a ground, surface or crown fires. Mixed fire regimes can also occur for example where surface and crown fires occur during the same fire (Keeley and Pausas, 2019; Bond and Keane, 2017).

Fire regimes vary between the different ecosystems across the globe (Bond and Keane, 2017). The smallest proportion of annual burnt area can be found in the humid tropical and temperate forest ecosystems, and dry deserts (Cochrane and Ryan, 2009). The continent with the greatest proportion of annual area burnt (70%) is Africa mainly fueled by grass, the remaining 30% can be predominantly attributed to fires occurring in Australia, South America and Central Asia (Bond and Keane, 2017). It is the variation in fire frequency, fire behaviour and fire severity that shapes and influences ecosystem structure and function, for example influencing the distribution and abundance of both vegetation and animal species (Bond and Keane, 2017).

Anthropogenic interference is increasingly affecting the natural fire regimes in many of Earth's ecosystems (Keeley and Pausas, 2019). An example of a change in fire regime due to anthropogenic action can be seen when looking at fire management in forested ecosystems. In many US ecosystems in particular the coniferous forests of Montana, Idaho and the Western states, fire suppression has been an active fire management strategy. This has led to an abnormal increase in the abundance of fuel on the surface which can then result in catastrophic wildfires, whereby the surface fuels act a ladder carrying surface fires into the canopy (Keane *et al.,* 2002). In comparison, some ecosystems are experiencing shifting patterns in fire regime where the presence, and then absence of anthropogenic action causes multifaceted changes. For example, in the Mediterranean annual burn area has increased by ~100x since the 1960s, primarily due to the decrease in pastoral farming on the land which has shifted a grassland ecosystem to a more flammable shrubland ecosystem (Pausas and Vallejo, 1999).

To help create ecosystem resilience in a climate that is changing, we need to better understand fire behaviour in order to explore the ecological effects it has on ecosystem functions and services (Keeley and Pausas, 2019). Those ecosystems where fire is a rare occurrence in their evolutionary history will likely be less resilient to the occurrence of wildfire compared to those that have experienced wildfires and have adapted to them (Allen *et al.,* 2002; Keeley and Pausas, 2019). However, even ecosystems that have had fire in their evolutionary history are struggling to cope with the changes in fire regimes brought about by human interference and climate change (Keeley and Pausas, 2019). Shrublands and forested ecosystems have been identified as being particularly sensitive to increases in fire frequency due to anthropogenic action. In crown fire ecosystems, for example, a higher fire frequency and shorter intervals between fires causes tree lost and means that there is a risk of these ecosystem types converting into non-forested ecosystems (Turner *et al.,* 2018; Keeley and Pausas, 2019).

Recent research is developing the charcoal reflectance method as a way with which to explore the relationship between fire behaviour and the formation of the residual charcoal (Belcher, New *et al.,* 2018). Such approaches to develop previously established methods, and create new methods, are needed if we are to better understand fire behaviour and the ecological effect on ecosystems. Measuring the reflectance of charcoal that has been embedded in resin, polished, and then measured under oil using a reflectance microscope has been a method that has been implemented to provide researchers with the means to establish the relationship between formation temperature of charcoal and reflectance values of charcoal (Ascough *et al.,* 2010).

However, in much of the existing research oven formed charcoal was used which is not necessarily the best method in which to replicate natural wildfires (Belcher and Hudspith, 2016). Research has shown that this method of forming charcoal does not capture the full range of combustion processes (Belcher and Hudspith, 2016). One process in particular is the heat flux generated by the fire which creates charcoal. During a natural wildfire the temperature field and therefore the distribution of heat is variable, while in an oven or furnace the temperature is set at a constant heat flux (Alexander, 1982; Finney *et al.,* 2015; Belcher and Hudspith, 2016). Therefore, the relationship between temperature/heat flux and reflectance values may be correct for those experiments which have used oven-based methods to create charcoal, but this does not represent real-world wildfire conditions and the charcoal which is naturally created. Therefore, oven created charcoal cannot be compared to charcoal produced by real-world wildfires.

Belcher and Hudspith (2016) have shown that the highest reflectance values are achieved not according to temperature but when fires switch from flaming to smouldering, the transition between pyrolysis and char oxidation, which means that charcoal reflectance more likely captures the amount of heating experienced by a plant material and not the temperature of the fire or flame. Using this finding Belcher and Hudspith (2016) suggested that reflectance measurements may be of use in providing a quantitative measurement to fire severity surveys. New *et al*., (2018) supports this by comparing qualitative fire severity scores and quantitative charcoal reflectance measurements and showing that these two methods do produce similar fire severity scores. But critically that charcoal reflectance appears to provide higher resolution in the medium and high severity categories, something which does not seem to be able to be picked up on by observation through the qualitative assessments.

Research has shown that reflectance is in a state of constant change throughout the combustion process, it is not a fixed property as previous oven-based experiments would suggest by solely looking at pyrolysis and linking reflectance measurements to temperature (Jones *et al.,* 1991; Scott, 2010; Ascough *et al.,* 2010). Belcher and Hudspith (2016) showed that reflectance constantly changes during the different stages of combustion, samples of different moistures and different species all experienced lower reflectance values when extracted at peak heat release rate (PHRR) and higher values at the latter stage of the combustion process when flaming ceases. More recently, researchers have shown that charcoal reflectance is also variable when comparing different fire regimes (Belcher, New *et al*., 2018; Roos and Scott, 2018). For example, Roos and Scott (2018) found that crown fires produced higher reflectance measurements than non-masticated surface fuels, whilst Belcher, New *et al*., (2018) found the surface fires in Canadian boreal forest formed lower charcoal reflectance than crown fires in the same ecosystem type. This recent research highlights the importance of conducting studies on fire behaviour through the development of analytical approaches involving charcoal.

Charcoal reflectance has been shown in recent research, and in this thesis, to be a metric with which researchers can gain quantitative information about the energy aspect of fire regimes (Belcher, New *et al.,* 2018). However, not only can charcoal reflectance provide information regarding the distribution of energy across an ecosystem and variations in fire severity, but it can also be used to inform researchers about long-term carbon budgeting for different fire regimes (Belcher, New *et al.,* 2018; Doerr *et al*., 2018). Charcoal is known to be an important source of pyrogenic carbon (PyC) (Bird *et al.,* 2015; Santin *et al.,* 2016). Research has shown that charcoal formed by higher heat fluxes and longer durations of heating is more recalcitrant and could remain in soils as long-term sink of carbon compared to those heated less (Belcher, New *et al.,* 2018; Doerr *et al*., 2018).

The direct influence of fire behaviour on fire effects on the ecosystems are not yet fully understood, which is part of the reason fire severity scoring systems have been developed as we currently lack the ability to go directly from fire behaviour to fire effects. Belcher *et al.,* (2016) highlights the importance of delving deeper to understand more directly how fuel types link to different fire behaviours and energy regimes. By using laboratory methods, such as cone calorimetry, to assess the flammability of vegetation and then link this back to leaf morphology, Belcher *et al.,* (2016) was able to suggest that changes in the fire regime i.e. the combination of fire behaviour and fire frequency, had an important effect on the ecosystem composition.

Previous work (Hudspith *et al*., 2014) has indicated that charcoal reflectance, also varies with fuel type across an ecosystem. For example, different fuel types in a raised bog ecosystem were found to be a key driver of pyrolysis intensity with angiosperms and gymnosperms being found to produce higher reflecting charcoal than bryophytes and peat (Hudspith *et al.,* 2014). It is important to note that overall angiosperms produced a higher median than gymnosperms, with an approximate difference of 0.5% in the Irish peatland studied (Hudspith *et al.,* 2014). These fuel-driven variations in charcoal reflectance highlight the significance of identifying the fuel type of the charcoal when assessing fire severity and fire intensity across a burned area. At the local scale fuel type has an important influence on fire behaviour, for example fuel type has been found to be a key driver of pyrolysis intensity (Hudspith *et al.,* 2014), and the bulk density of wood has also been found to determine the heat regime and the charcoal reflectance formed (Belcher, New *et al.,* 2018).

In this chapter I evaluate the differences in reflectance between factors such as fire regime, fuel type and ecosystem type, to better understand how charcoal reflectance can be used as a post-fire assessment tool. These factors are known to have an influence on fire behaviour, and different fire behaviours are known to influence charcoal reflectance. This chapter builds on previous research on fire behaviour and fire severity by comparing reflectance across multiple ecosystems, fuel types and fire regimes (e.g. Belcher, New *et al*., 2018; Roos and Scott, 2018).

6.3 Materials and methods

This study includes the analysis of charcoal reflectance from four different ecosystems: Boreal forest (Canada), Tropical Rainforest (Brazil), Tropical forest (Australia), Shrubland and a Moorland (UK). The Canadian data has been previously published in Belcher, New *et al*., (2018) and information about these fires and the Australian fires have been taken from the fieldwork journal of Dr Cristina Satin (personal communication 2019). A mixture of experimental and unmanaged wildfires has been included in this analysis. The Australian and one of the Canadian fires were experimental fires. The other Canadian fire was a wildfire but, in all cases, different wood types (Jack Pine (JP) and Western Red Cedar (WRC)) were placed into these fires by the researchers, rather than collecting charcoal post-fire from in-situ vegetation. The Amazonian and UK wildfires were unmanaged fires and charcoal was collected post-fire from in-situ vegetation (UK) or the soil (Amazonia) from the study locations. Taking a step back from looking at comparing ecosystems on a wider-scale I have included separated fuel data from Winter Hill to evaluate variation in reflectance with fuel type within one ecosystem type, a moorland ecosystem. The focus with the Winter Hill data on different fuel type and reflectance is to assess the local-scale variance in reflectance within an ecosystem. Further information about the study sites and sample collection protocol can be found below.

6.3.1 Study sites and charcoal sampling

Table 6.1 shows the study sites and information regarding them: site name, location and vegetation type.

Table 6.1: Table showing the study sites from which charcoal reflectance was analysed and information about the fire.

Site	Ecosystem	Fire(s) date	Vegetation/ Wood type	Fire regime
Carn Brea, UK	Heathland	26th May 2015	Heather (*Calluna sp*) Gorse (*Ulex europaeus*)	Surface
Winter Hill, UK	Moorland	11th June 2015	Grass (*Poaceae*) Bracken (*Pteridium sp*)	Surface
Feliz Natal, Brazilian Amazon	Tropical forest	Fires occurring between 2005-2009	Unknown angiosperm wood	Surface
Britannia Fire, Australia	Tropical forest	18th April 2006	Jack Pine (*Pinus banksiana*) and Western Red Cedar (*Thuja plicata*)	Surface
Pine Point plot, Canada	Boreal forest	30th June 2015	Jack Pine (*Pinus banksiana*) and Western Red Cedar (*Thuja plicata*)	Surface
Triangle plot, Canada	Boreal forest	2nd July 2015	Jack Pine (*Pinus banksiana*) and Western Red Cedar (*Thuja plicata*)	Crown

6.3.2 Feliz Natal, Brazilian Amazon, tropical forest ecosystem

Feliz Natal is located in the northeast of the state of Mato Grosso in southwestern Amazonia. Rapid deforestation due to an increase in soybean production has moved Feliz Natal into the top ten municipalities for deforestation and biomass burning (Agencia Brasil, 2009). Mean temperature in Feliz Natal ranges from 24-26°C with minimum air temperature not dropping below 18°C (Nimer, 1979). The wet period starts in November and ends in April when average rainfall is approximately 1850mm per year, followed by the dry period and burning season (Righi *et al.,* 2009).

Charcoal particles were collected from 9 sampling locations in total: FN01-FN09. Four of these were sent to me for analysis: FN03, 04, 05 and 09. The sampling locations were broken down into four subplots 50 x 50m, 100m apart (Figure 6.1).

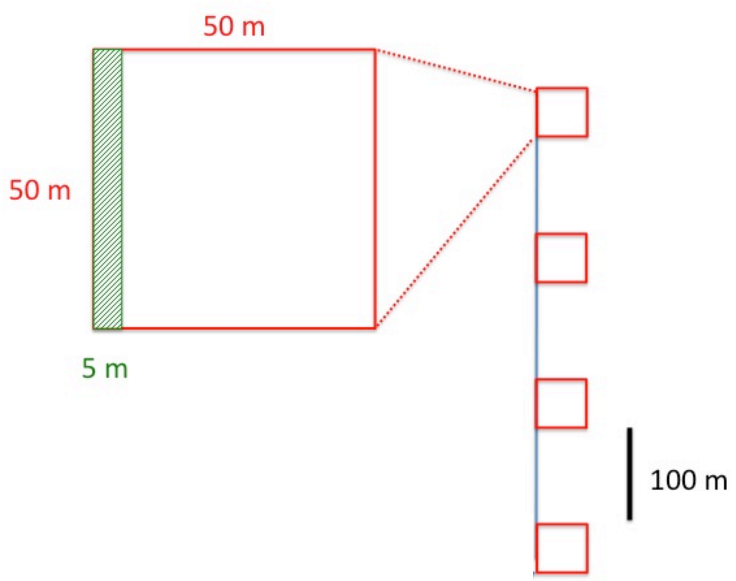

Figure 6.1: Feliz Natal charcoal sampling subplot design. The sampling locations were broken down into four subplots 50 x 50m, 100m apart. Source: Dr Ted R Feldpausch personal communication 2019.

Charcoal samples (Table 6.2) were taken from the 0-5cm depth portion of the soil profile, where the different sampling locations are believed to contain charcoal from unmanaged wildfires which occurred over several different years. The date of the fires cannot be conclusively stated as radiocarbon dating has not been conducted due to the small nature of the particles, and the removal of particles from resin as part of the charcoal reflectance method is not possible.

Table 6.2: Amazonian charcoal samples collected from the field and information regarding sampling collection and the study site. Information provided by Dr T R Feldpausch personal communication 2019.

Area name	Area info	Transect ID	Plots	Coordinates	Plot information
Fazenda 25 de Dezembro	Burnt in 2010	FN03	1	55°5'55.562"W;12°16'17.685"S	Many small diameter and few large trees in the plots. Many fallen trees, presence of many colonizing lianas and *Passiflora*. Thick litter, few overstory trees as standing dead, colonizing trees having low diversity.
			2	55°5'51.44"W;12°16'15.941"S	
			3	55°5'46.685"W;12°16'13.88"S	
			4	55°5'42.246"W;12°16'12.137"S	
Fazenda São Jorge	Logged area, unknown burn date	FN04	1	55°4'10.807"W;12°16'50.975"S	Formation of small clearings in the canopy, and consequently many seedlings. A high diversity of species, without fallen near trees, understory without bromeliads, presence of few lianas and grasses.
			2	55°4'7.319"W;12°16'48.122"S	
			3	55° 4'3.198"W;12° 16'44.793"S	
			4	55°3'58.759"W;12°16'42.098"S	
Fazenda São Jorge	Logged area, unknown burn date	FN05	1	55°2'7.693"W;12 15'54.467"S	Formation of small gaps in the canopy, and consequently many seedlings. A high diversity of species, without fallen near trees, understory without bromeliads, presence of few lianas and grasses.
			2	55°2'3.591"W;12 15'51.347"S	
			3	55 1'59.668"W;12°15'48.493"S	
			4	55°1'55.923"W; 12°15'45.373"S	
Fazenda Uirapuru	Burnt in 1999	FN09	1	54°11'51.477"W;12°0'19.872"S	Colonization of pioneer trees. Some open plots with high incidence of light, few grasses. In some plots, the lianas were dominant. Thick litter, apparently preventing seedling growth.
			2	54°11'54.654"W;12°0'10.639"S	
			3	54°11'54.654"W;12°0'10.639"S	
			4	54°11'56.64"W;12°0'6.171"S	

6.3.3 Carn Brea, UK, heathland ecosystem

As described in Chapter 3 an unmanaged heathland fire in a region dominated by heather (*Calluna sp*. *Erica* sp.) and gorse (*Ulex europaeus*) occurred on 26th May 2015, burning 7 ha in Carn Brea, Cornwall, UK (50.21418N, 5.25518W) (BBC, 2015). This heathland (maximum elevation 252m) is dominated by peat and gravelly acidic soils, and gorse and heather are the main fuel constituents; this mixed vegetation structure is heterogeneous across the heathland (Natural England, 2014). The patches of gorse and heather are intersected by several small streams and exposed granite outcrops (Natural England, 2014).

Charcoal samples were taken two days post fire. A transect was taken across the axis of the fire scar, and the charcoal sampling locations documented using a Global Positioning System (GPS) device and photographs taken at each site. Samples were collected every 1m using a 1m x 1m quadrat and collecting charcoal within that area. The fire started at the bottom of the heathland and travelled uphill to where a footpath intersected the heathland, which appeared to have acted as a 'natural' fire break.

6.3.4 Winter Hill, UK, moorland ecosystem

Winter Hill is located on Rivington Moor in Chorley near Manchester, UK, its highest point it is 456m (Ordnance Survey, 2019). The Winter Hill fire took place on the 11th June 2015 and covered an area approximately 1km by 500m (Manchester Evening News, 2015). Opportunistic sampling of the burn was conducted by Dr Victoria Hudspith on the 13th June 2015. Charcoal was collected from specific vegetation types: grass (*Poaceae*) and bracken (*Pteridium sp*), as this was opportunistic sampling samples were taken from areas that varied visually in terms of fire severity to gain a good representation of fire severity across the burn area.

6.3.5 Triangle plot and Pine Point, Canada, boreal forest ecosystem (information taken from the field journal of Dr Cristina Santin: personal communication, 2019 and Belcher, New et al., 2018)

Two experimental fires in the Canadian boreal forest ecosystem were instrumented and studied (more information about each of the fires can be found in the following paragraphs). The Pine Point plot fire took place on the 30th June 2015 and the Triangle plot fire took place on the 2nd July 2015. Rather than collecting charcoal from the native trees that were in-situ in the study areas pieces of wood were placed in the burn zone by researchers. In both fires fifteen 3cm x 3cm x 3cm blocks of Western Red Cedar (WRC) (*Thuja plicata*) samples from the wildFIRE Lab, University of Exeter, and fifteen pieces of native Jack Pine (JP) (*Pinus banksiana*) were placed in the study locations ~24 hours before the fires were ignited.

Pine Point plot: The area was slightly elevated and the litter layer was thin and very dry all the way to the mineral soil in some places. In comparison to the sparse understory in Triangle plot the understory in Pine Point was relatively dense (for example, *Juniperus* sp.) and the forest floor consisted of mainly needles and moss. Similarly, to Triangle plot the forest at Pine Point was made up of a mixture of black spruce (*Picea mariana*) and Jack Pine (*Pinus banksiana*).

Pine Point plot (60°49’38” N; 114°24’28’ W) was a low intensity surface fire’ however, ignition was caused by a lightning strike rather than human ignition like seen in the Triangle plot fire. Some trees were ignited using a Terra Torch as the fire was very patchy, some areas remained unburnt post-fire. Overall it was a very slow moving wildfire which meant that the study location could be instrumented and the 30 wood samples of WRC and JP could be placed before the fire front moved across the site. The fifteen samples of WRC and JP were placed 2m apart along a transect which ran parallel to the fire front (Belcher, New *et al.,* 2018).

Triangle plot: Triangle plot (61°34'055" N; 117°10'13" W) was an experimental high intensity crown fire, which aimed to mimic unmanaged/natural wildfire conditions. The study site contained a mixture of mature black spruce (*Picea mariana*) and Jack Pine (*Pinus banksiana*), with downed wood and a sparse understory present (Belcher *et al,* 2018). The fifteen samples of WRC and JP were randomly placed within a 15m x 15m plot. The fire was ignited with the Terra Torch and resulted in the fire moving through the study site very fast; a burn time of < 5 minutes, estimated fireline intensity of ~8,000-12,000kW.m^{-1} and flame lengths of > 5m above the canopy (Belcher, New *et al.,* 2018). From observations at the study site it appeared that the burn was very homogenous and that there were no unburnt or low-severity patches within the plot (Santin, personal communication, 2019). The canopy was completed consumed by the fire, all trees charred all the way to the top, all needles and small branches gone, and the understory and downed wood on the floor were also consumed by the fire.

6.3.6 Britannia Fire, Australia, tropical forest (information taken from the field journal of Santin and Doerr, 2016: personal communication)

The Britannia fire (37°48'43" S; 145°41'28" E) in Victoria (VIC), Australia, was a prescribed fire that took place on the 18th April 2016. Within the area planned for burning an area on a N/NW slope (330°N, slope angle of ~13°) was chosen to start the ignition; this was covered by dry eucalypt forest. The understory mainly consisted of thin, straight spiky shrubs approximately 0.5-3m high, a small amount of spreading wattle (*Acacia genistifolia*) was present along with a large amount of grass; both short and tall grass species present. The litter layer was predominately eucalyptus leaves and grass. Pieces of WRC were inserted into the pre-burn area and collected post-fire for analysis.

The fire was ignited through human ignition and started at the bottom of a slope with the hope the fire would move upslope. The fire was low intensity, with a small number of unburnt patches visible post-fire. Burning of the downed wood and bark on the standing trees was very variable, some of the larger trees were hardly scorched, this was the same for the WRC and JP pieces placed in the burn area pre-fire.

6.3.7 Laboratory work

Chapter 2 provides a more detailed account of the charcoal reflectance methodology, please see this chapter for more detail. All charcoal samples were oven dried at 40°C before preparing for analysis under the reflectance microscope. Charcoal samples were embedded in polyester resin blocks and subsequently ground and polished (Belcher and Hudspith, 2016). The type of embedding that this research has used is referred to as cold-mounting epoxy resin, this is a relatively simple technique consisting of two components, an adhesive and a hardener (Jones and Rowe, 1999). After the resin has fully set the surface of the block was ground and polished using a MetaServ 250 with Vector Power Head grinder-polishing machine (Buehler, Neckar, Germany. The surface polish quality of the blocks was checked under a Zeiss Axio-Scope A1 optical microscope, with a TIDAS-MSP 200 microspectrometer (SMCS Ltd, Baldock, UK), for any scratches (Jones, 1999; Hudspith *et al.,* 2014; Belcher and Hudspith, 2016). Measurements were obtained using a x50 objective (with x32 eyepiece magnification) and the measurement of reflectance manually taken at the cell-wall junction using *MSP200 v 3.27* software (Belcher and Hudspith, 2016). Where possible thirty reflectance measurements were taken per sample, for some of the Amazonian samples this was not possible due to the limited number of, and size of the particles. Again, where possible three replicates per tree were measured to ensure replicability, in all cases the points across the block showing the highest reflectance were measured to ensure that the surface of the bark was being captured.

6.4 Results

6.4.1 Ecosystem type

Reflectance measurements were obtained for all study sites and ecosystems in this study. The individual sites were combined based on the ecosystem to which they belong (Figure 6.2), for example the Pine Point and Triangle plot study sites in Canada were combined into a boreal forest (with crown) group and Winter Hill and Carn Brea were combined to create a shrubland group. The Brazilian Amazon and Australian sites were treated as separate entities and not combined to make a tropical group as these two ecosystems are very distinct from one another. When comparing the different ecosystem groups the boreal ecosystem was found to have produced significantly higher charcoal reflectance measurements compared to the shrubland and tropical ecosystems (Mann-Whitney U, $p < 0.001$) (Figure 6.2).

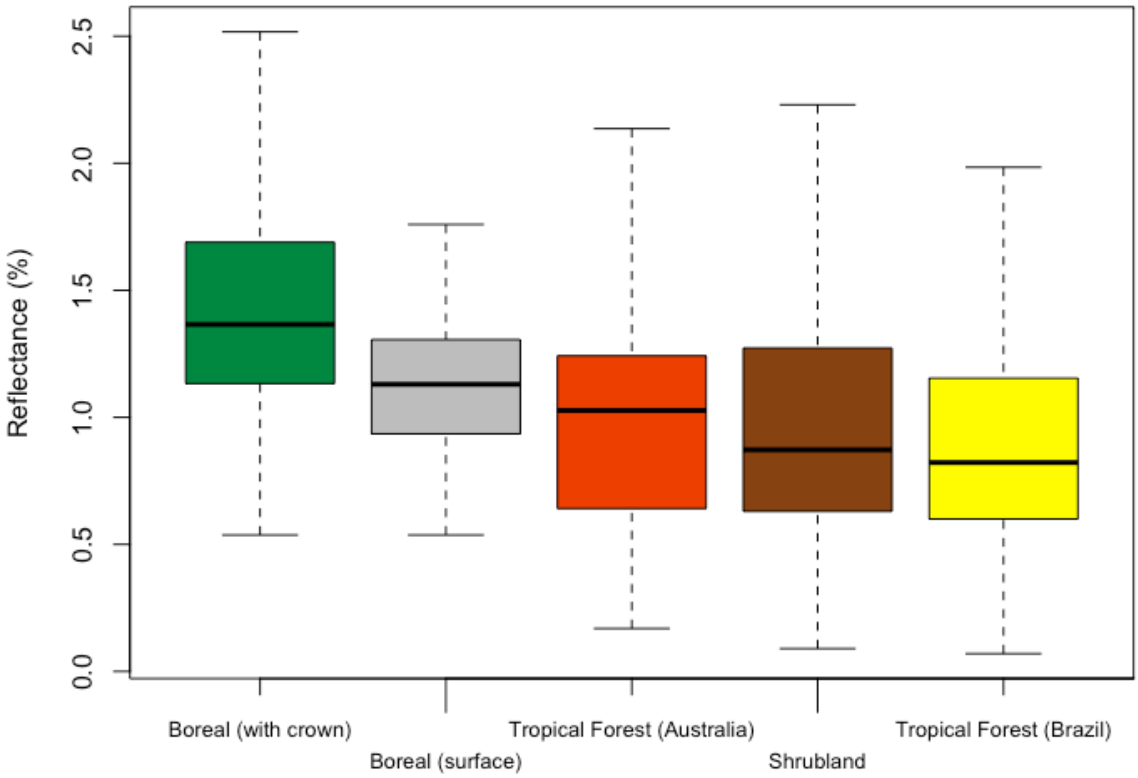

Figure 6.2: Boxplot showing the charcoal reflectance measurements for each of the ecosystems; the individual study sites described in the methods sections have been combined into their respective ecosystem type. All ecosystems apart from boreal (with crown) are surface fires. The boreal (with crown) data set includes all boreal data from Pine Point and Triangle plot. Those data points which lie 1.5x the interquartile range away from the 25th or 75th percentile are considered outliers and are not shown in this plot but are included in the analyses. Outliers have been removed to ease the interpretation of the data; due to the fact that there was a lot of Carn Brea data it produced a number of outliers at the top of the surface group which made the figure chaotic.

Mean reflectance values across the ecosystems varied ranging from 0.977% for the tropical forest in Brazil, to 1.431% for the boreal (with crown) group (Table 6.3). The shrubland ecosystem and the tropical forest (Australia) were intermediate with mean values of 1.116% and 1.121%, respectively. The boreal group was also plotted minus the crown fire (Triangle plot), this was done as it was believed that the crown fire may have an influence on the boreal group's mean as the rest of the fires across the different ecosystems were surface fires rather than crown. The difference between the two means of the boreal groups is 0.315%, with mean values of 1.431% and 1.116% for the boreal (with crown) and boreal (surface), respectively (Mann-Whitney U, $p < 0.001$). Interestingly the shrubland ecosystems and the boreal surface fire produced the same mean reflectance values, however, the medians are significantly different with boreal (crown) having a higher value, 1.130% compared to 0.872% (Table 6.3) (Mann-Whitney U, $p < 0.001$). A Mann-Whitney U test was used to assess whether there was still a significant difference with the crown fire data removed from the boreal group when compared to the tropical and shrubland ecosystems. The boreal group with the crown data removed was also found to be significantly different to the tropical and shrubland ecosystems, as was found for the ecosystem group with the crown fire data included (Mann-Whitney U, $p < 0.001$).

Table 6.3: Ecosystem types with mean reflectance values shown and the standard deviation.

Site	Mean (%)	Standard deviation
Boreal (with crown)	1.431	±0.436
Boreal (surface)	1.116	±0.255
Tropical forest (Australia)	1.121	±0.637
Shrubland	1.116	±0.764
Tropical forest (Brazil)	0.977	±0.587

6.4.2 Angiosperm and gymnosperm groups

When separating the ecosystem groups and plotting the individual study sites alongside one another there are clear differences in charcoal reflectance between sites. Charcoal reflectance varied across all sites (Figure 6.3) with values ranging from 0.07% (Amazon) to 4.97% (shrubland) (the highest value has not been shown in the figures containing boxplots as it was considered an outlier, and these have been removed to improve the clarity of the figure). When plotting the reflectance measurements, it became clear that there was a distinct separation of two groups in the data. Upon further research it was found that the data had highlighted that there were two significant types of vegetation being analysed; the data split into angiosperm and gymnosperm vegetation types (Figure 6.3 angiosperms are shown in yellow and gymnosperms in red).

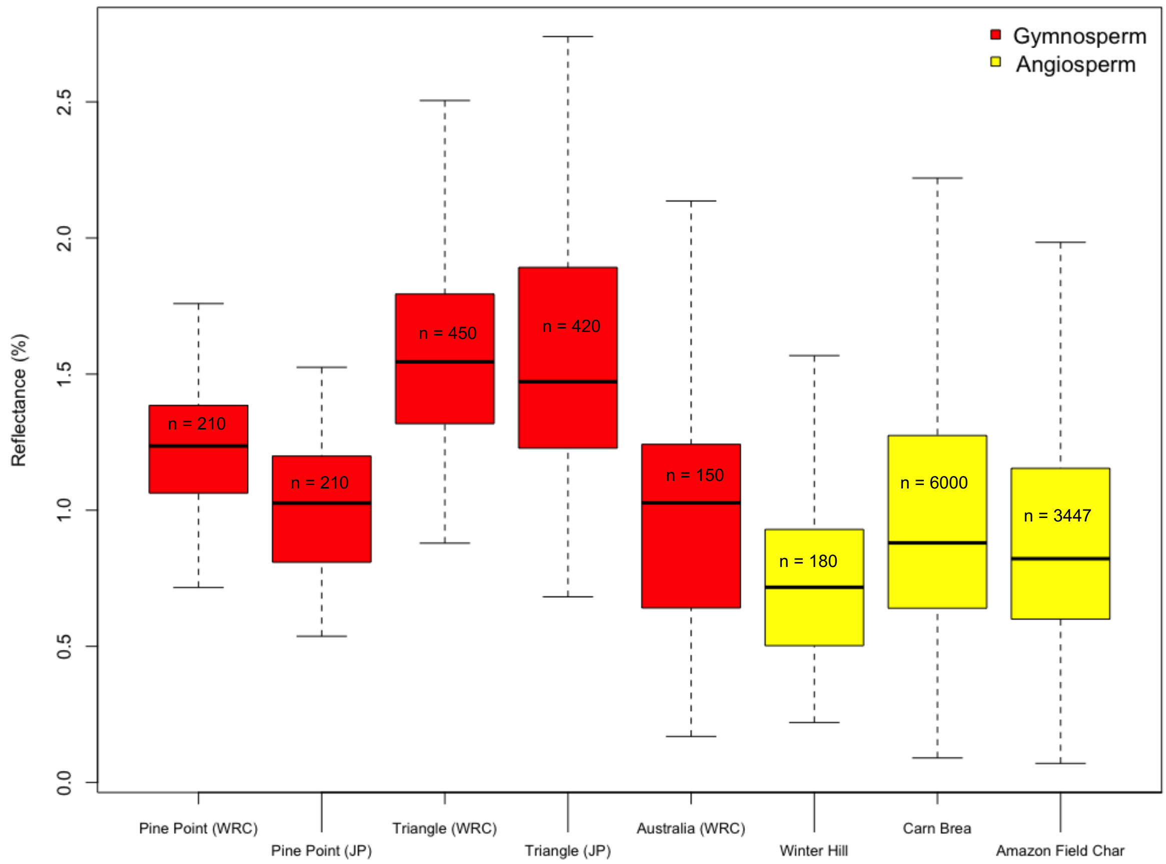

Figure 6.3: Boxplot showing the charcoal reflectance measurements for each of the sites in this study; excluding the laboratory results. The boxes have been coloured according to their fuel type i.e. yellow denotes angiosperms and red gymnosperms. Those data points which lie 1.5x the interquartile range away from the 25th or 75th percentile are considered outliers and are not shown in this plot, but are included in the analyses. Outliers have been removed to ease the interpretation of the data; due to the fact that there was a lot of Carn Brea data it produced a number of outliers at the top of the surface group which made the figure chaotic.

All the data were then combined into either angiosperm or gymnosperms, where Figure 6.4 indicates that sites where gymnosperm wood was measured yielded significantly higher charcoal reflectance values than those sites with angiosperms present (Mann-Whitney U, $p < 0.001$) (Figure 6.4). The sites with the angiosperm vegetation type present was found to produce a combined median value of 0.857% and the gymnosperm sites a combined median value of 1.323%.

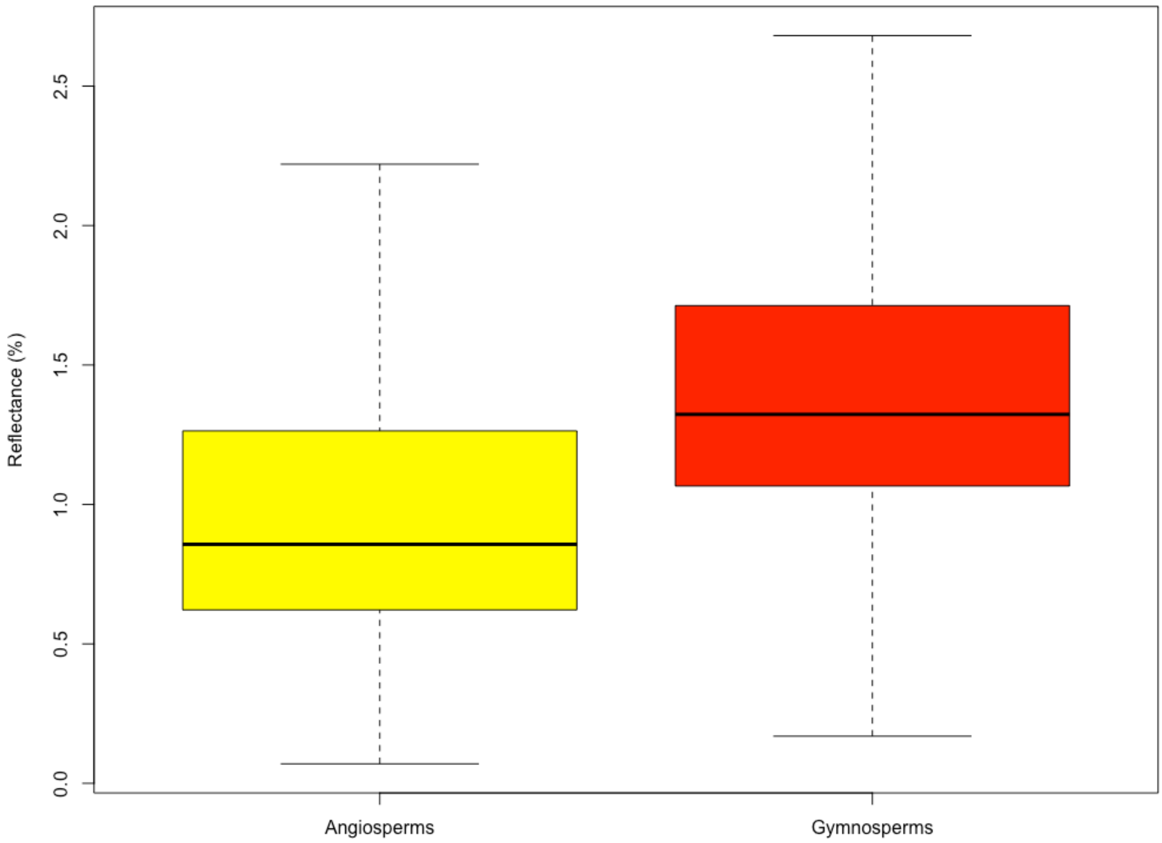

Figure 6.4: Boxplot showing the charcoal reflectance measurements for each of the sites in this study combined into the into the type of vegetation which was present in the study location (p <0.001). Those data points which lie 1.5x the interquartile range away from the 25th or 75th percentile are considered outliers and are not shown in this plot, but are included in the analyses. Outliers have been removed to ease the interpretation of the data; due to the fact that there was a lot of Carn Brea data it produced a number of outliers at the top of the surface group which made the figure chaotic.

6.4.3 Surface and crown fires

To better understand the effect of fire type on charcoal reflectance the comparison of surface and crown fires was also conducted (Figure 6.5). This comparison of fire type meant that all study sites except Triangle plot were collated into a surface fire group and compared to the crown fire which occurred at Triangle plot. When comparing the different fire regimes across the ecosystems it was found that crown fires produced significantly highly reflecting charcoal than surface fires (Mann-Whitney U, $p < 0.001$).

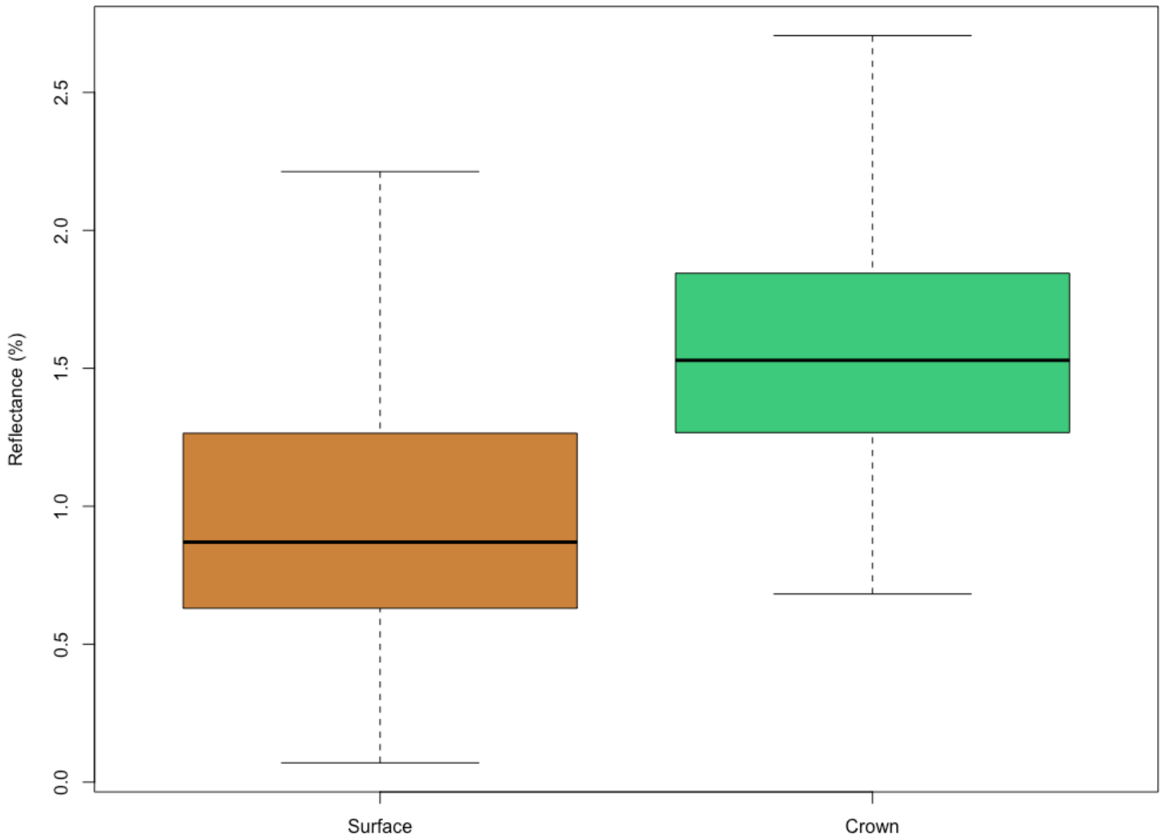

Figure 6.5: Boxplot showing the charcoal reflectance measurements for each of the fire types studied. All study sites except from Triangle plot are included in the surface fire group, the Triangle plot fire data has been renamed crown fire in this figure ($p < 0.001$).

6.5 Discussion

The results from this chapter indicate that the overall fire regime particularly the energy release aspects of the fire are a stronger driver of overall charcoal reflectance than variations in fuel type.

Initially the two Canadian sites, Triangle Plot and Pine Point were combined into a single boreal ecosystem group, ignoring that these two sites experienced different fire types; Triangle plot was a crown fire and Pine Point was a surface fire. The analysis of the charcoal reflectance showed that the Boreal forest ecosystem produced the highest overall reflectance measurements compared to the tropical and shrubland ecosystems. As part of the analysis of charcoal reflectance in this chapter I also looked at the comparison of surface and crown fires.

In three of the fires, Triangle and Pine Point (Canada) and Britannia (Australia) the same wood (Western Red Cedar and Jack Pine) were placed in the fires and this wood charred by the passing fire front and any residual heating. In these cases, the fuel moisture of the blocks was equal between fires. Therefore, differences in charcoal reflectance ought to be able to be ascribed to the behaviour of the fires themselves. It was found that the crown fire produced significantly higher reflecting charcoal than either of the surface fires. These results are in agreement with findings by Roos and Scott (2018) who compared the charcoal reflectance of surface and crown fires in the south-western USA. As charcoal reflectance has been shown to not only provide information on the severity of the fire that has created it but also to provide information on the amount of energy that has been delivered to the burned area (Belcher and Hudspith 2016; Belcher, New *et al.,* 2018), it has been suggested that these higher charcoal reflectance measurements found from canopy fires are likely due to the higher energy fluxes during fires in the canopy compared to surface fires (Belcher, New *et al*., 2018).

When comparing all the sites in the study the gymnosperm wood that was placed in the Canadian and Australian study areas produced charcoal of a higher reflectance when compared to the angiosperm woods analysed from the Brazilian Amazon and the UK heathland and moorland sites that carried surface fires. This indicates that potentially both fuel type and fire regime influences charcoal reflectance. It should be noted however, that this study has not included angiosperm pyrophytic ecosystems such as chaparral, South African Cape floras or shrub dryland areas. Future work should seek to include reflectance studies from these ecosystem types, as these typically carry intense fires.

Looking more closely at the individual fire regimes of the different ecosystems it is clear to see how charcoal reflectance could be considered as being driven by this aspect of fire. In Canadian boreal forests, the most wildfires occur in the summer season. Crown fires dominate in this ecosystem, although surface fires are also prevalent (de Groot *et al.,* 2013). Crown fires are common here primarily due to the fact that Spruce trees (*Picea*) dominate these boreal forests. These trees have highly flammable needles and branches that are low to the ground which form ladder fuels allowing smaller surface fires to easily climb to the canopy (de Groot *et al.,* 2013). Boreal forest fires in Canada tend to be large, high intensity and have high fuel consumption rates due to the dominance of crown fires, the latter of which leads to high amount of carbon loss from the ecosystem (de Groot *et al.,* 2013). It is this high intensity nature of the fires that occur in the Canadian boreal forest that is likely the key driver in the high reflectance values I have shown in this chapter. As we know from previous work by Belcher, New *et al.*, (2018) and Roos and Scott (2018) crown fires create higher reflecting charcoal due to the increased amount of energy being delivered to the fuel during burning.

When comparing the Canadian boreal forest fire regime to the Amazonian tropical forest fire regime, it is clear to see why the Amazon produced the lowest reflecting charcoal and the Canadian charcoal was the highest reflecting. Whilst the boreal ecosystem is dominated by high intensity crown fires, the Amazon is dominated by slow spreading, low intensity surface fires (Cochrane and Laurance, 2008). The slow-moving fire front is deadly to thin barked trees in the Amazon forest (Uhl and Kauffman, 1990); approximately 40% of trees > 10cm are killed (although the larger, thicker bark trees tend to survive the amazon's low intensity surface fires). In total only around 10% of the standing biomass is killed (Cochrane *et al.,* 1999; Barlow *et al.,* 2003). These fires typically open up clearings promoting the growth of surface fuels such as grasses and vines (which are flammable even when alive (Cochrane and Laurance, 2008)). This leads to subsequent fires that tend to be more intense and severe (Cochrane and Laurance, 2008). This is primarily due to the reduction in the moisture content of the surface fuels (e.g. grasses and vines compared to tropical trees) as a result of the newly created clearings drying the fuel and greater fuel loads on the surface (Cochrane *et al.,* 1999; Cochrane and Schulze, 1999). Even though the Amazonian study sites have some indication that either a previous fire has occurred or logging has cleared the canopy (Table 6.2), the low intensity nature of the surface fires compared to those crown fires in the boreal ecosystem is more than likely the reason I have found lower reflecting charcoal from the Amazonian tropical forest ecosystem.

The idea that the amount of energy being delivered to an ecosystem during a fire appears to be a key driver of charcoal reflectance is further supported by the Australian charcoal reflectance results. Seasonal ignition is highly important in Australian fire regimes and has been found to affect the intensity and size of fires (Russel-Smith *et al.,* 1997; Gill *et al.,* 2002; Bradstock, 2010). In southern Australia, where the site in this study is located, the fire regime tends to be of low frequency and high intensity, with the fire regime being driven by drought and fuel in the litter layer (Bradstock, 2010; Gill and Catling, 2002). The results in this chapter show that the Australian study site produced the 5th highest charcoal reflectance values out of the eight different study locations. However, this fire also produced the lowest reflectance values of all of the sites, including that in the Western Red Cedar blocks. This fire was a research fire that was lower intensity than would have been the case for a natural bush fire, therefore the amount of energy being delivered to the fuel was lower than might be typical for this ecosystem and therefore the charcoal reflectance values are reflective of this. Additionally, fires in this ecosystem typically move rapidly such that even when high intensity they do not remain in contact with the ground surface (where the WRC blocks were placed) for long hence these results are likely a balance of the intensity and duration of this fire regime. Comparing the Australian fire to the Canadian fires further supports the theory that the energy of the fire is driving charcoal reflectance values. Pine Point was a low intensity surface fire compared to the high intensity crown fire of Triangle plot. The Australian fire (Britannia) was found to have a similar median reflectance to that of Pine Point, 1.027% and 1.130%, respectively whereas the high intensity Triangle plot had a mean reflectance value of 1.529%.

The fuel structure and fuel types are very different in each of the ecosystems in this study, therefore it would be fair to assume that these factors have had an influence on the formation of charcoal and charcoal reflectance. As shown in Belcher, New *et al*., (2018), through our experiments using the iCone calorimeter we have found that high bulk density wood leads to higher reflectance values. When woods of different bulk densities were tested over two flaming durations it was found that both the duration of flaming and the bulk density of the wood influenced mean surface Ro% (Belcher, New *et al.,* 2018). Our laboratory experiments indicate that total heat release over time (THR) and fuel density (which itself influences THR), both showed strong correlations with charcoal reflectance and the depth of charring (Belcher, New *et al.,* 2018). However, taking these laboratory findings into account, I would expect to see that the higher density Amazonian woods, which have with a pan-tropical mean of 0.62g cm^{-3} across Amazonia and the tropics (Phillips *et al.,* 2019), would produce higher reflectance values than the boreal and tropical forest in Australia, which included WRC and JP woods, which have approximate densities of 0.38g cm^{-3} and 0.40g cm^{-3} (Gonzalez, 2004; OECD,2010). However, the results shown in this chapter have found that the lower density woods produce more highly reflective charcoal when compared to higher density wood. It therefore seems that that fire behaviour and the general fire regime of an ecosystem links to charcoal reflectance better than changes in the fuel being charred i.e. the bulk density over large spatial scales.

The UK moorland and heathland ecosystems (combined to make a shrubland group in the results) were found to produce similar charcoal reflectances to the Amazonian charcoal samples, producing median charcoal reflectance values of 0.872% and 0.822% respectively. However, when looking more closely at the fire regime of the shrubland group it could be suggested that the fires studied in this chapter may not be a true representation of the heathland and moorland ecosystems as a whole. Therefore, I suggest more research is needed in which fires from more of these shrubland ecosystems are analysed in terms of their charcoal reflectance. Fires in heathland and moorland ecosystems can be extraordinarily damaging as the deep soils and presence of peat means that fires can smoulder for months. This is especially likely in the summer months when the fuel is drier and more easily ignitable (Rein *et al.,* 2008; Santana and Marrs, 2014). Spring fires are also a key aspect of the fire regime in the heathland and moorland ecosystems. However, these fires tend to be less extreme, with surface fuels green and wet (Davies and Legg, 2008). The effects of winter frost on the desiccation of fuels can have an influence on the fire behaviour in heathland and moorland ecosystems (Davies and Legg, 2008). These fires, where the surface vegetation is predominately burnt, can be considered as mini independent crown fires (Alexander and Sando 1989; Fernandes *et al.,* 2000; Davies and Legg, 2019). These mini crown fires have been found to spread across the shrub canopies regardless of the flammability of the below ground fuel e.g. litter layer (Davies and Legg, 2019). High fire intensities in these shrubland ecosystems have been found even under conditions that are deemed marginal for sustaining a fire i.e. high fuel moisture and high presence of live fuel (Davies and Legg, 2019). This therefore suggests that these mini crown fires could be a key driver in determining the intensity of fire, as seen with the Canadian crown vs surface fire charcoal reflectance results in this chapter. The relatively low charcoal reflectance results for the heathland and moorland sites in comparison to the other ecosystems could therefore be due to the fact that these mini crown fires were not dominant; the fires occurred in summer period (Carn Brea occurred a few days before June) therefore it is more likely that surface fires burning the dead litter layer occurred, rather than burning the lush green shrubs that are seen in the spring months (Davies and Legg, 2019). Surface fires, as shown in this chapter, have produced lower reflecting charcoal thus could account for the lower reflecting charcoal in Carn Brea and Winter Hill. However, as I have not compared surface vs mini crown fire charcoal reflectance measurements from the heathland and moorland ecosystem I cannot conclusively state this. It is important to note that the vegetation in these heathland and moorland ecosystems are very different compared to the WRC and JP used in the Canadian and Australian systems, and even though I have shown that fire regime is a driving factor in determining charcoal reflectance, fuel type should not be ignored.

It is important to take into account when analysing the data from the individual ecosystems that the fuel type of the sites are different. The charcoal taken from the Canadian and Australian sites are gymnosperms, and the charcoal from the Brazilian Amazon and the UK shrublands are angiosperms. I found that gymnosperms produced more highly reflecting charcoal than angiosperms, this is in contrast to the results of Hudspith *et al*., (2014) and Belcher, New *et al.,* (2018) that indicated bulk density was important, where typically angiosperms have higher bulk density wood than gymnosperms. I also found that there was a significant difference between the reflectance values when comparing gymnosperms and angiosperms, with the gymnosperms studied (WRC and JP, both of which are on the lower bulk density end of gymnosperm woods) across all of the ecosystems producing higher charcoal reflectance values. This may be important for land managers and communities to consider when managing vegetation in and around increasingly fire vulnerable ecosystems and communities.

6.6 Conclusions

Charcoal reflectance is able to capture variations in fire behaviour and regimes post fire in different ecosystems. These findings therefore support the notion that charcoal reflectance makes an ideal post fire analysis jump between fire behaviour and fire effects, that others have used fire severity to fill. These positive results suggest that further exploration of charcoal reflectances produced by fires in different ecosystems has strong potential for us to understand how fire behaviour influences fire severity across different ecosystems.

I have shown in this chapter that in order to predict within site variations in fire behaviour you have to select or compare fuel type, but if you were looking at changes across the landscape ecosystem or ecosystems through time, to get a broad idea of fire regime this may not be necessary. With further research the community should be able improve their understanding of the impact of fire behaviour on global ecosystems, where understanding fire behaviour and the effects of wildfire are crucial if we are to build a resilient community and environment in the future.

Chapter 7

Synthesis

This chapter summarises the key findings of the research presented in this thesis. Limitations of the work and possible future directions are also presented, along with a section specifying how my work provides an original contribution to knowledge.

7.1 Summary of research

The work presented in this thesis has shown the development of charcoal reflectance into a metric which can be used to assess the amount of energy that has potentially been delivered to a burn scar. In each of the previous four chapters it has been shown that variations in aspects of fire e.g. fire severity and duration of heating, link to variations in the reflectance of the charcoal formed in corresponding fires. This research demonstrates that charcoal reflectance, in comparison to already established fire severity methods such as dNBR and qualitative matrices, is able to provide a more robust measurement of the severity of a fire whilst also potentially providing information regarding the energy regime of the fire that has created the charcoal.

7.2 Key findings

The research undertaken in this thesis has revealed that charcoal reflectance varies within and between ecosystems and has demonstrated that this is due to multiple drivers including fuel type, fire behaviour and overall fire regime.

The key finding from each thesis chapter is listed below:

1) Charcoal reflectance outperforms fire severity scores that are defined as ‘medium’ in a range of ecosystems (Heathland, Temperate Conifer forest – Chapter 3 and Chapter 4).

2) Areas of a burn scar that have high charcoal reflectance appear to be slower to regrow than those exhibiting lower reflectance (Carn Brea – Chapter 3).

3) Charcoal reflectance appears to correlate well with satellite dNBR measurements. This is encouraging as it indicates that reflectance performs as well as existing quantitative approaches. However, I have discovered that charcoal reflectance provides a higher resolution metric, such that a combination of dNBR with targeted reflectance measurements would provide the strongest approach to post-fire assessment (Chapter 4).

4) Managed and unmanaged fires yield different charcoal reflectance; hence reflectance may be useful in improving fire prescriptions where the aim is to mimic unmanaged/natural wildfire (Chapter 5).

5) Overall fire regime particularly the energy release aspects of the fire are a stronger driver of overall charcoal reflectance than variations in fuel type (Chapter 6).

7.2.1 Original contribution to knowledge

This thesis has significantly built upon the recommendations of Belcher and Hudspith (2016) that charcoal reflectance has the potential ability to be used in post-fire assessments as a metric with which to assess fire effects. It has tested the reflectance method for a range of fire types, including managed and unmanaged fires, as well as different ecosystems and fuel types in order to develop charcoal reflectance as a novel, quantitative post-fire metric (Figure 7.1).

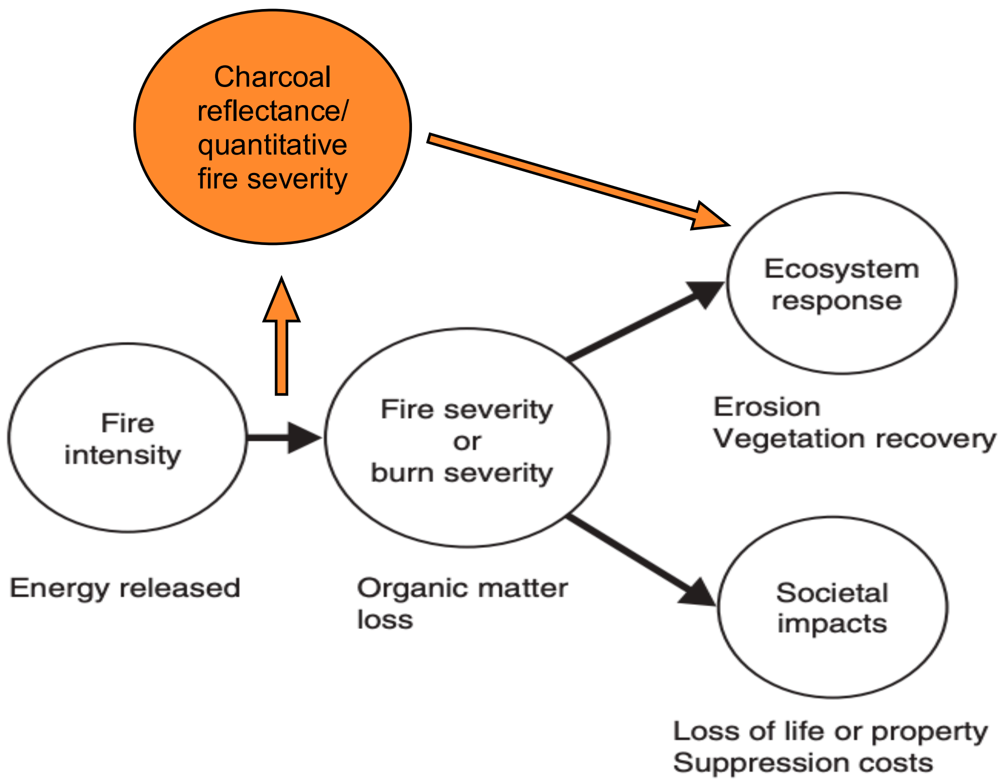

Figure 7.1: Adapted figure from Keeley (2009). I have added a new feature to the schematic which demonstrates where, in relation to the existing body of work regarding the study of fire and its effects, my research fits in i.e. my original contribution to the research field. Source: Adapted from Keely (2009:117).

The original figure shown in Chapter 1 (Figure 1.2) derives from Keeley (2009) who suggested that it is not possible to derive an ecosystem's response to fire directly from fire intensity (should it be known). Additionally, highlighting that fire or burn severity descriptors have been developed to gauge fire intensity, by describing organic matter loss, which may or may not be linked to ecosystem effects. In an ideal world we would be able to know a fire's behaviour and determine exactly how this might impact on the ecosystem, to understand or predict the ecosystem response. In this thesis I have tested the ability of charcoal reflectance to provide a quantitative metric that allows linkage between fire behaviour (energy release) and fire severity in order that we might begin to develop an approach to generate estimates of ecosystems response to fires.

On Figure 7.1 by making an orange circle labelled 'charcoal reflectance and quantitative severity', I suggest that the charcoal reflectance method provides an indirect quantitative estimate of variations in the amount of energy that has been delivered across a burn scar that links fire intensity, fire severity and ecosystem responses. For example, Chapter 3 has revealed that by comparing charcoal reflectances across a burned area (Carn Brea) it is possible to determine which areas across a burn scar might be slower to recover than others.

Both Chapter 3 and Chapter 4 have indicated that charcoal reflectance outperforms qualitative fire severity assessments, allowing improvement particularly in the mid-qualitative fire severity categories. Whilst Chapter 4 indicates that charcoal reflectance well correlates with qualitative approaches and satellite dNBR measurements that quantify vegetation loss. Hence quantifying vegetation loss and the energy distribution across the burned area using charcoal reflectance ought to, when coupled, have the potential to aid in prediction of rates of recovery of ecosystems.

7.3 Implications

7.3.1 Implications for fire management

Based on the findings presented in this thesis, charcoal reflectance may have the potential to aid future management and policy decisions regarding fire. In Chapter 5, it has been shown that charcoal reflectance measurements taken from transects of managed and unmanaged fires indicate that these yield different reflectances. This indicates different energy regimes between managed and unmanaged fires. Charcoal reflectance may therefore provide a useful post-burn metric for assessing variations in the impact of managed burns, compared with either natural or accidental fires in ecosystems. Indeed, Chapter 5 could be suggested as indicating that the current fire management practices (in the New Jersey Pine Barrens) do not well replicate the natural effects of an unmanaged wildfire in forested ecosystems in North America. Charcoal reflectance, therefore, may be able to provide information for developing appropriate fire prescriptions to best manage ecosystems, if it is the goal to mimic natural fire regimes where possible.

Also, of potential interest to land managers and policymakers, Chapter 6 indicated that there is a difference between fuel types, for example angiosperms and gymnosperms, in terms of charcoal reflectance. This provides us with information about the amount of energy being delivered by a fire. The results presented suggest that gymnosperm ecosystems carry higher energy fires compared to the angiosperms in this study, which could have important implications for future management strategies. I have also been able to determine that charcoal reflectance records aspects of the spatial distribution of heat across a burned area. The first three data chapters best show this, with study locations Carn Brea, Lost and Chat and Breeches Branch all demonstrating that charcoal reflectance varies across burn sites. Future studies of charcoal reflectance across burned areas could be utilized to make decisions on what vegetation may be planted in fire prone areas that human communities currently occupy i.e. the WUI (Wildland Urban Interface). Moreover, studies of reflectance in different fuels could be used to consider the variations in energy regime and fire severity where areas are considered for re-wilding. The climax community may be less fire prone, but the successional communities should also be considered. Hence charcoal reflectance might be able to aid with designing appropriate re-wilding schemes.

7.3.2 Implications for carbon budgeting

From the results in this thesis, I have been able to suggest that charcoal reflectance could potentially assist with future predictions of carbon budgeting in ecosystems. I have presented findings in Chapter 6 which show that higher reflecting charcoal has been found to be produced in fires which have delivered a high amount of energy. This has important implications for the carbon budgeting in an ecosystem as it has been found that high-intensity wildfires produce PyC that has higher recalcitrance than PyC formed in lower-intensity fires (Belcher, New *et al.,* 2018; Doerr *et al.,* 2018). Therefore, by measuring the ranges of charcoal reflectance across burn scars, it may be possible to improve estimates of carbon budgets for different fire types and consider long-term versus shorter-term cycling of carbon products from fires in order to better assess the impact of fire on the global carbon cycle.

7.4 Future research directions

7.4.1 Addressing the limitations of this thesis

There are limitations to this research. In Chapter 6 only one fire per ecosystem has been investigated and a mixture of experimental and unmanaged wildfires have been used across the different ecosystems. In this thesis, I have analysed a restricted range of fuel types and I would suggest that future work expands this range to include more tropical species of vegetation, especially trees and pyrophytic angiosperm communities (e.g. Chaparral).

Many of the limitations in this research are due to time limitations and the ad hoc nature of fire and charcoal collection, i.e. knowing that a wildfire is happening and being able to reach it and organising experimental fires and relying upon the correct weather to be able to conduct the burns. If this was a perfect experiment, multiple fires per ecosystem would be studied, along with different fire types for each ecosystem, i.e. unmanaged vs prescribed/experimental. This type of work needs to continue in the future to build on these results, so that we can better understand how fire behaviour affects different ecosystems. This is important as fire in these ecosystems is predicted to increase both in frequency and intensity due to climate change. Therefore, a better understanding of the fundamentals of fire behaviour and the effects of fire on an ecosystem is needed to help ecosystems and society build resilient communities in a changing climate.

One aspect of charcoal reflectance that has not been investigated fully is how well the measurements I have made across a burn scar accurately represent the whole burned area. In the majority of the study sites a single transect across the burn scar was analysed. In future work I suggest that the whole burned area should be analysed in terms of charcoal reflectance to assess how well a single transect represents a burned area. Ideally a number of experimental plots would be set up in order to assess this, with the whole area being analysed along with a single transect and these compared in order to make the assessment. A bootstrapping sample is one way to simulate a transect.

Another feature of charcoal reflectance which has not been considered is the minimum number of measurements needed in order to acquire an accurate fire severity assessment for a burn scar. This minimum number would create distributions for each fire severity score that are significantly different from each other. One way to determine this minimum number would be to bootstrap from the distributions I have already collected. This would allow me to assign a probability that there is a significant difference between distributions, to each sample number. From this I would then be able to have a certain level of confidence in a given sample size that it is truly representative.

Finally, as the charcoal reflectance metric is developed further, it is important to test how different aspects of the environment influence its measurements. An assessment of how different climatic conditions affect charcoal reflectance measurements has not been an aspect of this thesis, fuel moisture has also not been considered. These are two important aspects which are known to affect fire behaviour, and so must be investigated in the future in order to better understand how charcoal reflectance is influenced by these aspects of the environment.

7.4.2 Further research directions for fire severity

Qualitative fire severity metrics that have been used in the past have used a fairly simple table of descriptions, originating from Ryan and Noste's (1985) table, with which to assign fire severity values to a sampling location on a burn site. This table is adapted for differing ecosystems; the researcher adapts it according to ecosystem type, e.g. moorland, temperate forest, peatlands etc (see Hudspith *et al*., (2014) and New *et al*., (2018) for examples of adapted tables). For the pine ecosystems in this thesis (Lost, Chat and Breeches Branch) I noticed how the needles, both on the trees and on the ground, differed as I walked through the study sites, especially at the differing fire severities. When moving through the study site the first that was noticeable was that the pine needles on the trees were very variable i.e. it was clear to see what sites may have undergone a higher severity fire and sites that underwent a lower severity fire. This was mainly due to the number of needles still attached to the branches, and on the forest floor. The colour of the needles could also be observed as changing according to fire severity changes through the study site (Table 5.2 in Chapter 5). This change in colour results from the change in the chemical composition of the needles due to heating, scorching and surrounding death of trunk tissue. The loss of colour exhibited by the pine needles could indicate the death/future mortality of those needles and the section of the tree in which those needles are located i.e. the tree branch (Jolly *et al.,* 2012). This change in the colouration of needles can also be observed in pine trees that have been affected by beetle attacks (Jolly *et al.,* 2012). This is important to note as the colour and abundance of needles in relation to a fire severity matrix table is not something currently considered in the current literature on this topic. Therefore, I suggest that if qualitative metrics such as the descriptive table used in this thesis were to be used in future research in pineland ecosystems, then the needles, or lack of in some instances, should be a major aspect to take into account when assessing the burn area. I am not advocating the use of qualitative metrics as I have shown that charcoal reflectances is a superior metric with which to assess fire severity. However, if for some reason charcoal reflectance was not able to be performed, this observation I have made regarding the qualitative field assessment of fire severity may be of use.

7.4.3 Utility of charcoal reflectance for managing fuel

Fuel loads in forests are often managed with fire in prescribed burns, where burns are used to remove high fuel loads that might cause catastrophic wildfires in allowed to accumulate in fire prone ecosystems. These fires also serve as a means to return fire to wildlands, where it has been excluded. However, there is considerable debate as to what extent prescribed/managed fires mimic natural fires. Therefore, land managers may be able to utilize charcoal reflectance to design fuel management practices that are more natural, thereby ensuring that both the environment and the communities in wildland areas are both protected and receive the benefits of wildfire. In Chapter 5, charcoal reflectance indicated that current prescriptions for fire may not currently be meeting the needs of the ecosystem, i.e. management fires generate different fire behaviour and charcoal reflectances to unmanaged wildfires. Managing the needs of both the ecosystem (i.e. mimicking natural fire regimes) and the human communities that are increasingly moving into the wildland environment is something that land managers will have to consider in the future, as well as fires being an increasingly common threat. Hopefully the research in this thesis goes someway to helping begin this process, as reflectance can provide a tool with which to analyse the differences in energy regime with linkage to fire effects between managed and unmanaged fires. I suggest future work needs to continue this work by comparing charcoal reflectance from different managed/prescribed fires and natural fires in the same ecosystems.

7.4.4 Carbon cycling

Charcoal (also termed pyrogenic carbon) is one of the key products of wildfires and has been estimated to be produced at a rate of ~116–385Tg C yr^{-1} globally (Doerr et al., 2018). Charcoal is known to form one of the most degradation-resistant pools of organic carbon. It has been indicated that highly reflected charcoals are more inert than lower reflecting charcoals (Belcher, New *et al.*, 2018). However, researchers have questioned what happens to the charcoal deposited from previous fires when the same forest burns again. There are few studies that have considered this. Where some have considered this, it has been suggested that re-burning or re-charring caused additional loss of previously formed charcoal pools of between < 8–37% (*Saiz et al.,* 2014; Tinkham *et al.,* 2016). Recent research placed previously charred wood in a crown fire and a surface fire, where the reflectance was measured pre and post the 2^{nd} fire (Doerr *et al.,* 2018). These highly reflecting and previously charred samples exhibited lower mass loss than wood turned to charcoal in the same fires and remained more recalcitrant, although losses were still observed.

However, I suggest that if charcoal reflectance is to be used in the future as a metric with which to assess the effect of fire, the effect of multiple fires on the same pieces of charcoal must be explored. As discussed in this thesis, when wood is turned to charcoal this changes the ordering of the plant cells, allowing reflectance to be measured. What effect recharring has on already charred material has not yet been well explored in terms of reflectance. If charcoal formed in low intensity fires is subject to a more intense fire it is likely that the charcoal may increase its reflectance because more energy is being supplied to that piece of material. This is important to consider as charcoal recalcitrance and reflectance appear to be linked and therefore reflectance may, with additional research, be of use to carbon cycling post-fire and elucidate whether fire itself is a removal mechanism of charcoal ('inert' C) from the environment over the long-term.

7.5 Conclusion

In conclusion the study of charcoal reflectance needs to enter into the researcher toolkit of wildland fire. It may assist with determining linkages between energy regimes, fire severity and ecosystem effects, providing utility for re-designing management burns and provide an essential tool in estimating carbon storage and loss following wildfires. I have shown here through numerous studies that charcoal reflectance a tool taken originally from coal geology has much to offer towards aiding our understanding of wildland fire and the impacts that fires have on ecosystems and Earth system processes.

References

Agee, J. K. and Skinner, C. N. (2005) Basic principles of forest fuel reduction treatments. Forest Ecology and Management. 211: 83-96.

Agencia Brasil. (2009) Municıpio de Feliz Natal eincluıdo na lista dos que maisdesmatam em MT. Agencia de Notıcias Primeira Hora, 24 March 2009, website accessed 24th June 2019, available at <http://www.primeirahora.com.br/noticia.php?intNotID=9954>.

Alencar, A., Asner, G. P., Knapp, D. and Zarin, D. (2011) Temporal variability of forest fires in eastern Amazonia. *Ecological Applications*, *21*(7): 2397-2412.

Alexander, M. E. (1982) Calculating and interpreting forest fire intensities. *Canadian Journal of Botany*, *60*(4): 349-357.

Alexander, M.M.E. and R.W. Sando. (1989) Fire behaviour and effects in aspen– northern hardwood stands. In *Proceedings of the 10th conference on fire and forest meteorology*, 17-21 April 1989, Ottawa, Ontario, ed. D.C. MacIver, H. Auld, and R. Whitewood, 263–274. Ottawa: Canadian Forest Service and Environment Canada.

Allen, C. D., Savage, M., Falk, D. A., Suckling, K. F., Swetnam, T. W., Schulke, T., Stacey, P. B., Morgan, P., Hoffman, M. and Klingel, J. T. (2002) Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. *Ecological Applications*, *12*(5): 1418-1433.

Andela, N., Morton, D.C., Giglio, L., Chen, Y., Van Der Werf, G.R., Kasibhatla, P. S., DeFries, R. S., Collatz, G. J., Hantson, S., Kloster, S. and Bachelet, D. (2017) A human-driven decline in global burned area. *Science*, *356*(6345): 1356-1362.

Archibald, S., Lehmann, C. E., Gómez-Dans, J. L. and Bradstock, R. A. (2013) Defining pyromes and global syndromes of fire regimes. *Proceedings of the National Academy of Sciences*, *110*(16): 6442-6447.

Archibald, S., Lehmann, C. E., Belcher, C.M., Bond, W. J., Bradstock, R. A., Daniau, A. L., Dexter, K. G., Forrestel, E. J., Greve, M., He, T. and Higgins, S. I. (2018) Biological and geophysical feedbacks with fire in the Earth system. *Environmental Research Letters*, *13*(3): 1-18.

Ascough, P. L., Bird, M. I., Scott, A. C., Collinson, M. E., Cohen-Ofri, I., Snape, C. E., and Le Manquais, K. (2010) Charcoal reflectance measurements: Implications for structural characterization and assessment of diagenetic alteration. *Journal of Archaeological Science*, *37*(7): 1590–1599.

Balch, J. R. K., Nepstad, D. C., Brando, P. M., Curran, L. M., Portela, O., de Carvalho, O. and Lefebvre, P. (2008) Negative fire feedback in a transitional forest of southeastern Amazonia. *Global Change Biology*, *14*(10): 2276–2287.

Barlow, J., Peres, C, Lagan, B. and Haugaasen, T. (2003) Large tree mortality and the decline of forest biomass following Amazonian wildfires*. Ecology Letters*. 6: 6-8.

BBC. (2015) '*Carn Brea gorse fire land 'will take years to recover'*. Website accessed 24th June 2015, <http://www.bbc.co.uk/news/uk-england-cornwall-32955448>.

Belcher, C. M. and Hudspith, V. A. (2016) The formation of charcoal reflectance and its potential use in post-fire assessments. *International Journal of Wildland Fire*, *25*(7): 775-779.

Belcher, C. M. and Hudspith, V. A. (2017) Changes to Cretaceous surface fire behaviour influenced the spread of the early angiosperms. *New Phytologist*, *213*(3): 1521-1532.

Belcher, C. M., New, S. L., Santín Nuño, C., Doerr, S. H., Dewhirst, R. A., Grosvenor, M. J. and Hudspith, V. A. (2018) What Can Charcoal Reflectance Tell Us About Energy Release in Wildfires and the Properties of Pyrogenic Carbon?. *Frontiers in Earth Science*. 6(169): 1-13.

Belcher, C.M (2013) **Fire Phenomena and the Earth System: An Interdisciplinary Guide to Fire Science**, John Wiley and Sons, Oxford.

Bird, M. I., Wynn, J. G., Saiz, G., Wurster, C. M. and McBeath, A. (2015) The pyrogenic carbon cycle. *Annual Review of Earth and Planetary Sciences*, *43*: 73-298.

Boisramé, G., Thompson, S., Collins, B. and Stephens, S. (2017) Managed wildfire effects on forest resilience and water in the Sierra Nevada. *Ecosystems*, *20*(4): 717-732.

Bond, W. J. and Keane, R. E. (2017) Fires, ecological effects of. *Reference Module in Life Sciences*.

Bond, W. J. and Van Wilgen, B. W. (1996) Fire and Plants (population and community biology series 14). *Population and Community Biology*, *263*.

Bond, W.J. and Keeley, J.E. (2005) Fire as a global ‘herbivore’: the ecology and evolution of flammable ecosystems. *Trends in Ecology & Evolution*, *20*(7): 387-394.

Bond, W.J., Woodward, F.I. and Midgley, G.F. (2005) The global distribution of ecosystems in a world without fire. *New Phytologist*, *165*(2): 525-538.

Bowman, D. M. J. S., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane, M. A., D'Antonio, C. M., DeFries, R. S., Doyle, J. C., Harrison, S. P., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Marston, J. B., Moritz, M. A., Prentice, I. C., Roos, C. I., Scott, A. C., Swetnam, T. W., van der Werf, G. R. and Pyne, S. J. (2009) Fire in the Earth System, *Science*, 324: 481–484.

Bowman, D. M., Balch, J., Artaxo, P., Bond, W. J., Cochrane, M. A., D'antonio, C. M., DeFries, R., Johnston, F. H., Keeley, J. E., Krawchuk, M. A. and Kull, C. A. (2011) The human dimension of fire regimes on Earth. *Journal of Biogeography*, *38*(12): 2223-2236.

Boyd, H. P. (2008) **The Ecological Pine Barrens of New Jersey**. Plexus Publishing.

Bradley, C. M., Hanson, C. T. and DellaSala, D. A. (2016) Does increased forest protection correspond to higher fire severity in frequent-fire forests of the western United States?. *Ecosphere*, *7*(10): 1-13.

Bradley, T. J. Gibson. and W. Bunn. (2006) Fire severity and intensity during spring burning in natural and masticated mixed shrub woodlands. in: P.L. Andrews and B.W. Butler, compilers. *Proceedings of the conference: Fuels Management—How to Measure Success. USDA Forest Service Proceedings RMRS-P-41.* Rocky Mountain Research Station, Fort Collins, Colorado, USA, 41 (e01492): 419-428.

Bradstock, R. A. (2010) A biogeographic model of fire regimes in Australia: current and future implications. *Global Ecology and Biogeography*, *19*(2): 145-158.

Bradstock, R. A., Hammill, K. A., Collins, L. and Price, O. (2010) Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. *Landscape Ecology*, *25*(4): 607-619.

Brando, P. M., Balch, J. K., Nepstad, D. C., Morton, D. C., Putz, F. E., Coe, M. T., Soares-Filho, B. S. (2014) Abrupt increases in Amazonian tree mortality due to drought-fire interactions. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(17): 6347–52.

Brotons, L., Aquilué, N., De Cáceres, M., Fortin, M. J. and Fall, A. (2013) How fire history, fire suppression practices and climate change affect wildfire regimes in Mediterranean landscapes. *PLOS one*, *8*(e62392): 1-12.

Brown, L. E., Holden. J., Palmer, S. M., Johnston, K., Ramchunder, S. J. and Grayson R. (2015) Effects of fire on the hydrology, biogeochemistry, and ecology of peatland river systems. Freshwater Science 34(4): 1406–1425.

Bullock, J. M. and Webb, N. R. (1995) Responses to severe fires in heathland mosaics in Southern England. *Biological Conservation*, *73*(3): 207-214.

Bush, M. B., Silman, M. R., McMichael, C. and Saatchi, S. (2008) Fire, climate change and biodiversity in Amazonia: a Late-Holocene perspective. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *363*(1498): 1795-1802.

Certini, G. (2005) Effects of fire on properties of forest soils: a review. *Oecologia*, *143*(1): 1-10.

Clay, G.D. and Worrall, F. (2011) Charcoal production in a UK moorland wildfire – How important is it? Journal of Environmental Management, 92(3): 676-682.

Chafer, C. J., Noonan, M. and Macnaught. E. (2004) The post-fire measurement of fire severity and intensity in the Christmas 2001 Sydney wildfires. *International Journal of Wildland Fire,* 13(3): 227−240.

Chapin, F. S III., Viereck, L. A., Adams, P., Van Cleve, K., Fastie, C. L., Ott, R. A., Mann, D. and Johnstone, J. F. (2006) **Successional processes in the Alaskan boreal forest**. New York: Oxford University Press.

Cochrane, M. A. (2003). Fire science for rainforests. *Nature*, *421*(6926): 913–9

Cochrane, M. A. and Ryan, K. C. (2009) Fire and fire ecology: Concepts and principles. In *Tropical Fire Ecology*. Springer, Berlin, Heidelberg. 25-62.

Cochrane, M. A. and Laurance, W. F. (2008) Synergisms among fire, land use, and climate change in the Amazon. *AMBIO: A Journal of the Human Environment*, *37*(7): 522-527.

Cochrane, M.A. and Schulze, M.D. (1999) Fire as a recurrent event in tropical forests of the eastern Amazon: effects on forest structure, biomass, and species composition. *Biotropica*, 31(1): 2-16.

Cochrane, M.A., Alencar, A., Schulze, M.D., Souza. C. Jr., Nepstad, D., Lefebvre, P. and Davidson, E. (1999) Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science,* 284(5421): 1832-1835.

Cohen-Ofri, I., Weiner, L., Boaretto, E., Mintz, G., and Weiner, S. (2006) Modern and fossil charcoal: aspects of structure and diagenesis. *Journal of Archaeological Science*, 33(3): 428-439.

Collins, L., Bennett, A.F., Leonard, S.W. and Penman, T.D. (2019) Wildfire refugia in forests: Severe fire weather and drought mute the influence of topography and fuel age. *Global Change Biology*, *25*(11): 3829-3843.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A.F. and Krebs, P. (2009) Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. *Quaternary Science Reviews*, *28*(5-6): 555-576.

Davies, G. M. (2013) ‘Understanding Fire Regimes and the Ecological Effects of Fire’, In: Belcher, C. M. (Ed.), **Fire Phenomena in the Earth System – An Interdisciplinary Approach to Fire Science**. Wiley and Sons, London. 97-124.

Davies, G. M., Gray, A., Rein, G., and Legg, C. J. (2013) Peat consumption and carbon loss due to smouldering wildfire in a temperate peatland. *Forest Ecology and Management*, *308*: 169-177.

Davies, M.G., Gray, A., Hamilton, A. and Legg, C.J. (2008) The future of fire management in the British uplands. *The International Journal of Biodiversity Science and Management*, *4*(3): 127-147.

Davies, G. M. and Legg, C. J. (2008) Developing a live fuel moisture model for moorland fire danger rating. In: de las Heras, J., Brebbia, C. A., Viegas, D.X. (Eds.), **Forest fires: Modeling, Monitoring and Management of Forest Fires, WIT Transactions on the Environment**, vol. 119. WIT Press, Southampton, 225-236.

Davies, G. M., Legg, C.J., Smith, A. A. and MacDonald, A. (2006) Developing shrub fire behaviour models in an oceanic climate: Burning in the British Uplands. Forest Ecology and Management. 234S(S107): 1-15.

Davies, G. M., Legg, C. J., Smith, A. A. and MacDonald, A. (2019) Development and participatory evaluation of fireline intensity and flame property models for managed burns on Calluna-dominated heathlands. *Fire Ecology*, *15*(30): 1-15.

Davies, G. M., Kettridge, N., Stoof, C. R., Gray, A., Ascoli, D., Fernandes, P. M., Marrs. R., Allen, K. A., Doerr, S. H., Clay, G. D. and McMorrow. J. (2016) The role of fire in UK peatland and moorland management: the need for informed, unbiased debate. *Philosophical Transactions of The Royal Society B*, 371(1696): 1-17.

Davies, G. M., Smith, A. A., MacDonald, A. J., Bakker, J. D. and Legg, C. J. (2010) Fire intensity, fire severity and ecosystem response in heathlands: factors affecting the regeneration of Calluna vulgaris. *Journal of Applied Ecology,* 47(2): 356–365.

de Groot, W. J., Cantin, A. S., Flannigan, M. D., Soja, A. J., Gowman, L. M. and Newbery, A. (2013) A comparison of Canadian and Russian boreal forest fire regimes. *Forest Ecology and Management*, *294*: 23-34.

DeLuca, T. H., MacKenzie, M.D., Gundale, M. J. and Holben, W. E. (2006) Wildfire-produced charcoal directly influences nitrogen cycling in ponderosa pine forests. *Soil Science Society of America Journal*, *70*(2): 448-453.

Doerr, S. H., Santin, C., Merino, A. G., Belcher, C. M., & Baxter, G. (2018) Fire as a removal mechanism of pyrogenic carbon from the environment: effects of fire and pyrogenic carbon characteristics. *Frontiers in Earth Science*, *6*(127): 1-13.

Doerr, S. H. and Santín, C. (2016) Global trends in wildfire and its impacts: perceptions versus realities in a changing world. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696), 1:10.

Douglas, D. J., Buchanan, G. M., Thompson, P., Amar, A., Fielding, D.A., Redpath, S. M. and Wilson, J. D. (2015) Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. *Biological Conservation,* 191: 243–250.

Escuin, S., Navarro, R. and Fernández, P. (2008) Fire severity assessment by using NBR (Normalized Burn Ratio) and NDVI (Normalized Difference Vegetation Index) derived from LANDSAT TM/ETM images. *International Journal of Remote Sensing*, *29*(4): 1053–1073.

Esri, (2019) Base-map, ‘World Imagery’, ArcGIS Online content.

FAO. (2006) Fire Management Global Assessment. *Food and Agriculture Organization of the United Nations*, Rome, FAO Forestry Paper,151.

Fernandes, P. M., W. R. Catchpole. and Rego, F. C. (2000) Shrubland fire behaviour modelling with microplot data. *Canadian Journal of Forest Research*, 30: 889– 899.

Finney, M. A., Cohen, J. D., Forthofer, J. M., McAllister, S. S., Gollner, M. J., Gorham, D. J., Saito, K., Akafuah, N. K., Adam, B. A. and English, J. D. (2015) Role of buoyant flame dynamics in wildfire spread. *Proceedings of the National Academy of Sciences*, *112*(32): 9833-9838.

Flores, B. M., Fagoaga-Sánchez, R., Nelson, B. W., and Holmgren, M. (2016) Repeated fires trap Amazonian blackwater floodplains in an open vegetation state. *Journal of Applied Ecology*, 53(5):1597-1603.

Foereid, B., Lehmann, J., Wurster, C. and Bird, M. (2015) Presence of Black Carbon in Soil due to Forest Fire in the New Jersey Pine Barrens. *Journal of Earth Science and Engineering*, *5*: 91-97.

Forman, R. T. and R. E. Boerner. (1981) Fire frequency and the pine barrens of New Jersey. *Bulletin of the Torrey Botanical Club*, 34-50.

Fornacca, D., Ren, G. and Xiao, W. (2018) Evaluating the Best Spectral Indices for the Detection of Burn Scars at Several Post-Fire Dates in a Mountainous Region of Northwest Yunnan, China. *Remote Sensing*, *10*(8): 1-21.

Fulé, P. Z., Crouse, J. E., Roccaforte, J. P. and Kalies, E. L. (2012) Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behaviour?. *Forest Ecology and Management*, *269*: 68-81.

Gagnon, P. R., Passmore, H. A., Slocum, M., Myers, J. A., Harms, K. E., Platt, W. J. and Paine, C. T. (2015) Fuels and fires influence vegetation via above-and belowground pathways in a high-diversity plant community. *Journal of Ecology*, *103*(4): 1009-1019.

Gallagher, M. R. (2017) Monitoring fire effects in the New Jersey Pine Barrens with burn severity indices. PhD thesis, Rutgers, The State University of New Jersey.

Gazzard, R., McMorrow, J. and Aylen, J. (2016) Wildfire policy and management in England: an evolving response from Fire and Rescue Services, forestry and cross-sector groups. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696): 1-19.

Gill, A. M. and Catling, P. C. (2002) ‘Fire regimes and biodiversity afforested landscapes on southern Australia’, in **Flammable Australia: the fire regimes and biodiversity of a continent** (ed. by R.A.Bradstock, J.E. Williams and A.M. Gill). Cambridge University Press, Cambridge. 351–369.

Gill, A. M., Bradstock, R. A. and Williams, J. E. (2002) ‘Fire regimes and biodiversity: legacy and vision’, in **Flammable Australia: the fire regimes and biodiversity of a continent** (ed. by R.A.Bradstock, J.E. Williams and A.M. Gill). Cambridge University Press, Cambridge. 429–446.

Gimeno-Garcıa, E., Andreu, V. and Rubio, J.L. (2004) Spatial patterns of soil temperatures during experimental fires. *Geoderma*, *118*(1-2):17-38.

Gimingham, C. H., Hobbs, R. J. and Mallik, A. U. (1981) Community dynamics in relation to management of heathland vegetation in Scotland. In *Vegetation dynamics in grasslans, healthlands and mediterranean ligneous formations* (pp. 149-155). Springer, Dordrecht.

Gonzalez, J. S. (2004) Growth, properties and uses of Western Red Cedar (Thuja plicata Donn ex D. Don.). *Special Publication-Forintek Canada Corporation (Canada) eng no. SP-37R (Spec. no.)*, 1-51.

Government of Alberta. (2015) *Wildfire Behaviour.* Website accessed 20th May 2016, <http://wildfire.alberta.ca/wildfire-prevention-enforcement/wildfire-behaviour.aspx>.

Hamilton, A. (2000) The characteristics and effects of management fire on blanket-bog vegetation in north-west Scotland. PhD thesis, University of Edinburgh.

Hancock, M., Egan, S., Summers, R., Cowie, N., Amphlett, A., Rao, S. and Hamilton, A. (2005) The effect of experimental prescribed fire on the establishment of Scots pine Pinus sylvestris seedlings on heather Calluna vulgaris moorland. Forest Ecology and Management. 212:199–213.

Harper, K. A., Macdonald, S. E., Mayerhofer, M.S., Biswas, S.R., Esseen, P.-A., Hylander, K., Stewart, K.J., Mallik, A.U., Drapeau, P., Jonsson, B.-G., Lesieur, D., Kouki, J. and Bergeron, Y. (2015) Edge influence on vegetation at natural and anthropogenic edges of boreal forests in Canada and Fennoscandia. *Journal of Ecology*. 103(3): 550–562.

Hartford, R. A. and Frandsen, H. (1992) When it's hot, it's hot… or maybe it's not! (surface flaming may not portend extensive soil heating*). International Journal of Wildland Fire,* 2(3): 139− 144.

Haugaasen, T., Barlow, J. and Peres, C. (2003) Surface wildfires in central Amazonia: short-term impact on forest structure and carbon loss. *Forest Ecology And Management*, *179*(1-3): 321–331.

Hoadley, R. B. (2017) **Understanding Wood : A Craftsman's Guide to Wood Technology: Vol. Completely revised and updated**. Taunton Press.

Hood, S. M., Cluck, D. R., Smith, S. L. and Ryan, K. C. (2008) Using bark char codes to predict post-fire cambium mortality. *Fire Ecology*, *4*(1): 57-73.

Hoover, A. (2017) '11 fires that have burned through N.J.'s forests'. Website accessed 27th April 2019 <https://www.nj.com/burlington/2017/07/nj_forest_fires_through_the_years.html>.

Hoy, E. E., French, N. H., Turetsky, M. R., Trigg, S. N. and Kasischke, E. S. (2008). Evaluating the potential of Landsat TM/ETM+ imagery for assessing fire severity in Alaskan black spruce forests. *International Journal of Wildland Fire*, *17*(4): 500-514.

Hudak, A. T. and Brockett, B. H. (2004) Mapping fire scars in a southern African savanna using Landsat imagery. *International Journal of Remote Sensing*, 25(16): 3231–3243.

Hudspith, V. A. and Belcher, C. M. (2017) Observations of the structural changes that occur during charcoalification: implications for identifying charcoal in the fossil record. *Palaeontology*, *60*(4): 503-510.

Hudspith, V. A, Belcher, C. M. and Yearsley, J. M. (2014) Charring temperatures are driven by the fuel types burned in a peatland wildfire. *Frontiers in Plant Science*, 5(714): 1-12.

Hudspith, V. A., Belcher, C. M., Kelly, R. and Hu, F. S. (2015) Charcoal reflectance reveals early Holocene boreal deciduous forests burned at high intensities. *PLoS ONE*, *10*(4): 1–11.

Hudspith, V. A., Hadden, R. M., Bartlett, A. I. and Belcher, C. M. (2018) Does fuel type influence the amount of charcoal produced in wildfires? Implications for the fossil record. *Palaeontology*, 61(2): 159-171.

Jolly, W. M., Cochrane, M. A., Freeborn, P. H., Holden, Z. A., Brown, T. J., Williamson, G. J. and Bowman, D. M. (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature communications*, *6*(7537): 1-11.

Jolly, W. M., Parsons, R. A., Hadlow, A. M., Cohn, G. M., McAllister, S. S., Popp, J. B., Hubbard, R. M. and Negron, J. F. (2012) Relationships between moisture, chemistry, and ignition of Pinus contorta needles during the early stages of mountain pine beetle attack. *Forest Ecology and Management*, *269*: 52-59.

Jones, T. P. (1999) Polished blocks and reflected light microscopy. *Fossil Plants and Spores: Modern Techniques*, 82-86.

Jones, T. P., Chaloner, W. G. and Kuhlbusch, T. A. J. (1997) Proposed bio-geological and chemical based terminology for fire-altered plant matter. In *Sediment records of biomass burning and global change*, 51: 9-22. Springer Berlin Heidelberg.

Jones. T., Scott. A. C and Cope. M. (1991) Reflectance measurements against temperature of formation for modern charcoals and their implications for the study of fusain. Bulletin de la Societe Geologique de France 162: 193–200.

Kasischke, E. S., Verbyla, D. L., Rupp, T. S., McGuire, A. D., Murphy, K. A., Jandt, R., Barnes, J. L., Hoy, E. E., Duffy, P. A., Calef, M. and Turetsky, M. R. (2010) Alaska's changing fire regime—implications for the vulnerability of its boreal forests. *Canadian Journal of Forest Research*, *40*(7): 1313-1324.

Kauffman, J. B. (1991) Survival by sprouting following fire in tropical forests of the eastern Amazon, *Biotropica*, 23(3): 219-224.

Keane, R. E., Agee, J. K., Fulé, P., Keeley, J. E., Key, C., Kitchen, S. G., Miller, R. and Schulte, L. A. (2009) Ecological effects of large fires on US landscapes: benefit or catastrophe? A. *International Journal of Wildland Fire*, *17*(6): 696-712.

Keeley, J. E. (2009) Fire intensity, fire severity and burn severity: A brief review and suggested usage. International Journal of Wildland Fire, 18(1): 116–126.

Keeley, J. E. and Pausas, J. G. (2019). Distinguishing disturbance from perturbations in fire-prone ecosystems. *International Journal of Wildland Fire*, *28*(4): 282-287.

Keeley, J. E., Brennan, T. and Pfaff, A. H. (2008) Fire severity and ecosystem responses following crown fires in California shrublands. *Ecological Applications*, *18*(6): 1530-1546.

Keeley, J. E. (2008) 'Fire', Editor(s): Sven Erik Jørgensen, Brian D. Fath, **Encyclopaedia of Ecology**, Academic Press, 2008, 557-1564,

Keeley, J. E. and McGinnis, T. W. (2007) Impact of prescribed fire and other factors on cheatgrass persistence in a Sierra Nevada ponderosa pine forest. *International Journal of Wildland Fire*, *16*(1): 96-106.

Keith, H., Lindenmayer, D. B., Mackey, B. G., Blair, D., Carter, L., McBurney, L., Okada, S. and Konishi-Nagano, T. (2014) Accounting for biomass carbon stock change due to wildfire in temperate forest landscapes in Australia. *PloS one*, *9*(9): 1-17.

Kelly, R., Chipman, M. L., Higuera, P. E., Stefanova, I., Brubaker, L. B. and Hu, F. S. (2013) Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of the National Academy of Sciences*, *110*(32): 13055-13060.

Kennard, D. K., Gould, K., Putz, F. E., Fredericksen, T. S. and Morales, F. (2002) Effect of disturbance intensity on regeneration mechanisms in a tropical dry forest. *Forest Ecology and Management*, *162*(2): 197-208.

Key, C. H. and Benson, N. C. (2006) 'Landscape assessment: ground measure of severity, the Composite Burn Index'. In D. C. Lutes (Ed.), **FIREMON: Fire effects monitoring and inventory system. General Technical Report, RMRSGTR-164-CD:LA1-LA51**. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station.

Konovalov, I.B., Beekmann, M., Kuznetsova, I.N., Yurova, A. and Zvyagintsev, A.M. (2011) Atmospheric impacts of the 2010 Russian wildfires: integrating modelling and measurements of an extreme air pollution episode in the Moscow region. *Atmospheric Chemistry and Physics*, *11*(19): 10031-10056.

Kümmel, H. B. (1902). New Jersey Geological Survey: *Annual Report of the State Geologist for the Year 1902*. ed. N. J. G. Survey. Trenton, NJ: John B. Murphy Pub. Co.

La Puma, I. P., R. G. Lathrop. and N. S. Keuler. (2013) A large-scale fire suppression edge-effect on forest composition in the New Jersey Pinelands. *Landscape Ecology*, 28(9): 1815-1827.

Legg, C. (1995) Heathland dynamics: a matter of scale. In: Thompson, D. B. A., Hester, A. J. and Usher, M. B, eds. ***Heaths and Moorlands: Cultural Landscapes****. HMSO, Edinburgh*, 117-134.

Lentile, L. B., Holden, Z. A., Smith, A. M., Falkowski, M. J., Hudak, A. T., Morgan, P., Lewis, S. A., Gessler, P. E. and Benson, N. C. (2006) Remote sensing techniques to assess active fire characteristics and post-fire effects. *International Journal of Wildland Fire*, *15*(3): 319-345.

Lowden, L. and Hull, T. (2013) Flammability behaviour of wood and a review of the methods for its reduction. *Fire Science Reviews*, 2(1): 1-19.

Maestrini, B., Alvey, E. C., Hurteau, M. D., Safford, H. and Miesel, J. R. (2017) Fire severity alters the distribution of pyrogenic carbon stocks across ecosystem pools in a Californian mixed-conifer forest. *Journal of Geophysical Research: Biogeosciences*, *122*(9): 2338-2355.

Maltby, E., Legg, C. J., & Proctor, M. C. F. (1990) The ecology of severe moorland fire on the North York Moors: effects of the 1976 fires, and subsequent surface and vegetation development. *The Journal of Ecology*, 78: 490-518.

Manchester Evening News (2015) 'Video: Aftermath of huge moorland blaze on Winter Hill'. Website accessed June 24th 2017, <https://www.manchestereveningnews.co.uk/news/greater-manchester-news/video-winter-hill-fire-drone-9438488>.

Martin, R. A. and Hamman, S. T. (2016) Ignition patterns influence fire severity and plant communities in Pacific Northwest, USA, prairies. *Fire Ecology*, *12*(1): 88-102.

McMorrow, J., Lindley, S., Aylen, J., Cavan, G., Albertson, K. and Boys, D (2009). In: Bonn, A., Allott, T., Hubacek, K. and Stewart, J (Eds.). **Drivers of Change in Upland Environments**. 1st ed. Abingdon : Routledge; 2009. 404-431.

Merrill, D. F. and Alexander, M. E (eds), Fourth edition. (1987) *Glossary of forest fire management terms*. Canadian Committee on Forest Fire Management, National Research Council of Canada, Ottawa, ON. Pub. NRCC No. 26516. 91 p.

Michaletz, S. T. and Johnson, E. A. (2007) How forest fires kill trees: a review of the fundamental biophysical processes. *Scandinavian Journal of Forest Research*, *22*(6): 500-515.

Mooney, S. D., and Tinner, W. (2011) The analysis of charcoal in peat and organic sediments. *Mires and Peat*, *7*(09): 1-18.

Natural England (2014) '155: Carnmenellis. Natural England Publications'. Available at <http://publications.naturalengland.org.uk/publication/6254102417768448?category=587130>.

Ndalila, M., Williamson, G. and Bowman, D. (2018) Geographic patterns of fire severity following an extreme Eucalyptus forest fire in Southern Australia: 2013 Forcett-Dunalley fire. *Fire*, *1*(3): 1-28.

Neary, D. G., Klopatek, C. C., DeBano, L.F. and Ffolliott, P. F. (1999) Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management*, 122: 51–71.

Nepstad, D. C., Jipp, P., Moutinho, P., Negreiros, G. and Vieira, S. (1995) Forest recovery following pasture abandonment in Amazonia: canopy seasonality, fire resistance and ants. In *Evaluating and monitoring the health of large-scale ecosystems* (333-349). Springer Berlin Heidelberg.

Nesmith, J. C., Caprio, A. C., Pfaff, A. H., McGinnis, T. W. and Keeley, J. E. (2011) A comparison of effects from prescribed fires and wildfires managed for resource objectives in Sequoia and Kings Canyon National Parks. *Forest Ecology and Management*, *261*(7): 1275-1282.

New Jersey Department of the Treasury, O. o. M. a. B ---. 2016. State of New Jersey: *The Governor's FY2017 Detailed Budget*. D-114.

New Jersey Department of the Treasury, O. o. M. a. B. ---. 2012. State of New Jersey: *The Governor's FY2013 Detailed Budget*. 563.

New Jersey Department of the Treasury, O. o. M. a. B. ---. 2014. State of New Jersey: *The Governor's FY2015 Detailed Budget*. 586.

New Jersey Pinelands Commission. (2006) ‘Pinelands Facts. New Jersey Pinelands Commission'. Website accessed 27th April 2019, <https://rucore.libraries.rutgers.edu/rutgers-lib/18025/pdf/1/>, 1-3.

New, S. L., Hudspith, V. A. and Belcher, C. M. (2018) Quantitative charcoal reflectance measurements better link to regrowth potential than ground-based fire severity assessments following a recent heathland wildfire at Carn Brea, Cornwall, UK. *International Journal of Wildland Fire*, *27*(12): 845-850.

New York Times (2018) ‘Take a Look at How Quickly a Forest Can Recover From Fire’. Website accessed January 2019, <https://www.nytimes.com/2018/09/25/nyregion/nj-pine-barrens-fire-regrowth.html>.

Nimer, E. (1979) Climatologia do Brasil. *IBGE*, Rio de Janeiro, Brazil, 0-421.

North, M. P. and Hurteau, M. D. (2011) High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest. *Forest Ecology and Management*, *261*(6): 1115-1120.

OECD (2010), "Section 2 - Jack Pine (Pinus banksiana)", **in Safety Assessment of Transgenic Organisms, Volume 3: OECD Consensus Documents**, OECD Publishing, Paris, 57-90.

Ordnance Survey (2019) 'WINTER HILL, BLACKBURN WITH DARWEN (BL6 6SL)'. Website accessed 21st April 2019, <https://getoutside.ordnancesurvey.co.uk/local/winter-hill-blackburn-with-darwen>.

Oyedun, A. O., Lam, K. L. and Hui, C. W. (2012) Charcoal production via multistage pyrolysis. *Chinese Journal of Chemical Engineering*, *20*(3): 455-460.

Page, S. E., Siegert, F., Rieley, J. O., Boehm, H. D. V., Jaya, A. and Limin, S. (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, *420*: 61-65.

Pan, Y., Birdsey, R., Hom, J., McCullough, K. and Clark, K. (2006) Improved estimates of net primary productivity from MODIS satellite data at regional and local scales. Ecological Applications, 16(1):125−132.

Parisien, M.A., Miller, C., Parks, S. A., DeLancey, E. R., Robinne, F. N. and Flannigan, M. D. (2016) The spatially varying influence of humans on fire probability in North America. *Environmental Research Letters*, *11*(7): 1-18.

Parsons, A. L., Balch, J. K., de Andrade, R. B. and Brando, P. M. (2015) The role of leaf traits in determining litter flammability of south-eastern Amazon tree species. *International Journal of Wildland Fire*, *24*(8): 1143-1153.

Paton, D., Buergelt, P. T. and Flannigan, M. (2015) Ensuring That We Can See the Wood and the Trees: Growing the capacity for ecological wildfire risk management. In *Wildfire Hazards, Risks and Disasters*, Elsevier: 247-262.

Pausas, J. G. (2015) Bark thickness and fire regime. *Functional Ecology*, *29*(3): 315–327.

Pausas, J. G. and Keeley, J. E. (2019) Wildfires as an ecosystem service. *Frontiers in Ecology and the Environment*, *17*(5): 289-295.

Pausas, J. G. and Vallejo, V. R. (1999) The role of fire in European Mediterranean ecosystems. In *Remote sensing of large wildfires*, 3-16. Springer, Berlin, Heidelberg.

Penman, T. D., Collins, L., Price, O. F., Bradstock, R. A., Metcalf, S. and Chong, D. M. O. (2013) Examining the relative effects of fire weather, suppression and fuel treatment on fire behaviour–a simulation study. *Journal of Environmental Management*, *131*: 325-333.

Peres, C. A. (1999) Ground fires as agents of mortality in a Central Amazonian forest. *Journal of Tropical Ecology*, *15*(4): 535–541.

Peters, M. P., Iverson, L. R., Matthews, S. N. and Prasad. A.M. (2013) Wildfire hazard mapping: exploring site conditions in eastern US wildland–urban interfaces. *International Journal of Wildland Fire*, 22:567-578.

Phillips, O. L., Sullivan, M. J., Baker, T. R., Mendoza, A. M., Vargas, P. N. and Vásquez, R. (2019) Species Matter: Wood Density Influences Tropical Forest Biomass at Multiple Scales. *Surveys in Geophysics*, 40(4): 913-935.

Picotte, J. J. and Robertson, K. M. (2011) Validation of remote sensing of burn severity in south-eastern US ecosystems. *International Journal of Wildland Fire*, *20*(3): 453-464.

Pinõl, J., Beven K. and Viegas, D. (2005) Modelling the effect of fire-exclusion and prescribed fire on wildfire size in Mediterranean ecosystems. *Ecological Modelling*, 183(4): 397–409.

Quesada, C. A., Lloyd, J., Schwarz, M., Patino, S., Baker, T. R., Czimczik, C., Fyllas, N. M., Martinelli, L., Nardoto, G. B., Schmerler, J. and Santos, A. J. B. (2010). Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. *Biogeosciences*, *7*(5): 1515-1541.

Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S. and McKeefry, J. F. (2005) The wildland–urban interface in the United States. *Ecological Applications*, *15*(3): 799-805.

Randerson, J. T., Liu, H., Flanner, M. G., Chambers, S. D., Jin, Y., Hess, P. G., Pfister, G., Mack, M. C., Treseder, K. K., Welp, L. R. and Chapin, F. S. (2006) The impact of boreal forest fire on climate warming. *Science*, *314*(5802): 1130-1132.

Rein, G. (2013) Smouldering Fires and Natural Fuels, Chapter 2 in: **Fire Phenomena in the Earth System – An Interdisciplinary Approach to Fire Science**, pp. 15–34, Belcher (editor). Wiley and Sons, 2013.

Rein, G., Cleaver, N., Ashton, C., Pironi, P. and Torero, J.L. (2008) The severity of smouldering peat fires and damage to the forest soil. *Catena*, *74*(3): 304-309.

Righi, C. A., de Alencastro Graça, P. M. L., Cerri, C. C., Feigl, B. J. and Fearnside, P. M. (2009) Biomass burning in Brazil's Amazonian “arc of deforestation”: Burning efficiency and charcoal formation in a fire after mechanized clearing at Feliz Natal, Mato Grosso. *Forest Ecology and Management*, *258*(11): 2535-2546.

Rogers, B. M., Soja, A. J., Goulden, M.L. and Randerson, J. T. (2015) Influence of tree species on continental differences in boreal fires and climate feedbacks. *Nature Geoscience*, *8*(3): 228-234.

Roos, C. I. and Scott, A. C. (2018) A comparison of charcoal reflectance between crown and surface fire contexts in dry south-west USA forests. *International Journal of Wildland Fire*, *27*(6): 396-406.

Roos, C. I., Scott, A. C., Belcher, C. M., Chaloner, W. G., Aylen, J., Bird, R. B., Coughlan, M. R., Johnson, B. R., Johnston, F. H., McMorrow, J. and Steelman, T. (2016) Living on a flammable planet: interdisciplinary, cross-scalar and varied cultural lessons, prospects and challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696): 1-11.

Russell-Smith, J., Yates, C.P., Whitehead, P.J., Smith, R., Craig, R.,Allan, G.E., Thackway, R., Frakes, R., Cridland, S., Meyer,M.C.P. and Gill, A.M. (2007) Bushfires 'down under': patterns and implications of contemporary Australian landscape burning. *International Journal of Wildland Fire*,16: 361–377.

Ryan KC (2002) Dynamic interactions between forest structure and fire behaviour in boreal ecosystems. *Silva Fennica* 36(1): 13–39.

Ryan, K. and Noste, N. (1985) Evaluating prescribed fires (230-238) in: JE Lotan et al.(tech. coor) *Proceedings - Symposium and Workshop on Wilderness Fire. USDA Forest Service Intermountain Forest and Range Experiment Station, General Technical Report INT-182*, 230-238, Washington, D.C.

Ryan, K. C., Knapp, E. E. and Varner, J. M. (2013) Prescribed fire in North American forests and woodlands: history, current practice, and challenges. *Frontiers in Ecology and the Environment*, *11*(s1): 15-24.

Saiz, G., Goodrick, I., Wurster, C. M., Zimmermann, M., Nelson, P. N. and Bird, M. I. (2014) Charcoal re-combustion efficiency in tropical savannas. *Geoderma,* 219–220: 40–45.

Santana, V.M. and Marrs, R.H. (2014) Flammability properties of British heathland and moorland vegetation: models for predicting fire ignition. *Journal of Environmental Management*, *139*: 88-96.

Santin, C., Doerr, S.H., Kane, E.S., Masiello, C.A., Ohlson, M., de la Rosa, J.M., Preston, C.M. and Dittmar, T. (2016) Towards a global assessment of pyrogenic carbon from vegetation fires. *Global Change Biology*, *22*(1): 76-91.

Schepers, L., Haest, B., Veraverbeke, S., Spanhove, T., Vanden Borre, J. and Goossens, R. (2014) Burned area detection and burn severity assessment of a heathland fire in Belgium using airborne imaging spectroscopy (APEX). *Remote Sensi*ng, 6(3): 1803–1826.

Schlachter, K. J. and Horn, S. P. (2010) Sample preparation methods and replicability in macroscopic charcoal analysis. *Journal of Paleolimnology*, 44(2): 701-708.

Schwilk, D. W. and Ackerly, D. D. (2001) Flammability and serotiny as strategies: correlated evolution in pines. *Oikos*, *94*(2): 326-336.

Schwilk, D. W., Keeley, J. E., Knapp, E. E., McIver, J., Bailey, J. D., Fettig, C. J., Fiedler, C. E., Harrod, R. J., Moghaddas, J. J., Outcalt, K. W. and Skinner, C. N. (2009) The national Fire and Fire Surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. *Ecological Applications*, *19*(2): 285-304.

Scott, A. C. (2010) Charcoal recognition, taphonomy and uses in palaeoenvironmental analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *291*(1): 11-39.

Scott, A. C., Cripps, J. A., Collinson, M. E. and Nichols, G. J. (2000) The taphonomy of charcoal following a recent heathland fire and some implications for the interpretation of fossil charcoal deposits. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *164*(1-4): 1–31.

SGL Group The Carbon Company. (2016) '*Lexicon of Materials – C*'. Website accessed 20th May 2016, <https://www.sglgroup.com/cms/international/products/lexicon-of-materials/index.html?letter=Cand__locale=en>.

Shlisky, A., Waugh, J., Gonzalez, P., Gonzalez, M., Manta, M., Santoso, H., Alvarado, E., Nuruddin, A.A., Rodríguez-Trejo, D.A., Swaty, R. and Schmidt, D. (2007) Fire, ecosystems and people: threats and strategies for global biodiversity conservation. *Arlington: The Nature Conservancy*.

Silvério, D. V, Brando, P. M., Balch, J. K., Putz, F. E., Nepstad, D. C., Oliveira-Santos, C. and Bustamante, M. M. C. (2013) Testing the Amazon savannization hypothesis: fire effects on invasion of a neotropical forest by native cerrado and exotic pasture grasses. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 5(*368)*: 1-8.

Skowronski, N., Clark, K., Nelson, R., Hom, J. and Patterson, M. (2007) Remotely sensed measurements of forest structure and fuel loads in the Pinelands of New Jersey. *Remote Sensing of Environment*, *108*(2): 123-129.

State of New Jersey (2019). 'SPRING HILL WILDFIRE IN PINELANDS REACHES 1000 PREENT CONTAINMENT'. Website accessed 9th May 2019 < https://www.nj.gov/dep/newsrel/2019/19_0022.htm>.

Stephens, S. L. and Ruth, L. W. (2005) FEDERAL FOREST-FIRE POLICY IN THE UNITED STATES. *Ecological applications*, *15*(2): 532-542.

Stephens, S. L., McIver, J. D., Boerner, R. E., Fettig, C. J., Fontaine, J. B., Hartsough, B. R., Kennedy, P. L. and Schwilk, D. W. (2012) The effects of forest fuel-reduction treatments in the United States. *BioScience*, *62*(6): 549-560.

Stephens, S. L., Moghaddas, J. J., Hartsough, B. R., Moghaddas, E. E. and Clinton, N. E. (2009) Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest Publication No. 143 of the National Fire and Fire Surrogate Project. *Canadian Journal of Forest Research*, *39*(8): 1538-1547.

Stocks, B. J., Mason, J. A., Todd, J. B., Bosch, E. M., Wotton, B. M., Amiro, B. D., Flannigan, M.D., Hirsch, K. G., Logan, K. A., Martell, D. L. and Skinner, W. R. (2003) Large forest fires in Canada, 1959–1997. *Journal of Geophysical Research: Atmospheres*, *108*(8149): 1-12.

Sturtevant, B. R., Miranda, B. R., Yang, J., He, H. S., Gustafson, E. J. and Scheller, R. M. (2009) Studying fire mitigation strategies in multi-ownership landscapes: Balancing the management of fire-dependent ecosystems and fire risk. *Ecosystems*, *12*(3): 445-461.

Swezy, D. M. and Agee, J. K. (1991) Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. *Canadian Journal of Forest Research*, *21*(5): 626-634.

Tedrow, J. C. F. (1986) Soils of New Jersey. *New Jersey agricultural experiment station publication A-15134–1-82 Malabar*, FL: Krieger Publishing Co.17.

Thompson, J. R., Spies, T. A. and Ganio, L. M., (2007) Reburn severity in managed and unmanaged vegetation in a large wildfire. *Proceedings of the National Academy of Sciences*, *104*(25): 10743-10748.

Tinkham, W. T., Smith, A. M. S., Higuera, P. E., Hatten, J. A., Brewer, N. W., and Doerr, S. H. (2016) Replacing time with space: using laboratory fires to explore the effects of repeated burning on black carbon degradation. *International Journal of Wildland Fire,* 25: 242–248.

Tran, B., Tanase, M., Bennett, L. and Aponte, C. (2018) Evaluation of spectral indices for assessing fire severity in Australian temperate forests. *Remote Sensing*, *10*(11): 1680.

Turetsky, M. R., Benscoter, B., Page, S., Rein, G., Van Der Werf, G. R. and Watts, A. (2015) Global vulnerability of peatlands to fire and carbon loss. *Nature Geoscience*, *8*(1) 11-14.

Turetsky, M. R., Kane, E. S., Harden, J. W., Ottmar, R. D., Manies, K. L., Hoy, E. and Kasischke, E. S. (2011) Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nature Geoscience*, *4*(1): 27-31.

Turner, M. G., Hargrove, W. W., Gardner, R. H. and Romme, W. H. (1994) Effects of fire on landscape heterogeneity in Yellowstone National Park, Wyoming. *Journal of Vegetation Science,* 5: 731–742.

Turner, M. G., Harvey, B. J., Hansen, W. D. and Braziunas, K. H. (2018) Changing fire regimes and resilience of lodgepole pine forests in Yellowstone. Abstract. In '*Contributed Talks: 103rd Annual Meeting Ecological Society of America*', 5–10 August 2018, New Orleans, LA, USA.

Uhl, C. and Kauffman, J.B. (1990) Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. *Ecology*, *71*(2): 437-449.

Umbanhowar Jr, C. E. and Mcgrath, M. J. (1998) Experimental production and analysis of microscopic charcoal from wood, leaves and grasses. *The Holocene*, 8(3): 341-346.

United States Forest Service (2015). The Rising Cost of Wildfire Operations: Effects on the Forest Service's Non-fire Work. *USDA Forest Service*.

Van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y. V. and van Leeuwen, T. T. (2010) Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmospheric Chemistry and Physics*, *10*(23): 11707-11735.

Van Wagtendonk, J. W. and Lutz, J. A. (2007) Fire regime attributes of wildland fires in Yosemite National Park, USA. *Fire Ecology*, *3*(2): 34-52.

Waddington, J. M., Morris, P. J., Kettridge, N., Granath, G., Thompson, D. K. and Moore, P. A. (2015) Hydrological feedbacks in northern peatlands. *Ecohydrology*, *8*(1): 113-127.

Warner, T. A., Skowronski, N. S. and Gallagher, M. R. (2017) High spatial resolution burn severity mapping of the New Jersey Pine Barrens with WorldView-3 near-infrared and shortwave infrared imagery. *International Journal of Remote Sensing*, *38*(2): 598-616.