CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2006, **15**, 319–345

Remote sensing techniques to assess active fire characteristics and post-fire effects

Leigh B. Lentile[A,D*], *Zachary A. Holden*[A*], *Alistair M. S. Smith*[A*], *Michael J. Falkowski*[A],
Andrew T. Hudak[B], *Penelope Morgan*[A], *Sarah A. Lewis*[B], *Paul E. Gessler*[A]
and Nate C. Benson[C]

[A]Department of Forest Resources, University of Idaho, Moscow, ID 83844-1133, USA.
[B]Rocky Mountain Research Station, USDA Forest Service, Moscow, ID 83843, USA.
[C]National Park Service, National Interagency Fire Center, 3833 S. Development Avenue, Boise, ID 83705-5354, USA.
[D]Corresponding author. Email: lentile@uidaho.edu

Abstract. Space and airborne sensors have been used to map area burned, assess characteristics of active fires, and characterize post-fire ecological effects. Confusion about fire intensity, fire severity, burn severity, and related terms can result in the potential misuse of the inferred information by land managers and remote sensing practitioners who require unambiguous remote sensing products for fire management. The objective of the present paper is to provide a comprehensive review of current and potential remote sensing methods used to assess fire behavior and effects and ecological responses to fire. We clarify the terminology to facilitate development and interpretation of comprehensible and defensible remote sensing products, present the potential and limitations of a variety of approaches for remotely measuring active fires and their post-fire ecological effects, and discuss challenges and future directions of fire-related remote sensing research.

Additional keywords: burn severity; burned area; ecological change; fire atlas; fire intensity; fire perimeters; fire radiative power; fire severity; Normalized Burn Ratio; Normalized Difference Vegetation Index; radiative energy.

Introduction

Fire is an important ecosystem process that significantly impacts terrestrial, aquatic, and atmospheric systems throughout the world. Over the past few decades, wildfires have received significant attention because of the wide range of ecological, economic, social, and political values at stake. Additionally, fires impact a wide range of spatial and temporal scales, and stakeholders are only beginning to understand relationships between pattern, process, and potential restorative measures.

At the local scale, fire can stimulate soil microbial processes (Wells *et al.* 1979; Borchers and Perry 1990; Poth *et al.* 1995; Wan *et al.* 2001; Choromanska and DeLuca 2002), promote seed germination, seed production, and sprouting (Lyon and Stickney 1976; Hungerford and Babbitt 1987; Anderson and Romme 1991; Lamont *et al.* 1993; Perez and Moreno 1998), and combust vegetation, ultimately altering the structure and composition of both soils and vegetation (Ryan and Noste 1985; Wyant *et al.* 1986; Ryan and Reinhardt 1988; McHugh and Kolb 2003).

At the regional scale, fires may also affect the quantity and quality of water yield (Minshall *et al.* 2001; Spencer *et al.* 2003), accelerate erosion and sedimentation (Scott and Van Wyk 1990; Robichaud *et al.* 2000; Ice *et al.* 2004) and result in a myriad of beneficial, neutral, or detrimental consequences for aquatic systems (Gresswell 1999; Vieira *et al.* 2004). Wildfires are potentially hazardous to human life and property (Bradshaw 1988; Beebe and Omi 1993; Cohen and Butler 1998; Cohen 2000), and the economic costs of fire management and suppression in the United States have over the past two decades been among the highest on record. Departure from the historical frequency, timing, extent, and severity of some fires, particularly in the dry forests, has led to significant ecological and policy changes (Dellasalla *et al.* 2004). Fire is also important in the creation and maintenance of landscape structure, composition, function, and ecological integrity (Covington and Moore 1994; Morgan *et al.* 2001), and can influence the rates and processes of ecological succession and encroachment. At local to regional scales, criteria pollutants (e.g. ozone, carbon monoxide, nitrogen

---

[*] Leigh B. Lentile, Zachary A. Holden and Alistair M. S. Smith contributed equally to this paper.

10.1071/WF05097 1049-8001/06/030319

Table 1. Remote sensing systems relevant to fire detection and monitoring
VIS-MIR, visible, mid-infrared; TIR, thermal infrared

Sensor and additional web resources	Temporal resolution	Spatial resolution (km)	VIS-MIR bands (μm)	TIR bands (μm)
Advanced Along Track Scanning Radiometer http://www.le.ac.uk/ph/research/eos/aatsr/	2 days	1.00	0.56, 0.66, 0.86, 1.6	3.7, 11, 12
Advanced Land Imager http://eo1.gsfc.nasa.gov/Technology/ALIhome1.htm	16 days	0.010–0.09	0.44, 0.48, 0.56, 0.64, 0.79, 0.87, 1.25, 1.65, 2.23	
Advanced Spaceborne Thermal Emission and Reflection Radiometer http://asterweb.jpl.nasa.gov/	16 days	0.015–0.09	0.56, 0.66, 0.82, 1.65, 2.17, 2.21, 2.26, 2.33, 2.34	8.3, 8.65, 9.1, 10.6, 11.3
Along Track Scanning Radiometer http://www.atsr.rl.ac.uk/	3 days	1.00	0.55, 0.67, 0.87, 1.6	3.7, 10.8, 12
Advanced Very High Resolution Radiometer http://www.nesdis.noaa.gov/	4 daily	1.10	0.63, 0.91, 1.61	3.74, 11, 12
Hot Spot Recognition Sensor System http://www.itc.nl/research/products/sensordb/getsen.aspx?name=HSRS		0.37		3.8, 8.9
Hyperion http://eo1.gsfc.nasa.gov/technology/hyperion.html	16 days	0.03	[220 bands: 0.38–2.5 μm]	
IKONOS http://www.spaceimaging.com/	3 days	0.001–0.004	0.48, 0.55, 0.67, 0.81	
Indian Remote Sensing-1A,B http://www.isro.org/	22 days	0.036–0.072	0.55, 0.65, 0.83	
Indian Remote Sensing-1B,C http://www.isro.org/	24 days	0.023–0.188		
Landsat 5, 7 http://landsat.gsfc.nasa.gov/	16 days	0.015–0.09	0.48, 0.56, 0.66, 0.85, 1.65, 2.17	11.5
Moderate Resolution Imaging Spectroradiometer http://modis.gsfc.nasa.gov/	4 daily	0.25–1.0	19 bands	16 bands
Quickbird http://directory.eoportal.org/pres_QUICKBIRD2.html	1–5 days	0.001–0.004	0.48, 0.56, 0.66, 0.83	
VEGETATION http://www.spot-vegetation.com/	1 daily	1.15	0.55, 0.65, 0.84, 1.62	

dioxide, sulphur dioxide, and particulate matter) emitted by fires impact air quality (Hardy *et al.* 2001) and raise concern about risks to human health (Brauer 1999).

At the global scale, fire emissions have direct and significant impacts on atmospheric and biogeochemical cycles and the Earth's radiative budget (Crutzen and Andreae 1990; McNaughton *et al.* 1998; Andreae and Merlet 2001; Smith *et al.* 2005*a*). The influence of fire spans a wide range of temporal and spatial scales, and the interpretation of causal factors, fire effects, and ecosystem response is a challenge to both research and management.

These issues of scale and more practically, the size and inaccessible nature of many wildfires, make remotely sensed data an important and widely applied resource for fire science and management (Hardy *et al.* 1999). Space and airborne sensors have been used to assess environmental conditions before and during fires and to detect changes in post-fire spectral response (Table 1). Remotely sensed data have been used to detect active fires (Roy *et al.* 1999; Ichoku *et al.* 2003); map fire extents at local (Parsons 2003; Holden *et al.* 2005), regional (Eva and Lambin 1998*a*; Smith *et al.* 2002) and continental (Scholes *et al.* 1996) scales; estimate surface and crown fuel loading (Nelson *et al.* 1988; Means *et al.* 1999; Lefsky *et al.* 2002; Falkowski *et al.* 2005); assess active fire behavior (Kaufman *et al.* 1998; Wooster *et al.* 2003; Smith and Wooster 2005; Dennison 2006; Dennison *et al.* 2006); examine post-fire vegetation response (Turner *et al.* 1994; White *et al.* 1996; Díaz-Delgado *et al.* 2003), and identify areas where natural recovery may prove to be problematic (Bobbe *et al.* 2001; Ruiz-Gallardo *et al.* 2004). Multi-temporal remote sensing techniques have been effectively employed to assess and monitor landscape change in a rapid and cost-effective manner. Remotely sensed data give researchers a means to quantify patterns of variation in space and time. The utility of these data depends on the scale of application. Coarse-scale maps of fire regimes based largely on remotely sensed biophysical data have been used for planning and prioritizing fuels treatments at regional and national levels, but may have limited local applicability (Loveland *et al.* 1991; Morgan *et al.* 1996, 2001; Hardy *et al.* 1999). Higher spatial-resolution remote sensing of spectral patterns before, during, and after wildfire may facilitate prediction of areas likely to burn or experience uncharacteristic effects when they burn, and may assist with strategic decisions about fuels management before fires occur, suppression as fires burn, and post-fire rehabilitation efforts.

Since the mid 1980s, numerous remote sensing techniques have been developed to assess how 'severe', in terms of ecological change, a fire is on both local and regional ecosystems. Early studies inferred fire-caused vegetation change from spectral changes measured by satellite sensors, whereas more recent studies have sought to relate ecological measures to fire-induced physical changes on the land surface (e.g. Milne 1986; Jakubauskas *et al.* 1990; White *et al.* 1996). When vegetation is burned, there is, at the spatial resolution of most satellite sensors (pixel size >30 m), a drastic reduction in visible-to-near-infrared surface reflectance (i.e. 0.4–1.3 μm) associated with the charring and removal of vegetation (Eva and Lambin 1998*a*; Trigg and Flasse 2000). At finer spatial resolutions (pixel size <5 m), the combustion of large quantities of wood (or other fuels) can in some cases lead to an increase in surface reflectance due to the deposition of white ash (Landmann 2003; Roy and Landmann 2005; Smith and Hudak 2005; Smith *et al.* 2005*b*). This is typically accompanied by a rise in short wave infrared reflectance (i.e. 1.6–2.5 μm) and brightness temperatures, which is attributed to the combined effects of increased soil exposure, increased radiation absorption by charred vegetation, and decreased evapotranspiration relative to the pre-fire green vegetation (Chuvieco and Congalton 1988; Eva and Lambin 1998*a*, 1998*b*; Stroppiana *et al.* 2002; Smith *et al.* 2005*b*). The degree of post-fire change may vary depending on vegetation type, annual differences in growing season weather, and overall time since fire. For this reason, stratification among vegetation types, comparison of images with similar vegetation phenology, and image differencing techniques including pre-, immediate post-, and 1-year-post-fire images have been recommended to assess fire effects and ecological change (White *et al.* 1996; Cocke *et al.* 2005; Hudak *et al.* 2005). Further fire effects such as canopy mortality, ground charring, and changes in soil color can be readily detected, provided sensors have adequate spatial and spectral resolution (White *et al.* 1996).

The observation of broad spectral changes due to burning has led to the use of a variety of spectral indices (combinations of different sensor bands), including the Normalized Burn Ratio (NBR), the difference in the Normalized Burn Ratio between pre- and post-fire images (dNBR), and the Normalized Difference Vegetation Index (NDVI). NBR and dNBR are widely used to infer fire severity from remotely sensed data (Key and Benson 2002, 2006; van Wagtendonk *et al.* 2004; Cocke *et al.* 2005; Smith *et al.* 2005*b*; Roy *et al.* 2006) and are commonly used to produce maps for Burned Area Emergency Response (BAER) teams (Parsons 2003). Other recent remote sensing research has focused on the development of techniques used to remotely infer fire behavior and fuel combusted through the assessment of thermal infrared imagery (Kaufman *et al.* 1998; Wooster 2002; Riggan *et al.* 2004; Roberts *et al.* 2005; Smith and Wooster 2005; Wooster *et al.* 2005; Zhukov *et al.* 2006).

The objective of the present paper is to review current and potential remote sensing tools and techniques that can quantify and monitor fire-related processes that cause change in soil and vegetation. For information on the remote sensing of fuels and fire hazards, see Keane *et al.* (2001), Hardy (2005), and Tian *et al.* (2005). In the present paper, we clarify the terminology to facilitate development and interpretation of comprehensible and defensible remote sensing products, present the potential and limitations of a variety of approaches for remotely measuring active fires and their post-fire ecological effects, describe field assessment of surface change, and discuss management implications and future directions of fire-related remote sensing research.

Fire and fire effects terminology

The terms fire intensity, fire severity, and burn severity are three descriptors that exist on a temporal continuum associated with pre-fire conditions, active fire characteristics, and post-fire ecosystem response (DeBano *et al.* 1998; Jain *et al.* 2004).

Although remotely sensed imagery has been used to assess each of these descriptors, there remains a need to clarify linkages between remotely sensed measurements and the physical or ecological processes that each measure infers. Additionally, overlapping and inconsistent use of fire terminology has created a need to spell out the ecological meanings and implications of each term. For instance, the term 'severity' is frequently used to describe the magnitude of ecological change caused by fire. In the remote sensing literature, severity has been related to vegetation consumption (Conard *et al.* 2002; Miller and Yool 2002; Kasischke and Bruhwiler 2003; Zhang *et al.* 2003), white ash production (Landmann 2003; Smith and Hudak 2005), changes in surface reflectance (White *et al.* 1996; Key and Benson 2002; Smith *et al.* 2005*b*), alteration of soil properties (Ketterings and Bigham 2000; Lewis *et al.* 2006), and long-term post-fire vegetation mortality and recovery (Patterson and Yool 1998). In some cases, fire descriptors of intensity and severity are used interchangeably within the same document (e.g. White *et al.* 1996; Díaz-Delgado *et al.* 2003; Landmann 2003), and exactly what is being measured is often unclear or largely inferential. More often, however, severity is used very generally, without reference to a specific process (soil, hydrologic, vegetation) or vegetation strata (understory, overstory). In particular, the terms fire severity and burn severity are often confused and used interchangeably in both the ecological and remote sensing literature. Although this confusion has been highlighted by recent studies (e.g. Hardy 2005; Smith *et al.* 2005*b*), clarification of the different fire descriptors is needed.

One of the sources of confusion arises owing to where on the temporal gradient the fire severity and burn severity terms lie. Fire severity is usually associated with immediate post-fire measures (e.g. vegetation consumption, vegetation mortality, soil alteration), whereas burn severity relates to the amount of time necessary to return to pre-fire levels or function. For example, in grassland ecosystems, fires typically consume large portions of aboveground biomass, which would be indicative of high fire severity. However, in these ecosystems, grasses and forbs typically rejuvenate quickly, indicating low burn severity. It is apparent that although fire severity may refer to short-term effects more directly related to fire intensity, the overlap between fire severity and burn severity is inevitable. We will clarify each term and then propose adoption of more precise and descriptive terminology.

Fire descriptors

Fire intensity is a description of fire behavior quantified by the temperature of, and heat released by, the flaming front of a fire (Whelan 1995; Neary *et al.* 1999; Morgan *et al.* 2001). Fire intensity is measured by two factors: the rate of spread, calculated by the number of meters burned per second, and energy flux, the amount of kilowatts a fire generates per meter burned. Physical attributes used to quantify fire intensity include temperature, flame length duration, and the emission of pyrogenic gases. Fire intensity and rate of spread are partly controlled by factors such as vegetation type (forests, shrubs, herbaceous plants), vegetation moisture content, weather (wind speed, atmospheric stability, and humidity), and topography (DeBano *et al.* 1998). Fire intensity can be measured by measuring kinetic temperature (via thermocouples), via thermal remote sensing systems, or by inferring observations of flame length and fire spread rate (Key and Benson 2002; Smith *et al.* 2005*b*; Dennison *et al.* 2006). Fire intensity is typically reported in kilojoules per second per meter.

Fire severity integrates active fire characteristics and immediate post-fire effects on the local environment. Even though the fire intensity often influences fire severity (Key and Benson 2002; van Wagtendonk *et al.* 2004), these phenomena are not always correlated (Hartford and Frandsen 1992; Neary *et al.* 1999; Miller and Yool 2002; Smith *et al.* 2005*b*). Fire severity differs from fire intensity by its focus on how much of the duff, logs, and other dense organic matter on the soil surface burns (Parsons 2003; Ice *et al.* 2004). Fire behavior may be simultaneously influenced by several factors, resulting in high vertical and horizontal spatial heterogeneity of fire effects and subsequent ecological responses. Fire duration, which determines the amount of heat transferred to the soil and the amount of aboveground vegetation consumed, often has a greater impact on fire severity than the fire intensity (Neary *et al.* 1999). In turn, the nature of the fuels available for burning and fire duration determine the energy produced by the fire and are the contributing forces for many ecosystem fire effects (DeBano *et al.* 1998). For example, a high-intensity, fast-moving fire transfers less heat into the soil (i.e. most of the energy is dissipated horizontally and vertically via radiation or convection) than a low-intensity, slow-moving (or smouldering) fire, and therefore leaves belowground processes largely intact. A high-intensity fire of the former type may actually benefit the ecosystem by increasing the amount of available nutrients (Neary *et al.* 1999), and as such would be correctly described as low fire severity. In contrast, a low-intensity slow-moving fire impacts aboveground and belowground plant components, killing a majority of the vegetation, and therefore might have a more immediate impact on ecosystem health, and as such would be correctly described as high fire severity.

Burn severity incorporates both short- and long-term post-fire effects on the local and regional environment. Burn severity is defined by the degree to which an ecosystem has changed owing to the fire (Morgan *et al.* 2001; Key and Benson 2002; National Wildfire Coordinating Group 2005). Vegetation influences burn severity as biomass production often exceeds decomposition and some plants are specifically adapted to the characteristics of fires that commonly burn in these systems (Key 2005) (Fig. 1). Several aspects of burn severity can be quantified, but burn severity cannot be expressed as a single quantitative measure that relates to all resource impacts (DeBano *et al.* 1998; Robichaud *et al.* 2000). Relative magnitudes of burn severity are often expressed in terms of post-fire appearance of vegetation, litter, and soil. However, it is easier to measure what remains following fire than it is to know what was there before the fire. Although the physical manifestations of burn severity vary continuously, for practicality burn severity is often broadly defined and partitioned into discrete classes ranging from low (less severe) to high (more severe). Burn severity is typically assessed after a fire by measuring soil characteristics (char depth, organic matter loss, altered infiltration, and color) (Ryan and Noste 1985; DeBano *et al.* 1998; Neary *et al.* 1999), and aboveground vegetation consumption, mortality, scorch, and recovery (Morgan *et al.* 2001). Burn severity serves as a baseline with which other data layers may be integrated.

Severe burns have long-lasting ecological effects because they alter belowground processes (hydrologic, biogeochemical, microbial), which are essential to the health and sustainability of aboveground systems (Neary *et al.* 1999). Long-term ecological changes can potentially result from severe fires that remove aboveground overstory vegetation, even if impacts to belowground processes are minimal. Post-fire weather conditions can also influence severity, in particular when looking at vegetation change through time in relation to severity (Key 2005). Remotely sensed measures of burn severity may reflect inter-annual phenological change of vegetation, as well as the interaction of longer-term climate patterns such as drought. Image acquisition date, in relation to time of field data collection and time since fire, may be more important than type of imagery or index used to compare severity measures. Hudak *et al.* (2004) attributed low

Fig. 1. Low, moderate, and high 'burn severity' sites in California (CA) chaparral, Montana (MT) mixed-conifer forests, and Alaska (AK) black spruce forests. Burn severity was classified via consistent visual assessment of ground and canopy fire effects.

correlations between field and remotely sensed measures of burn severity to post-fire wind and precipitation events that may have transported ash and soil off-site following fire in chaparral systems in southern California.

Burn severity is not a direct measure, but a judgement that changes based on the context. It is likely that severity may vary depending on the issue or resource being addressed (e.g. vegetation mortality, soil erosion, soil nutrition), leading Jain *et al*. (2004) to propose abandoning the categorical descriptions of low, moderate, and high severity, commonly used in the ecological and remote sensing literature. Burn severity classifications are often driven by objectives. For example, burn severity mapping is an important part of the analysis of US BAER teams including emergency treatment specifications and identification of potential deleterious effects. Burn severity mapping is used in post-fire project planning and monitoring, by researchers exploring relationships between pre-, during, and post-fire characteristics and response, and, in some cases, as evidence in legal debates. Considerable confusion surrounds definitions and interpretations of burn severity. However, these terms are useful descriptors, which are deeply entrenched in the nomenclature of fire managers and rehabilitation teams to describe post-wildfire effects in the USA. Thus wholesale abandonment is neither possible at this stage, nor advisable given the diverse array of users employing these descriptors.

In the fire-behavior and fire-effects modelling communities, the terms 'first-order' and 'second-order' fire effects are often used, although these terms do not directly correspond to the descriptors of fire intensity, fire severity, and burn severity. First-order fire effects include the direct and immediate fire effects on the environmental parameter of interest. First-order fire effects such as plant injury and death, fuel consumption, and smoke production are the direct result of the combustion process and, as such, are best described as active fire characteristics. Second-order fire effects result from the indirect effects of fire and other post-fire interactions such as weather and, as such, are best described as post-fire effects. Some important second-order fire effects are smoke dispersion, erosion, and vegetation succession, which may be evident immediately to many decades after a fire (Reinhardt *et al.* 2001). To non-fire modellers, this jargon can be confusing as these terms do not implicitly describe a temporal dimension, but rather suggest relative degrees of severity within a given parameter (e.g. degrees or 'orders' of soil char or biomass combustion within an area). Therefore, to assist in separating the different remote sensing studies that have been described as quantifying fire intensity, fire severity, and burn severity, the present paper will henceforth refer to these fire descriptors as either 'active fire characteristics' or 'post-fire effects'. The active fire characteristics include 'immediate' variables that can only be measured during the fire's combustion (whether flaming or smouldering), whereas post-fire effects include short- and long-term effects that impact the environment following the passage of the fire. Following a brief description of the available satellite sensor systems, this paper will provide a review of how remotely sensed imagery has been used to monitor and evaluate these fire descriptors.

Remote sensing instruments and platforms

Many different sensor platforms and instruments have been used to remotely map and monitor active fire characteristics and post-fire effects (Table 1). In terms of the remote sensing of active fire characteristics and post-fire effects, we can divide the available sensor systems into passive or active and then further into aerial or satellite sensors. The most commonly applied types of active (i.e. rather than passive) remote sensing systems used to evaluate fire-related information are light detection and ranging (lidar) systems. These provide information on the elevation (and thus relative height) of a surface by measuring the time taken for a pulse of laser light to journey between a sensor and a surface. Lidar systems are predominately aerial-based and have been widely used to characterize individual tree and stand-level canopy structure (e.g. Lefsky *et al.* 1999, 2005; Means *et al.* 1999, 2000; Falkowski *et al.* 2006; Hudak *et al.* 2006), with limited studies directly evaluating fire fuels information (Seielstad and Queen 2003).

The majority of remote sensing systems that have been used to infer active and post-fire characteristics have been passive sensors measuring the reflection or emission of electromagnetic radiation from surfaces. Multispectral airborne and satellite sensors use radiometers that are sensitive to narrow bandwidths (bands) of the electromagnetic spectrum. For example, the Landsat Thematic Mapper (TM) sensor has six bands that span visible to mid-infrared wavelengths, and a thermal band that is sensitive to the surface brightness temperature. Like many satellite sensors, the Landsat TM bandwidths were selected in part to maximize sensitivity to the dominant factors controlling the spectral reflectance properties of green vegetation.

The utilization of aerial or satellite sensors depends greatly on the intended application. The data quality issues of most satellite sensor imagery are widely known and several software packages exist that can assist in their analysis. In contrast, aerial systems add a level of complexity, with most images needing 'fixes' to correct for the pitch, roll, and yaw of the aircraft. The advantages of aerial acquisitions are that imagery with very high spatial resolutions (<0.5 m per pixel) can be acquired. More importantly, aerial systems have the potential to allow a 'rapid response' system to be implemented. Given flight clearance, most aerial systems can fly on demand and thus characterize specific fire-related processes in a timely manner. There is a clear trade-off when comparing aerial and sensor acquisitions. Although the user is restricted by the imagery having both a specific pixel size and the sensor flying at specific times of day (and night), the sensor will always acquire the data even when aerial acquisitions are not permitted.

Remote assessment of active fire characteristics

Numerous measures have been applied to describe active fire characteristics within both the remote sensing and fire ecology literature (Table 2). The remote assessment of active fire characteristics can, however, be grouped into two main application branches:

1. The detection of actively burning areas using a combination of optical and thermal imagery; and
2. The use of thermal imagery (airborne and satellite) to estimate the energy radiated from the fire as it burns.

Detecting and counting active fires

The accurate identification of fire events has been recognized by international research organizations, such as the International Geosphere and Biosphere program (IGBP), to be crucial in the development of a broader understanding of how fire extent and frequency impact global environmental processes (Giglio *et al.* 1999; Ichoku *et al.* 2003). Actively burning fires can be detected using thermal infrared bands (3.6–12 μm range) from coarse spatial resolution sensors such as the Advanced Very High Resolution Radiometer (AVHRR), the Along Track Scanning Radiometer (ATSR), or the Moderate Resolution Imaging Spectroradiometer (MODIS). Thermal emissive power from fires is orders of magnitude more intense than from the surrounding background. Such high contrast allows active fires to be reliably detected even when the fire covers small fractions (for example $<0.01\%$, or 1 ha of a 1 km^2 area) of the pixel (Robinson 1991). Numerous algorithms for active fire detection have been developed (e.g. Kaufman *et al.* 1990; Justice *et al.* 1993, 1996; Flasse and Ceccato 1996; Pozo *et al.* 1997; Fraser *et al.* 2000; Seielstad *et al.* 2002; Dennison 2006; Dennison *et al.* 2006), and prior reviews of several of these methods have been presented by Li *et al.* (2001) and Ichoku *et al.* (2003).

Broad-scale fire effects have been inferred from active fire images (Pozo *et al.* 1997; Roy *et al.* 1999; Fraser *et al.* 2000;

Table 2. Selected examples of measures of active fire characteristics

Characteristic description	Type of measure	Reference examples
Flame length and height	Heat-sensitive objects	Hely *et al.* (2003)
	Direct observation	Stocks *et al.* (1996)
	Video	
Fire duration	Thermocouples	McNaughton *et al.* (1998)
		Smith *et al.* (2005*b*)
Fire temperature	Heat-sensitive paint or ceramics	Hely *et al.* (2003)
	Thermocouples	McNaughton *et al.* (1998)
	Thermal infrared cameras and imagery	Riggan *et al.* (2004)
Integrated temperature with time	Thermocouples	McNaughton *et al.* (1998)
		Smith *et al.* (2005*b*)
Rate of spread	Thermocouples	Smith *et al.* (2005*b*)
	Visual records, stop watches	Stocks *et al.* (1996)
	Video	
Direct pyrogenic emissions	Gas analyzers	Andreae *et al.* (1996)
	Fourier transform infrared spectroscopy	Yokelson *et al.* (2003)
		Yokelson *et al.* (1996)
Fuel combusted	Forest fuel and duff combustion	Ottmar and Sandberg (2003)
	In situ fire fuel sampling	Smith *et al.* (2005*a*)
	Change in laser profiling data	n/a
	Fire radiative power/energy	Kaufman *et al.* (1998)
		Wooster (2002)
Fire energy output	Fire line intensity	Byram (1959)
		Trollope *et al.* (1996)
		Smith and Wooster (2005)
	Fire radiative power/energy	Kaufman *et al.* (1998)
		Wooster *et al.* (2003, 2005)
		Roberts *et al.* (2005)

Li *et al.* 2000*a*, 2000*b*). Pozo *et al.* (1997) applied a technique in south-eastern Spain in which the total area burned was calculated by measuring the total number of active fire pixels over the period of a fire event. A major limitation of such methods is that they only identify pixels containing active fires when the satellite has passed overhead. The limited temporal coverage of most satellite sensors (e.g. Landsat 5 acquisitions occur approximately once every 16 days) likely results in major errors of omission, which are magnified by the effects of cloud cover (Pereira and Setzer 1996; Fraser *et al.* 2000). Such limitations have been addressed by incorporating active fire pixel detection techniques with methods employing spectral indices to detect the area burned in either neighboring pixels or the same pixels days after the active fire (Barbosa *et al.* 1999*a*, 1999*b*; Roy *et al.* 1999; Fraser *et al.* 2000). Fraser *et al.* (2000) developed the automated Hotspot And NDVI Differencing Synergy (HANDS) technique for use in boreal forest environments. The HANDS technique combined the simple active-fire pixel method with a post-fire burned area mapping technique utilizing presumed post-fire decrease in surface near-infrared reflectance. The relationship between burned areas from HANDS and Landsat TM has also been reported over a wide range of boreal fires in Canada (Fraser *et al.* 2004). Although these hotspot-based techniques have been widely applied to data acquired from the mid-infrared channel (3.55–3.93 μm) of the AVHRR sensor (Kaufman *et al.* 1990; Justice *et al.* 1996; Randriambelo *et al.* 1998; Fraser *et al.* 2000), the availability of more thermal channels from the MODIS sensor increases the potential for such techniques (Kaufman *et al.* 1998; Justice *et al.* 2002). An added advantage of MODIS is that it is now available on two satellites allowing 2–4 daily (night and day) image acquisitions. Considerable research is ongoing to develop applications of the freely available MODIS products for detecting active fires and burned area.

Estimating the energy radiated by a fire

The energy produced by a fire is lost to the environment through a combination of conduction, convection, and radiation (Kaufman *et al.* 1998). Thermal infrared remote sensing research has focused on inferring information from the radiative component, as the convective and conductive components are difficult to directly quantify. The earliest research and development into using remote sensing to analyze the energy radiated by fires was performed in the late 1960s by the Fire Laboratory in Missoula, where a US Department of Defense sensor was modified and tested for fire detection (Wilson *et al.* 1971). Subsequent research has demonstrated that thermal infrared remote sensing data can provide a useful measure of the rate of energy released from fire, termed the fire radiative power (FRP) (Kaufman *et al.* 1998; Wooster 2002; Wooster *et al.* 2003, 2005; Butler *et al.* 2004; Riggan *et al.* 2004; Ichoku and Kaufman 2005; Roberts *et al.* 2005; Smith and Wooster 2005). Simply stated, this method relies on the assumption that the amount of energy produced by combusting a quantity of mass X is half that emitted by burning a quantity of the same material of mass 2X. Assuming that the proportions of energy emitted as conductive, convective, and radiative are constant, the measure of the radiative energy released from burning biomass is indicative of the quantity of biomass combusted. If the combustion efficiency of the biomass is known, (as established through burn experiments), then the biomass burned to produce a measured quantity of heat can be calculated (Wooster 2002; Wooster *et al.* 2005).

FRP has been derived from spectral measurements made by the MODIS sensor, and is directly related to the rate of fuel combusted (Kaufman *et al.* 1998; Wooster *et al.* 2003). FRP for a given fire pixel from the MODIS 3.9 μm band is defined as (Wooster *et al.* 2003):

$$\mathrm{FRP} = \mathrm{A_{samp}}[1.89 \times 10^{7}(\mathrm{L_{MIR,f}} - \mathrm{L_{MIR,bg}})] \times 10^{-3}, \quad (1)$$

where FRP is in kW; $\mathrm{L_{MIR,f}}$ and $\mathrm{L_{MIR,bg}}$ denote the radiance recorded in the MODIS mid-infrared (MIR; 3.9 μm) channel ($\mathrm{W/m^2/sr/\mu m}$) at the fire and background non-fire pixels, respectively; $\mathrm{A_{samp}}$ is the MODIS ground sample area at the relevant scan angle of the observation. The middle infrared region of the electromagnetic spectrum is particularly suited to the FRP method, because the radiative energy component as given by the Planck function for temperatures consistent with wildfires (i.e. 1000–2000 K) is approximately ten times greater than the emittance of the Earth's ambient surface in this wavelength region (Wooster *et al.* 2005).

The integration of FRP over the lifetime of the fire provides a means to calculate the Fire Radiative Energy (FRE), which is the total energy radiated by the fire (i.e. the area under the FRP with time curve). FRE has been experimentally demonstrated to be directly proportional to the total amount of fuel combusted (Kaufman *et al.* 1998; Wooster 2002; Roberts *et al.* 2005; Wooster *et al.* 2005). The underlying assumption of the FRP method is that if sufficient observations are made during the fire, it should be possible to well characterize the FRP with time curve (e.g. see Roberts *et al.* 2005). Remote instantaneous measures of FRP can be produced using the MODIS 'active fire product'. Apart from this product (i.e. MOD14), other sensor systems are being evaluated to characterize both FRP and FRE measures from wildfires. Wooster *et al.* (2003) used the Bi-directional InfraRed Detection (BIRD) sensor to measure FRE from Australian fires; Roberts *et al.* (2005) measured FRP with the Spinning Enhanced Visible and Infrared Imager (SEVIRI), and Wooster *et al.* (2005) used 4-km spatial-resolution imagery from the Geostationary Operational Environmental Satellite (GOES-8) sensor to detect MIR fire pixels. Although MODIS affords a temporal resolution of >2 images per day, via both the TERRA and AQUA satellites, this temporal sampling interval is only sufficient for a 'snap-shot' estimate of FRP. In contrast, research with both aerial systems (e.g. Riggan *et al.* 2004) and the geo-stationary SEVIRI satellite sensor (Roberts *et al.* 2005) have allowed near-continuous FRP measurements.

FRP data from MODIS were recently used to compare energy radiated from boreal forest fires in Russia and in North America (Wooster and Zhang 2004). The Russian fires radiated considerably less energy and subsequently released fewer emissions than American fires, owing in part to a difference in dominant fire type. Fires in Russian boreal forests are typically driven by surface fuels and burn less fuel per unit area, in contrast with the more intense crown fires that burn more fuel per unit area in North America. Mottram *et al.* (2005) supported these findings, by demonstrating that the observed FRP differences were not due to associated sensor effects. In a further application of FRP, Smith and Wooster (2005), in a study in African savannas, demonstrated that the FRP of backing fires was an order of magnitude lower than that observed in heading fires, a finding consistent with field measures of fire-line intensity (Trollope *et al.* 1996). Therefore, FRP could potentially be used to remotely discern the fire type that burned an area. Additionally, as the conductive component of the energy might be expected to impact post-fire processes, more research is needed to understand the relationships between FRP and impacts on soil, forest floor, and vegetation recovery.

Remote assessment of post-fire effects

The assessment of short- and long-term fire effects on local, regional, and global processes has been conducted using a wide range of *in situ* and remote methods (Table 3). The application of remotely sensed imagery to monitor and assess the impacts of fire on local and regional environments can be broadly divided into:

1. Burned area and perimeter methods; and
2. Methods that assess a surface change (cover, fuel, etc.) caused by the fire.

Burned areas, fire perimeters, and spatial heterogeneity

The simplest and most common remote measure of post-fire effects is a map of the area burned. The raster nature of digital imagery naturally lends itself to burn area mapping. A fire perimeter map is a vector representation of the burn area boundary that can be rendered digitally from remotely sensed imagery or by moving along the burn area boundary on the ground with a global positioning system (GPS). Reliance on overhead imagery is increasing as it offers a bird's-eye view of burned areas and therefore has a decided advantage over field fire perimeter maps, which often fail to capture the heterogeneity and patchiness of fires and fire effects. Yet field fire perimeter maps will remain important not only for validation purposes, but when the atmosphere

Table 3. Selected examples of measures of post-fire effects
VIS-MIR, visible, mid-infrared

Characteristic description	How measured	Reference examples
Char and ash cover	*In situ* measurements	Smith *et al.* (2005*b*)
	Aerial photographs	Smith and Hudak (2005)
	VIS-MIR sensor imagery	Landmann (2003)
Surface temperature changes	*In situ* measurements	Trigg and Flasse (2000)
	Thermal infrared imagery	Kaufman *et al.* (1998)
Surface reflectance changes	*In situ* measurements	Trigg and Flasse (2000)
	VIS-MIR sensor imagery	Fuller and Fulk (2001)
Area burned and fire perimeters	*In situ* records	Eva and Lambin (1998*a*)
	VIS-MIR sensor imagery	Pereira (1999)
Vegetation consumption	Field	Lenihan *et al.* (1988); Cocke *et al.* (2005)
	VIS-MIR sensor imagery	Hall *et al.* (1980); Miller and Yool (2002)
Vegetation mortality	Field	Wyant *et al.* (1986); Cocke *et al.* (2005)
	VIS-MIR sensor imagery	Patterson and Yool (1998)
Vegetation recovery	Field	Lyon and Stickney (1976); Anderson and Romme (1991); Turner *et al.* (1997); Lentile (2004)
	Changes in multi-date imagery	Henry and Hope (1998); Díaz-Delgado *et al.* (2003)
Canopy scorch	Field	Ryan and Reinhardt (1988); McHugh and Kolb (2003)
Soil charring	*In situ* measurements	DeBano *et al.* (1979); Lewis *et al.* (2006)
	Hyperspectral imagery	Laes *et al.* (2004)
Soil water repellency	*In situ* measurements	Lewis *et al.* (2006); Doerr *et al.* (2000)
	Hyperspectral imagery	
Atmospheric chemistry changes	Atmospheric sounders	Spichtinger *et al.* (2001)

is too cloudy or smoky (a problem minimized using infrared imagery) to obtain useable imagery, and when the remotely sensed data is not available when needed. 'Real-time' data acquisition, however useful to map burned areas, is commonly constrained by logistical and economic factors. More thorough reviews of the comparatively large body of burn area mapping via remote sensing literature have already been accomplished (e.g. Barbosa *et al.* 1999*b*; Pereira 2003), so here we will only note a few key research papers and previous reviews.

Remote assessment of burned areas has been conducted using a wide variety of aerial and satellite sensors. Since the 1980s, the majority of techniques have been developed for data acquired from the AVHRR sensor, and as such were restricted to a limited number of reflectance and thermal bands (Flannigan and Vonder Haar 1986; Kaufman *et al.* 1990; Setzer and Pereira 1991; Kasischke and French 1995; Razafimpanilo *et al.* 1995; Fernandez *et al.* 1997; Randriambelo *et al.* 1998; Barbosa *et al.* 1999*a*, 1999*b*; Fraser *et al.* 2000; Al-Rawi *et al.* 2001; Fuller and Fulk 2001; Nielsen *et al.* 2002). Although data from the AVHRR sensor is restricted by a relatively large pixel size (i.e. 1.1 km), global data have been obtained from a series of different satellites for over 20 years, and importantly, these data can be obtained at no cost. These data have enabled the long-term monitoring of large-scale fires in remote and isolated areas (e.g. African savannas and boreal regions). In more recent years, other sensors have been developed that provide a greater selection of bands.

These sensors, which have also been used to evaluate burned area, include the Advanced Long Track Scanning Radiometer (Eva and Lambin 1998*a*; Smith *et al.* 2002), MODIS (Roy *et al.* 2005), SPOT-VEGETATION (Stroppiana *et al.* 2002; Silva *et al.* 2003; Zhang *et al.* 2003), and Landsat (Salvador *et al.* 2000; Russell-Smith *et al.* 2003; Holden *et al.* 2005). Several regional-scale products also exist that apply tailor-made algorithms to various satellite sensors (i.e. GBA2000, GLOBSCAR, the MODIS burned area product, etc.). Essentially, until recently (e.g. MODIS on TERRA and AQUA), there was not a space-based system design specifically to 'look' at terrestrial Earth. Previous to MODIS, most other sensor systems (e.g. AVHRR – an atmospheric mission), were opportunistic exploitations of band ratios for terrestrial products (e.g. NDVI).

The vast majority of satellite-based burned area mapping studies use information on differences in spectral or thermal properties of a land surface before and after a fire (e.g. Eva and Lambin 1998*a*, 1998*b*; Barbosa *et al.* 1999*a*, 1999*b*; Fraser *et al.* 2000; Fuller and Fulk 2001; Nielsen *et al.* 2002). Novel spectral indices including the Burned Area Index (Chuvieco *et al.* 2002), a thermal variation of the Global Environmental Monitoring Index (Pereira 1999), different thermal variations of the VI-3 index (Barbosa *et al.* 1999*a*, 1999*b*), thermally enhanced variations of common indices (Holden *et al.* 2005), and the Mid-infrared Bispectral Index (Trigg and Flasse 2001) have recently been developed and tested. A limited number of studies have also investigated the utility of principal components analysis (Richards and Jia 1999; Garcia-Haro *et al.* 2001; Hudak and Brockett 2004), texture analysis (Smith *et al.* 2002; Hann *et al.* 2003), spectral mixture analysis (Cochrane and Souza 1998; Sa *et al.* 2003), and neural networks (Al-Rawi *et al.* 2001). Although most studies do compare a suite of several methods within their particular study areas (e.g. Pereira 1999; Chuvieco *et al.* 2002; Holden *et al.* 2005), there still exists a need to assess how such methods work over the wide range of fire-affected environments.

Remotely sensed data have been used to retrospectively produce fire history, frequency, and perimeter information (Chuvieco and Congalton 1988; Salvador *et al.* 2000; Hudak and Brockett 2004; Holden *et al.* 2005), although the data availability can limit such approaches. Such data are of immediate use to land managers in the United States as a potential surrogate for fire perimeter data, ‘digital fire polygon histories’ or ‘fire atlases’, which are typically collated after the fire (sometimes weeks, months or years later) using a combination of paper records, aerial photographs, and local experience (Morgan *et al.* 2001). Land management agencies in the United States including the National Park Service (NPS) and the United States Forest Service (USFS) have begun developing atlases of burned area (or fire atlases) from satellite imagery, field maps, and aerial photographs as part of fire management efforts. As yet, no standardized protocol has been developed for building digital fire perimeter layers, which may lead to questionable quality, accuracy, and reproducibility of atlases developed from these data sources (Morgan *et al.* 2001).

Fire atlases provide perspectives on the location and spatial distribution of fires on the landscape. Limitations include the relative lack of details on the spatial variation within fires, as well as the changes in mapping standards, methods, and recording over time (Morgan *et al.* 2001). The overall accuracy is largely unknown. Remote sensing has great potential to supplement existing information on fire regimes by enabling researchers to acquire data at broad spatial scales, in areas where fire atlases do not exist, and in previously inaccessible areas. However only ∼30 years of satellite images and ∼70 years of aerial photographs are available now, and many people want to characterize fire regimes over much longer time intervals, and across areas exhibiting a range of land use practices.

High-to-moderate spatial resolution (pixel sizes between 1 and 30 m) satellite sensors, such as IKONOS, SPOT, and Landsat, enable the assessment of the degree of heterogeneity within large and remote fires. Turner *et al.* (1994) used Landsat TM imagery to explore the effects of fire on landscape heterogeneity following the 1988 Yellowstone fires. Smaller patches (<1250 ha) were often more heterogeneous in fire effects, whereas larger patches were more homogeneous in effects (Turner *et al.* 1994). The heterogeneity of fire effects in patches of various size, shape, and distance from living vegetation differentially impact species and influence successional trajectories (Picket and White 1985; Turner *et al.* 1999). The fine-grained pattern of living and dead vegetation in patches ranging from square meters to thousands of hectares has major implications for recovery processes. Fire effects on soil and vegetation recovery rates may vary according to the specific interactions between fire behavior and available fuels (Ryan and Noste 1985; Agee 1993; Turner and Romme 1994; DeBano *et al.* 1998). Remote sensing has great potential for studying fine-scale heterogeneity in fire effects across large areas; such studies could help us understand the causes and consequences of spatial variability in active fire characteristics and post-fire effects.

Remotely-sensed estimates of post-fire heterogeneity and spatial arrangement of burned patches have also been used to explore causal relationships (Rollins *et al.* 2001; Ruiz-Gallardo *et al.* 2004), to document rates of recovery (Turner *et al.* 1994; Lentile 2004), and to prioritize areas for fuels reduction (Hardy *et al.* 1998, 1999) and post-fire rehabilitation (Parsons 2003). Variation in fire effects due to weather, topography, and vegetation type and structure occurs even within large fires (Eberhardt and Woodard 1987; Turner *et al.* 1994), and heterogeneous or ‘mixed’ effects occur at some scale in all fires. Remotely sensed data allow researchers to conduct multi-scale and spatially explicit analyses of fires relative to topography, pre-fire vegetation structure or composition, and land use. Rollins *et al.* (2001) found that the area burned in 20th century fires in the Gila/Aldo Leopold Wilderness Complex (New Mexico) and the Selway-Bitterroot Wilderness areas (Idaho and Montana) was influenced by elevation, drought, and land use. Lentile (2004) found that pre-fire vegetation as influenced by stand history and abiotic gradients was the best predictor of post-fire effects and subsequent vegetation recovery in ponderosa pine forests of the South Dakota Black Hills. Turner *et al.* (1997) found significant effects of burn severity on most biotic responses including seedling density and cover following the Yellowstone fires. However, geographic location, particularly as it related to broad-scale patterns of serotiny in lodgepole pine (*Pinus contorta*), was the most important variable influencing forest reestablishment and pathways of succession (Turner *et al.* 1997). Post-fire tree regeneration is dependent on adequate seed dispersal and favorable microsite conditions, which are in turn related to competitive interactions at fine scales, and landscape position (i.e. elevation, slope, and aspect) at broad scales (Turner *et al.* 1994, 1997; Chappell and Agee 1996). Identification of factors influencing vegetation dynamics at multiple spatial scales will improve our understanding of how post-fire environmental heterogeneity relates to fuel accumulations and burn severity patterns in forested landscapes.

Remote assessment of surface change

The analysis of post-fire effects from satellite imagery is not a new concept. Hall *et al.* (1980) classified multi-temporal Landsat Multi-spectral sensor data of tundra fires in north-western Alaska into light, moderate, and severe fires as defined by the abundance of live post-fire vegetation. Over the next 20 years, others assessed the correlation of satellite data with different ground-based inferences of fire severity relating to vegetation consumption (Milne 1986; Miller and Yool 2002) and mortality (Patterson and Yool 1998).

Although the majority of remote assessments of post-fire effects have employed moderate spatial-resolution imagery from the Landsat sensor (30 m) (e.g. Fiorella and Ripple 1993; Turner *et al.* 1994; Viedma *et al.* 1997), other sensors such as SPOT XS (Henry and Hope 1998) and AVIRIS (Riaño *et al.* 2002) have also been used. Furthermore, the use of temporal series (Henry and Hope 1998; Kushla and Ripple 1998; Díaz-Delgado *et al.* 2003) and transformations (Henry and Yool 2002) are widespread. A wide range of remote sensing approaches have been applied across a diversity of fire regimes and environments including temperate coniferous stands in Oregon (Fiorella and Ripple 1993), chaparral vegetation in California (Henry and Hope 1998; Riaño *et al.* 2002), forested shrublands of southern Spain (Viedma *et al.* 1997), and coniferous forests of Yellowstone National Park (Turner *et al.* 1994).

The NDVI has been widely used to assess post-fire vegetation regrowth. This is appropriate as long as direct change in green vegetation cover is the main ecological process being measured. Several studies have applied NDVI and similar spectral indices to remotely assess post-fire effects (Fiorella and Ripple 1993; Henry and Hope 1998; Díaz-Delgado *et al.* 2003).

Significant developments in the spectral analysis of post-fire effects were made by Ekstrand (1994), who used field data, aerial photographs, and Landsat bands 4 and 5 to assess the degree of defoliation in Norway spruce stands in Sweden following fire. White *et al.* (1996) used field data, post-fire aerial photographs, and Landsat data within a variety of vegetation types in the Flathead National Forest and Glacier National Park, Montana, to compare remotely sensed measures of severity. However, these techniques in general do not relate actual spectral reflectance or brightness temperature collected *in situ* to changes in radiance or thermal emittance as measured by the satellite sensor. In contrast, the development of two spectral indices, namely the mid-infrared bispectral index (MIRBI) for burned savanna surface assessment (Trigg and Flasse 2001) and the NBR (Eqn 2) for 'burn severity' assessment of forested regions (Key and Benson 2002; Brewer *et al.* 2005), incorporate information of the spectral changes at the surface to infer post-fire effects.

$$\mathrm{NBR} = (\rho_4 - \rho_7)/(\rho_4 + \rho_7) \tag{2}$$

where ρ_4 and ρ_7 are the surface spectral reflectances as measured in bands 4 (0.76–0.90 μm) and 7 (2.08–2.35 μm) of the Landsat Enhanced Thematic Mapper (ETM+) sensor.

Through collection of the spectral reflectance of pre- and post-fire surfaces, both of these methods incorporate the observed decrease in spectral reflectance in the visible–mid-infrared region with a corresponding increase in mid-infrared (2.2 μm) reflectance. Although MIRBI was developed purely for burned area assessment, NBR and dNBR are widely being used to assess landscape-scale post-fire effects in the USA (Key and Benson 2002; van Wagtendonk *et al.* 2004; Brewer *et al.* 2005; Cocke *et al.* 2005) and in southern African savannas (e.g. Roy *et al.* 2005; Smith *et al.* 2005*b*). The band ratio that is now commonly referred to as NBR was initially developed and used by Lopez-Garcia and Caselles (1991) using ratios of Landsat bands 4 and 7 to map burned areas in Spain. In addition to measuring burned area, NBR is used to infer the degree of post-fire ecological change.

van Wagtendonk *et al.* (2004) used the AVIRIS airborne hyperspectral sensor (a spectral instrument with 224 bands over the visible to mid-infrared range) to demonstrate that the largest spectral decrease in visible–near infrared reflectance between pre-fire and post fire occurred at AVIRIS bands 47 (0.788 μm) and 60 (0.913 μm), whereas the largest spectral increase at mid-infrared wavelengths occurred at AVIRIS band 210 (2.370 μm). This research suggested that an improved NBR index could be used if imagery were available with these wavelengths. In a similar fashion, Smith *et al.* (2005*b*) used ground-based spectroradiometer data in southern African savannas to evaluate which Landsat spectral band ratios could best characterize fire severity, as defined by the duration of the fire at a point. Smith *et al.* (2005*b*) demonstrated that simple ratios of the blue, green, or red bands with the Landsdat SWIR (band 7) band each outperformed NBR. Therefore, NBR may not be the optimal remote indicator of post-fire effects, particularly in grasslands and shrublands. Further research to evaluate other approaches is warranted.

Others have sought to develop spectrally-derived post-fire effect metrics based on the spectral reflectance of post-fire surfaces. The spectral reflectance of such surfaces can provide important insights into the degree of combustion completeness within the fire (McNaughton *et al.* 1998; Landmann 2003). Incomplete combustion produces residual carbon residue termed char or black ash (Robinson 1991; Trigg and Flasse 2000; Smith *et al.* 2005*a*), whereas complete combustion produces incombustible mineral residue termed white ash (Landmann 2003; Smith *et al.* 2005*b*). The quantity of white mineral ash produced per unit area could therefore be considered a measure of fuel consumption (Landmann 2003; Roy and Landmann 2005; Smith and Hudak 2005).

As stated earlier, in most environments and fire regimes, fires result in a net decrease in visible and near-infrared reflectance due to deposition of black char onto the surface (Robinson 1991; Eva and Lambin 1998*a*). This assumption is not always valid as complete combustion of large woody debris or large quantities of other fuels can produce patches of white mineral ash (i.e. silica), which is highly reflective (i.e. >50%) between 0.3 and 2.5 μm (Landmann 2003; Roy and Landmann 2005; Smith and Hudak 2005; Smith *et al.* 2005*b*). In savannas, the post-fire surface reflectance typically decreases initially (<20 min) as black ash replaces green vegetation, then increases when fires of long duration produce increasing quantities of white ash (Roy and Landmann 2005; Smith *et al.* 2005*b*). Smith *et al.* (2005*b*) demonstrated that in order for remotely sensed imagery to detect the spatial density of common white ash patches produced in woodland savanna fires, imagery with pixel sizes less than 5 m are needed and as such, Landsat or imagery of similar spatial resolution (i.e. 15–60 m) are not suitable. Such a fine spatial resolution (i.e. 1–5 m) to detect patches of grey ash (which is simply a mixture of black and white ash) may be suitable in forested environments, where owing to higher fuel loads, the potential white ash patch density might be more significant (Smith and Hudak 2005; Smith *et al.* 2005*b*). Therefore, in addition to remote sensing producing coarse-scale measures of area burned, very high spatial resolution imagery can potentially allow the remote assessment of more localized post-fire effects such as soil water repellency and vegetation mortality.

Field assessment of active fire and post-fire effects

The assessment of active fire and post-fire effects using remotely sensed data relies on a thorough understanding of what precise measure or process is being recorded on the ground. There are few, if any, consistent, quantifiable indicators of active and post-fire effects that are linked to remotely sensed data. Even ground-based indicators of fire effects are largely qualitative. Most studies have not incorporated scales of spatial variability in fire effects, thus limiting inferences that can be drawn from remotely sensed imagery. A lack of spatial context limits the confidence that can be placed in data of a particular resolution. Remote sensing has the potential to greatly increase the amount of information available to researchers and managers; however, it is still challenging to adequately characterize enough ground reference locations across the full range of variability in fire effects. Traditional study designs are typically too coarse to account for the varying scales of spatial complexity of fire effects. Field sampling to verify and characterize remotely sensed data must include sampling across the full range of variability in topography and vegetation structure and composition, in a time frame that will allow comparison between data sets. Quantification of the spatial variability of active and post-fire effects will provide a better understanding of the relevant scales at which research questions can be addressed with remotely sensed data, and facilitate more effective and accurate application and interpretation of these data.

Field measures of active fire effects

Field measures of active fire characteristics have traditionally included *in situ* measures such as fire-line intensity, flame length, and rate of spread of the fire front (Byram 1959; Albini 1976; Alexander 1982; Trollope and Potgieter 1985; Trollope *et al.* 1996), whereas more recent techniques have involved monitoring the temperature generated by the fire through the use of thermal infrared cameras (e.g. Riggan *et al.* 2004), spectroradiometers (Wooster 2002), heat sensitive crayons and paints (Hely *et al.* 2003), and thermocouples (Stronach and McNaughton 1989; Stocks *et al.* 1996; Ventura *et al.* 1998; Molina and Llinares 2001; Smith *et al.* 2005*b*). In addition to instruments estimating fire thermal characteristics, other active fire characteristics can include assessment of trace gases within smoke plumes (Yokelson *et al.* 1996, 2003), which have important implications for regional air quality (Hardy *et al.* 2001), and *in situ* assessment of fuel combusted (Trollope *et al.* 1996; Smith *et al.* 2005*a*).

The assessment of such parameters ideally requires unfettered access and timely (i.e. rapid response) measurements, both of which are often impractical during wildfires owing to safety concerns. Remote locations of many fires make accessibility difficult. The application of remotely sensed optical and thermal imagery over large fires is a very important and necessary tool from the standpoint of both researchers and land resource managers.

Field measures of post-fire effects

Field-based measures of fire effects have included an assessment of the change in soil color (Wells *et al.* 1979; Ryan and Noste 1985; DeBano *et al.* 1998; Neary *et al.* 1999); soil infiltration and hydrophobicity (DeBano 1981; Neary *et al.* 2004; Lewis *et al.* 2006); change in vegetation char and ash cover (Landmann 2003; Smith 2004) and amount of canopy scorch (Ryan and Reinhardt 1988; McHugh and Kolb 2003); tree scarring (Barrett *et al.* 1997; Grissino-Meyer and Swetnam 2000; Lentile *et al.* 2005), and organic fuel consumption (Lenihan *et al.* 1988). In an attempt to integrate a variety of these different post-fire effect measures, Key and Benson (2006) developed the ground-based Composite Burn Index (CBI). The CBI is based on a visual assessment of the quantity of fuel consumed, the degree of soil charring, and the degree of vegetation rejuvenation (van Wagtendonk *et al.* 2004). CBI was designed as a field-based validation of the post-fire NBR spectral index. Fire effects on 30 × 30 m sample plots in five strata (soils, understory vegetation, mid-canopy, overstory, and dominant overstory vegetation) are evaluated individually and later combined for an overall plot-level burn severity value. The CBI method is rapid but very subjective.

Management use of remote sensing fire effects products

Remote sensing has the potential to provide data to address pre-, active, and post-fire characteristics over broad spatial scales and remote areas. However, the utility of such data is determined by temporal availability, spectral and spatial resolution of data, ground-truthing, and accurate interpretation at appropriate scales. Additionally, integral to the advancement of remote sensing science is the quantification of variables that relate reflected or emitted radiation to ground and canopy combustion processes.

'Severity classifications' and implications for recovery

The occurrence of areas with similar fire environments, behaviors, and effects have led to the use of 'severity classes' within both the ecological and remote sensing literature (Ryan and Noste 1985; DeBano *et al.* 1998; Patterson and Yool 1998; Robichaud *et al.* 2000; Isaev *et al.* 2002; Díaz-Delgado *et al.* 2003). Yet there is considerable variation in low, moderate, and high severity classifications across regions and vegetation types (Fig. 1). Additionally, such burn severity classes have been inconsistently characterized in the remote sensing literature (Table 4). Many studies have relied on Ryan and Noste's (1985) field characterization of post-fire effects and consistent visual assessment of ground and canopy fire effects (White *et al.* 1996; Ruiz-Gallardo *et al.* 2004). Ryan and Noste's (1985) classification provided a physical description for assessing the heat impact on overstory and understory vegetation, fuels, litter, and soils. This model has been particularly useful to classify remotely sensed data because the discriminating features are detectable from satellite data (White *et al.* 1996). However, in forested environments, remotely sensed burn severity maps are often highly correlated with fire effects on overstory vegetation and exhibit low correlations with ground and soil variables where the vegetation occludes the ground (Patterson and Yool 1998; Hudak *et al.* 2004). Satellite imagery integrates changes in all parts of the forest, illuminating areas of low canopy closure; thus, field assessment is necessary to verify which parts of the soil and vegetation strata are affected (White *et al.* 1996; Hudak *et al.* 2004; Cocke *et al.* 2005; Epting *et al.* 2005).

The degree of post-fire change typically increases with increasing vegetation mortality and proportion of charred soil and vegetation, and is linked with long duration of soil heating. For example, high burn severity classes are attributed to areas with high quantities of reddened soil and charred fuels and vegetation, but high burn severity may differentially impact ecosystem function depending on the pre-fire environment and vegetation types. For example, high burn severity resulting in increased water repellency may be common in California chaparral systems, yet rare in Alaska black spruce (*Picea mariana*) forests owing to major differences in pre-fire soil and forest floor conditions, vegetation characteristics, and the relative occurrence of hydrophobic conditions (Fig. 1). Fires of all sizes will have some very localized effects that could be classified as high severity, and heterogeneous mosaics of fire effects occur at some scale in all fires (Fig. 2). The scale and homogeneity of fire effects is important ecologically. Often, larger fires and large patches within fires are dominated by high severity components (Turner *et al.* 1994; Graham 2003). Hudak *et al.* (2004) suggested that high severity fires resulted in more spatially homogeneous fire effects on soil and vegetation than moderate or especially low severity fires, whereas Turner *et al.* (1994) found that large burns (~500–3700 ha) tended to have a greater percentage of crown fire and a smaller percentage of light surface burns. Such severely burned areas may be more vulnerable to invasive species and soil erosion and may not return to pre-fire conditions for extended time periods. Patch size and the spatial mosaic of severity exert a strong influence on vegetation and nutrient recovery. Extensive areas of high burn severity may have fewer resprouting individuals or surviving trees to provide seeds (Turner *et al.* 1999). Unburned or lightly burned patches within high severity regions may provide seed sources to increase rates of plant recovery. The post-fire environment may change greatly within 1 year, some aspects of which may be predictable, whereas others may be more driven by local and regional weather. Thus, depending on the timing and extensiveness of the field data collection effort, it is possible, for example via geostatistical kriging techniques, to infer ecological processes from remotely sensed landscape patterns of fire effects and use this information to guide post-fire planning decisions.

Table 4. Selected examples of approaches that remotely assess degree of post-fire change

Approach to divide classes of post-fire effects	No. classes	Reference
No. fine branches remaining on woody plants	7	Díaz-Delgado *et al.* (2003)
Complete and partial stand mortality	2	Isaev *et al.* (2002)
Weighted carbon storage in different fuel components	3	Zhang *et al.* (2003); Conard *et al.* (2002); Conard and Ivanova (1997)
USFS fire classification rules (cf. Cotrell 1989) – degree of canopy and soil organic matter consumption	4	Patterson and Yool (1998)
Fuel consumption and proportion of grey ash endmember	2	Landmann (2003)

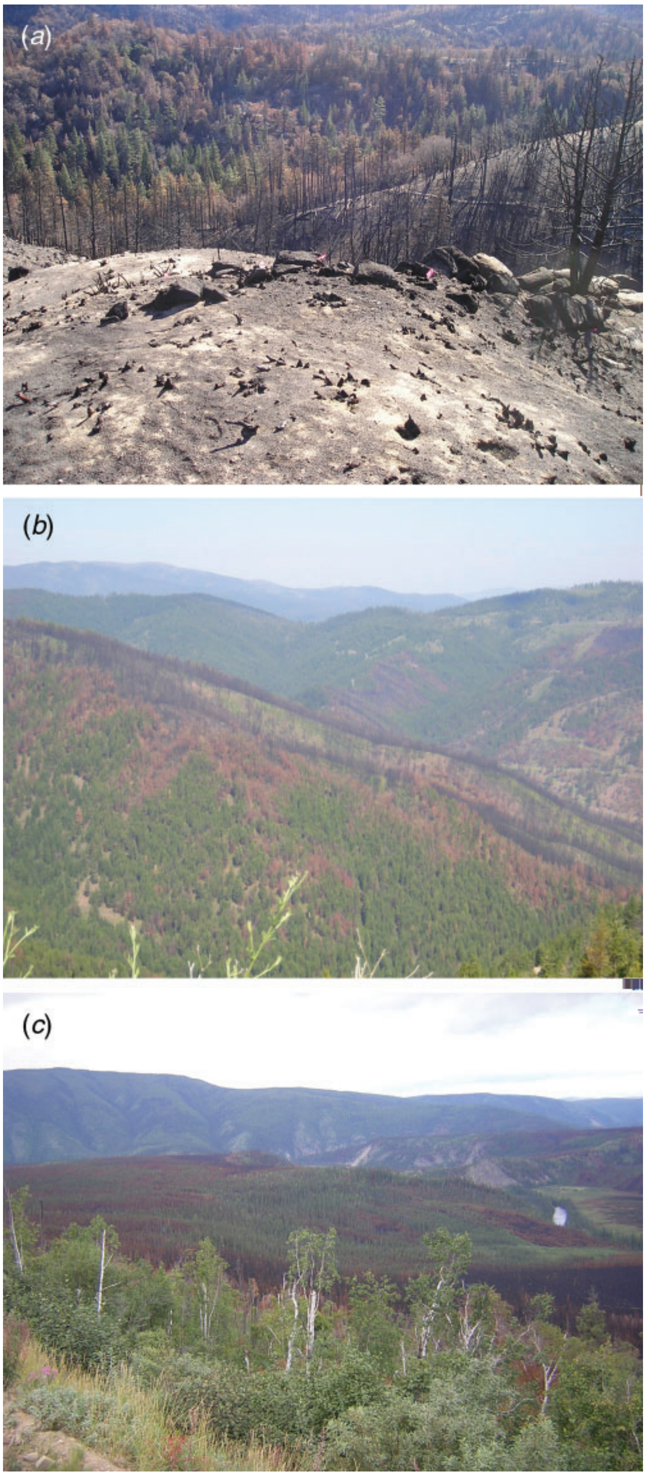

Fig. 2. Landscape-scale heterogeneity following fires. (*a*) California, (*b*) Montana, and (*c*) Alaska.

Current applications of remote sensing fire effects products

The USFS Remote Sensing Applications Center (RSAC) and the USGS EROS Data Center (EDC) provide satellite imagery and image-derived products for managing and monitoring wildfires. RSAC produces Burned Area Reflectance Classification (BARC) maps for use by BAER teams to identify social, ecological, and economic values at risk. BARC products are based on dNBR values or, if pre-fire imagery is unavailable, then NBR values, from satellite imagery such as Landsat TM, Landsat Enhanced Thematic Mapper Plus (ETM+), SPOT, Multispectral (SPOT-Xi), and MODIS.

BARC maps are made as soon as possible during a significant wildfire event. These preliminary maps of post-fire condition are assessed and modified by BAER teams to aid in planning and implementing erosion mitigation in severely burned areas. BARC maps measure satellite reflectance and may be used by BAER teams to develop burn severity maps. BAER teams are assigned to measure and map severity based on ground and soil characteristics rather than canopy vegetation (Miller and Yool 2002; Parsons and Orlemann 2002; Lewis *et al*. 2006). However dNBR and NBR correlate more highly to vegetation attributes, especially those of dense upper canopy layers, rather than ground and soil attributes (Hudak *et al*. 2004).

Post-fire maps may substantially vary depending on when and how burn severity is assessed and for what objectives (Fig. 3). In many cases, managers have abandoned traditional sketch maps based on ground and helicopter surveys and have become dependent on the Landsat sensor and its associated BARC products to provide short-term decision support. There are varying levels of confidence associated with remote sensing products, and even very experienced managers need better initial ground validation and longer-term monitoring protocols to build confidence in these products. In a comparison of field validations of BARC maps, Bobbe *et al*. (2003) found the dNBR to be no more accurate than NBR for indicating immediate post-fire effects. Some BAER teams have opted to use a combination of available imagery, existing geographic information system (GIS)-based maps of topography and pre-fire forest condition, and local knowledge to guide post-fire assessments (Fig. 3). Severity assessments often fail to specifically identify whether vegetation, soil, or erosion potential was low, moderate, or high, but have nonetheless been used to guide management activities such as post-fire timber harvest and reforestation activities. Often those other management activities would be better served with dNBR-based assessments using post-fire images taken 1 or 2 years post fire, accompanied by extensive ground-truthing (Cocke *et al*. 2005).

Determining the scale appropriate for management decisions may help to streamline approaches to post-fire rehabilitation. For example, it is often assumed that high burn severity classes are positively correlated with increasing soil water repellency (Doerr *et al*. 2000). Many studies have shown that pre-fire soil texture, the amount and depth of litter cover, soil water, soil organic matter, and the temperature and residence time of the fire all affect the degree of soil

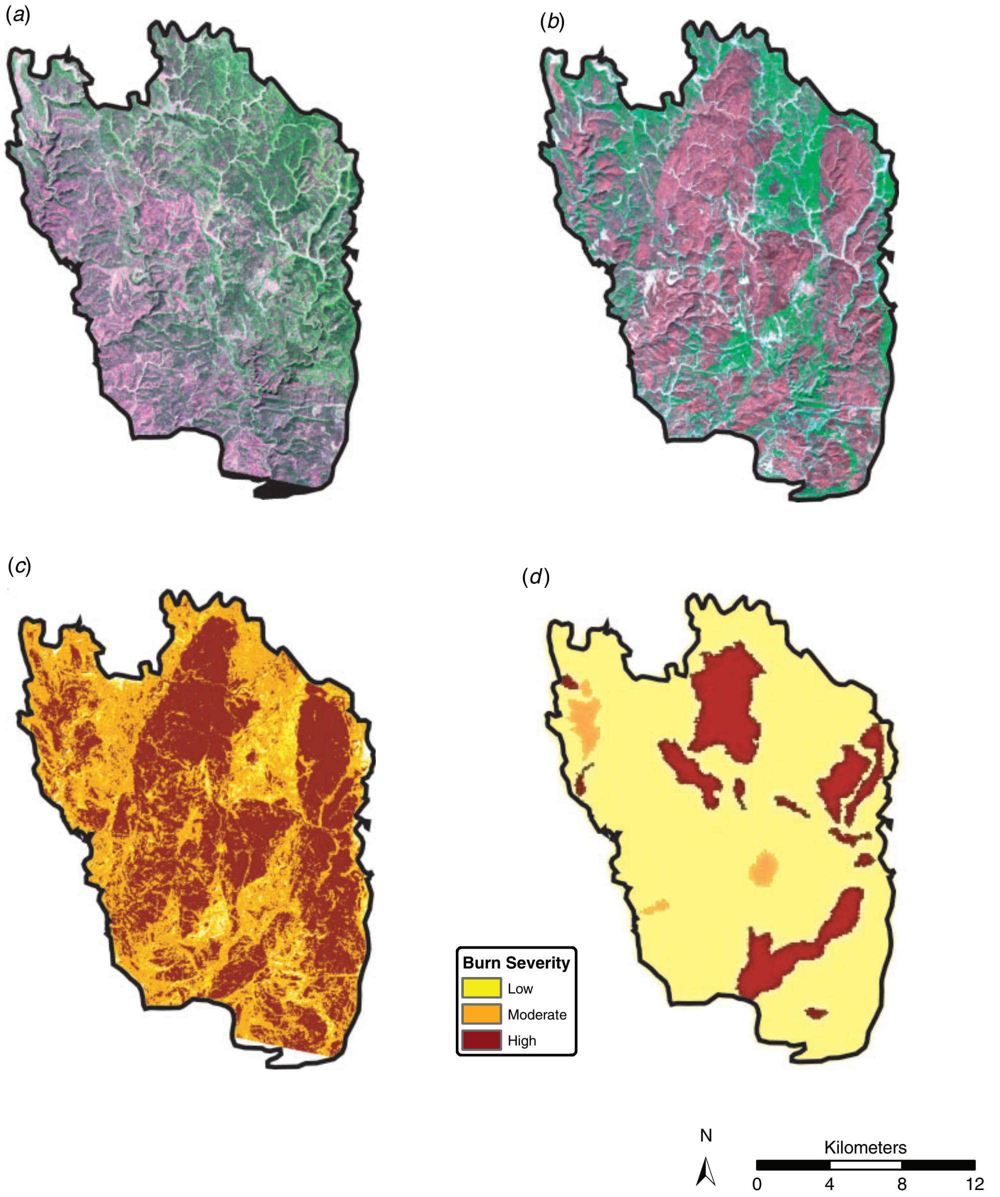

Fig. 3. (*a*) Pre-fire Landsat 7 image (7-4-3 false-color composite) acquired on 18 August 1999; (*b*) post-fire Landsat 7 image (7-4-3 false-color composite) acquired on 14 September 2000; (*c*) burn severity map produced for the Jasper fire in the South Dakota Black Hills from images in (*a*) and (*b*) according to dNBR methods (Key and Benson 2006); (*d*) burn severity map produced by the BAER team for the Jasper fire using a single date post-fire Landsat image, geographic information system-based maps of topography and pre-fire forest condition, and field assessment.

modification during fires and the resulting soil water repellency (Giovannini and Lucchesi 1997; Doerr *et al*. 2000; Wondzell and King 2003). Laes *et al*. (2004) attempted to use airborne high spatial/spectral resolution (4 m/224 bands) hyperspectral imagery to identify surface water-repellent soils over the Hayman fire in the summer of 2002. Hyperspectral imagery may have the potential to indirectly detect soil water repellency via detection of an ash signal in the soil (Lewis *et al*. 2006). Processing of hyperspectral data is time-consuming, and protocols are not yet standardized for interpreting fire effects. Furthermore, data acquisition is comparatively expensive and logistically challenging, particularly if accomplished via aircraft in an active fire zone. Further study is needed to learn whether such high spatial and/or spectral resolution is needed to capture soil microsite heterogeneity, or if the resolution of 20 m SPOT-Xi (4 bands) or 30 m Landsat-TM (6 bands) imagery may be adequate for BAER teams to identify large areas at risk of erosion, sedimentation, and landslide events. Rapid and defensible delineation of large, severely burned areas with high potential for erosion could reduce the time necessary for BAER teams to conduct evaluations, improve recommendations for treatment, and decrease the amount of money spent on rehabilitation projects.

Remote sensors have the potential to be used for carbon budget investigations (Conard *et al.* 2002). Fires release carbon that is stored in trees, shrubs, and herbaceous vegetation, litter, duff, and even the soil if the fire is intense and long-lasting. Vegetation recovery draws carbon back in from the atmosphere. The dNBR technique is currently being applied by researchers around Yosemite National Park, CA, to estimate fire-use emissions and monitor air quality. Other management applications of the dNBR include production of GIS-based fuel layers in Glacier National Park, MT, and Grand Teton National Park, WY, as well as identification of extreme fire risk zones and propensity for post-fire erosion and landslides around the Salmon-Challis National Forest in Idaho. For more information, see http://www.nrmsc.usgs.gov/research/ndbr.htm and http://giscenter.isu.edu/research (verified 29 June 2006).

Future directions of fire-related remote sensing research

The influence of fire spans a wide range of temporal and spatial scales, and the interpretation of causal factors, fire effects, and ecological responses is a challenge to both research and management. As outlined in the present review, current fire effects terminology is used inconsistently. However, simply classifying remotely sensed measures as either active or post-fire characteristics is difficult as the effects of fires vary temporally and with topography and vegetation, and multiple current and new sources of remote sensing data continue to accrue. Challenges remain in how to infer active and post-fire characteristics using remotely sensed data.

Challenges

Landscape-level ecological effects of fires are not well understood

Predicting where on the landscape fires are likely to cause severe short- and long-term ecological effects and understanding why these effects vary are central questions in fire science and management. Remote sensing can help us to characterize the fuels, vegetation, topography, fire effects, and weather before, during, and after fires. Doing so is critical to understanding which factors and which interactions between them are most important in influencing immediate and long-term fire effects at local, regional, and global scales. For instance, low spatial resolution imagery (i.e. 0.25–1 km pixel size) can provide coarse-scale maps of area burned, whereas high spatial resolution imagery (i.e. 1–5 m pixel size) can help provide information on the fine-scale spatial heterogeneity of post-fire effects (e.g. patches of white ash or soil char). For remotely measuring fuel combusted within a fire, an upper constraint can be produced by multiplying the mean fuel load with the broad measure of area burned, whereas detailed imagery can provide information on fine-scale patchiness that is not resolved in the coarse-resolution imagery. The accuracy of estimates of biomass burned will likely be improved by incorporating data from higher spatial resolution imagery.

Studies linking active fire characteristics, post-fire effects, and pre-fire stand conditions are limited

Direct measurement of fire behavior is difficult. More work is needed in this area to understand the dynamics of the tightly interrelated factors of active fire characteristics, post-fire effects, and pre-fire stand conditions. We need to expand remotely sensed systems that characterize real-time energy transfer, and, when possible, avoid attribution of retrospective causality. Mechanistic models based on an understanding of how energy transfer translates to fire effects and post-fire recovery are needed. For example, direct measurement of forest floor consumption and surface-to-canopy fire transition is of crucial value to forest managers for fire management planning. We lack data that connect current stand and vegetation condition to fire behavior and ecological response. In particular, we need improved techniques to detect post-fire effects on the surface where residual canopy density is high or where fire consumes only litter (Patterson and Yool 1998; Holden *et al.* 2005). In these fires, the integration of ground-based and remote measures of active and post-fire effects is especially important.

Remote sensing and field assessments are poorly integrated

The NBR and NDVI indices have been widely used to measure fire-induced vegetation loss. However, these indices and others should be tested against field data (e.g. canopy scorch, tree mortality, ground char, fuels consumption, ash cover) across a variety of vegetation biomes and fire regimes to determine where they are most useful and what they actually measure in terms of post-fire ecological effects. For example, further studies comparing these indices to field data, such as CBI, could help us understand whether values of post-fire ecological change arise from fire effects on canopy, understory vegetation, or soil. Thoughtful combinations of field and remotely sensed data collection, interpretation, and analysis and appropriate application are important to increase confidence in the ability of remote sensing to address many applied questions and to streamline associated costs.

Need to improve analysis at differing spatial and temporal scales

Incorporation of different data sources to refine remotely sensed measures of active fire and post-fire ecological measures would take advantage of the spatial and spectral resolution of different satellite sensors. There are a wide range of potential uses of different sensors, and the appropriate technique and image data sources may depend on the objective of the study. For example, sensor requirements to assess post-fire resprouting of chaparral shrubs are likely different to those of managers trying to assess watershed-level erosion potential following wildfire near homes in southern California. Although Landsat TM and ETM data are most commonly used to assess post-fire ecological effects in North America, application of alternative sensors (ASTER, MODIS, Quickbird, IKONOS, airborne hyperspectral sensors) with varying spectral, spatial, and temporal resolutions warrants further investigation. For example, once ASTER data are available for an area, post-fire tasking of the ASTER TERRA satellite sensor with higher spatial resolution than Landsat in the near-infrared wavelength bands could provide better information about post-fire effects. Furthermore, in comparison with the single short wave infrared (SWIR) band of Landsat that is used in NBR (i.e. Landsat band 7), the ASTER sensor has five SWIR bands. These alternative SWIR bands (or alternative NBR variants) may vary in their effectiveness with soil type and other factors. Many units of the NPS have purchased high spatial resolution Quickbird or IKONOS imagery as part of their inventory and monitoring efforts. These sensors may also provide better information on the potential for fine-scale slope failure, regeneration capacity of vegetation post burn, and the longer-term effects of fire on ecological integrity. Additional research is needed to explore the potential value of airborne sensors that can be continuously tasked to study temporal, as well as high spatial and spectral variations.

Traditional remote sensing platforms are limited to two-dimensional data

The predominant availability of only 2-D satellite sensor data limits inferences about crown height, crown base height, and crown bulk density, all of which influence fire behavior, fire intensity, and hence both fire and burn severity. The availability of light detection and ranging (lidar) systems, and their ability to accurately measure vegetation height, should facilitate studies that incorporate information from both two and three-dimensional data sets to improve estimates of post-fire effects and pre-fire fuel conditions. Lidar has particular potential for assessing crown bulk density, described as the foliage biomass divided by the crown volume, because it does not saturate at high biomass levels (Drake *et al.* 2002; Riaño *et al.* 2003). Crown bulk density has been regarded as one of the most critical variables for modelling crown fire behavior (Scott 1999), because where trees are dense, fire easily spreads from one tree to the other. Lidar is able to detect subtle differences in vertical structure (recording accuracy of 5–15 cm, Baltsavias 1999). Pre-fire lidar can provide a three-dimensional canopy fuels measurement that can be used to describe crown volume and structure. As such, lidar may allow the development of an improved metric for use in crown fire models, instead of the current reliance of models on crown bulk density. Some researchers have integrated multi-spectral and structural (i.e. lidar) data to model canopy fuels (Hudak *et al.* 2002).

Recommendations

Scientists and managers use remote sensing to map, understand, and predict the ecological effects of fire. Much has been learned; challenges remain. Our recommendations for increased effectiveness follow.

Use terminology consistently

Jain *et al.* (2004) recommend that researchers simply report what they are actually measuring (be clear about level of inference in methods), identify the temporal and spatial scale that is being referenced, avoid categorical description (low, moderate, and high, unless defined with range of observations), and define all terminology (active *v.* post-fire effects). We agree. Such an approach should enable scientists to communicate more effectively and managers who juggle a variety of resource objectives to make more informed decisions about where within the fire disturbance continuum to concentrate prevention, suppression, or mitigation efforts (Jain *et al.* 2004). If there is a need to categorize or group different measures, then we advocate limited use of the expressions ‘fire intensity’, ‘fire severity’, and ‘burn severity’ (owing, in many instances, to their clear overlap on the temporal gradient). Instead, we propose that various processes associated with fire intensity and severity be evaluated purely in terms of either active fire characteristics or post-fire effects. As adopted within the present review, active fire characteristics would be concerned with all timely measurements ‘during’ the fire (e.g. information on the heat generated by the fire, the fire duration, the immediate combustion of the biomass, and other ecosystem changes induced by the fire process), which could include the flaming, smouldering, or residual combustion stages. These are the direct, first-order fire effects (Reinhardt *et al.* 1997, 2001). In contrast, post-fire effects would involve all measurements acquired after the fire has passed (e.g. soil charring, nutrient changes, surface spectral changes, vegetation response). These are the indirect, second-order fire effects (Reinhardt *et al.* 1997, 2001).

Quantify and validate metrics of post-fire effects

There are no consistent indicators or classifications of post-fire effects (Morgan *et al.* 2001). Those that exist are largely qualitative and plot-based. Quantitative indicators of post-fire effects are needed that encompass fire effects on both the overstory and the soil surface (Morgan *et al.*

2001). These indicators must be useful across a broad range of site conditions, readily mapped remotely or in the field and remotely, and linked to conditions representing pre-fire (e.g. fuels and forest structure), during fires (fire behavior, fuel consumption, and soil heating) and post fire (vegetation response, soil erosion potential, and invasive species risk). A new generation of tools is needed to support strategic fire management before (fuels management), during (fire management), and after (rehabilitation) wildfires.

With increased reliance on remote sensing, field validation data becomes even more important, but where and how the field data are collected (e.g. plot size, stratification) must be adapted to the spatial resolution of the sensor and the wide range of conditions represented in the imagery. However logical it may seem that higher spatial resolution will likely better represent the fine-scale heterogeneity found in most fires, this has not been proved.

The remote sensing measure should be validated for each application environment by comparing it to equivalent surface processes or properties. For instance, concern has appropriately been raised about the widespread application of spectral index-based methods without establishing the validity and mechanistic relations between post-fire effects and such spectral indices across a variety of environmental conditions (Roy *et al.* 2005; Smith *et al.* 2005*b*). For example, the NDVI index applied to satellite imagery effectively provides a measure of the greenness of each pixel. In the case of post-fire assessment, an equivalent surface measure would include an average measure of green vegetation cover within a corresponding area of interest on the ground. Likewise, if a change in NDVI is used to assess differences between pre- and post-fire environments, an equivalent surface measure could be the change in green vegetation cover before and following the fire.

Validation of dNBR should be conducted in a wide range of environments to ensure that the adopted range of dNBR values, as cited by Key and Benson (2002) and commonly used in post-fire assessment studies, are valid for those environments, or that a process be recommended for local calibration. The authors of the dNBR technique never intended the burn severity class break values developed for fires in Glacier National Park, MT, (i.e. the location of the original dNBR study) to be universal thresholds (cf. Key and Benson 2006). Further, as each index (NBR and dNBR) has a different range of values, separate breaks should be developed for analysis at different temporal periods following fire and depending on which of these methods are applied.

Importantly, the seven levels of dNBR proposed by Key and Benson (2002) are only valid in other environments if the changes in the surface properties that occur in the environment of interest are similar to those observed within Glacier National Park. When considering the wide variation of different fuel conditions and fire regimes, this is unlikely. Understanding that many prior studies have used CBI, the solution is to follow the original methodology used by Key and Benson (2002). For each environment of interest, make local field measurements of the CBI over a range of post-fire conditions. The CBI methods are described in FIREMON (Lutes *et al.* 2006). Then, correlate the dNBR for the same locations with the CBI values measured in the field, and use that relationship to identify the thresholds between burn severity classes (e.g. Key and Benson 2002; van Wagtendonk *et al.* 2004; Cocke *et al.* 2005). Rather than then using the Glacier National Park dNBR ranges to classify the satellite imagery, the CBI field measure could be used to set locally meaningful dNBR ranges by providing for each separate environment of interest the dNBR ranges associated with fixed ranges of CBI values (e.g. Epting *et al.* 2005). The intent of the CBI was to be sufficiently robust to accommodate most vegetation communities. The CBI may require some minor refinements in some communities, but these refinements remain within the conceptual framework of the CBI (cf. Key and Benson 2006). For example, in Alaska, tundra tussocks dominated by sedges, grasses, low shrubs, and mosses are treated as heavy fuel. For each environment, this recalibration should be conducted at a consistent and available spatial scale (e.g. the 30 m scale of the Landsat TM sensor), as van Wagtendonk *et al.* (2004) illustrated that the relationship between CBI and dNBR for a single environment is dependent on the spatial scale of the remote sensing instrument. This variation of post-fire inferred effects with satellite sensor pixel size has further been highlighted by Key (2005).

Synthesize knowledge about fire patterns over time and space

The causes and consequences of spatial variability in fire effects is one of the largely unexplored frontiers of information. Research needs include a better understanding of how post-fire effects and spatial variability are related to the pre-fire fuels and topography, pre-fire climate and active fire weather, vegetation structure and composition, and land use. Recognizing this need, a multi-agency project, Monitoring Trends in Burn Severity (MTBS), sponsored by the Wildland Fire Leadership Council, has been tasked to generate burn severity data, maps, and reports for all large fires since 1984 (http://www.nps.gov/applications/digest, verified 25 June 2006). These data will provide a baseline for monitoring the recovery of burned landscapes and a framework to address highly relevant fire and other natural resource management questions. Knowledge relating to when and where various fuel treatments and fire suppression efforts are likely to be effective will greatly assist managers in prioritizing and making strategic decisions.

Link remotely sensed measures to the fire process

Mechanistically linking surface processes to imagery is the goal of remote sensing science. As such the characteristics and scale of both the patterns and the inferred processes must be clearly defined. Remote sensing data may represent many interacting processes. For example, processes such as soil water infiltration may be spatially variable at fine spatial scales (e.g. sub-meter and sub-surface), whereas the imagery used to view the process may be too coarse to detect sub-pixel variation of the process. The methodological approach must be transparent, repeatable, and robust if we are to compare results from one geographical area with another or among sensors. Additionally, it is challenging to deal with fine-scale pattern when assigning an overall severity class to a pixel, stand (Fig. 1), or landscape (Figs 2, 3).

One such approach is to measure the fraction of a specific cover type present within an area at both the field plot and satellite pixel scales. A traditional field interpretation of severity was the assessment of 'green, brown, and black' as indicators of low, moderate, and high severity. This simplistic protocol has a direct parallel to the remote sensing method of spectral mixture analysis (SMA), which can allow the measurement of the fractional cover within each separate pixel (Drake and White 1991; Wessman *et al.* 1997; Drake *et al.* 1999; Vafeidis and Drake 2005). SMA can be applied to commonly available multispectral satellite imagery. Moderate spatial resolution satellite sensors, such as Landsat (30 m pixel size), however, are not of adequate spatial resolution to accurately capture the fine-scale soil char or white ash fractions or their distribution patterns across the landscape (Smith and Hudak 2005; Smith *et al.* 2005*b*). Therefore, we propose that SMA research only be used to evaluate the fractional cover of unburned (green), scorched (brown), bare soil, and charred (black) vegetation, as these measures are analogous to the traditional field 'severity' indicators. Evaluation of such fractions provides a link between what we can interpret from satellite imagery and what effects have occurred on the ground. Further, as fractions are inherently scalable, SMA allows a truly mechanistic link between field and remote sensing measures.

Until we can understand underlying processes and link them directly to remotely sensed measures, we are doomed to developing empirical relationships for many different environments. Fire effects are often 'symptoms' of the impact to an underlying process that has been affected by fire. Many fire effects are driven by the heat pulse below the soil surface and subsequent impacts on belowground processes, in particular nutrient cycling and soil water infiltration. Understanding how post-fire effects relate to pre-fire conditions (forest structure and fuels) and fire behavior will facilitate the development of improved tools for predicting and mapping the degree of ecosystem change induced by the fire process (e.g. heat penetrating soil, consumption of organic materials, change in soil color). This information can lead to improved understanding of the role of fire in creating conditions that drive sustainable ecosystem processes, structures, and functions, and in turn to quantitative measures that will improve the utility and interpretability of remote sensing assessments.

Develop and test novel remote sensing methods

Few remote sensing research studies have actually collected spectral reflectance and thermal information from pre- and post-fire surfaces. Although such data have been collected in African savannas (e.g. Trigg and Flasse 2000; Landmann 2003; Smith *et al.* 2005*b*) and in early NBR research in North America (e.g. Key and Benson 2002), a lack of post-fire spectral data exists over the multitude of other fire regimes. This lack of data is problematic as several remote sensing methods rely on recalibration within each new application environment. Failure to collect these needed data could result in use of methods that are not calibrated for a given biome. Further to the lack of site-dependent spectral data, the majority of current studies assessing the extent of area burned or the degree of ecological change with Landsat TM data do not use all the data provided to them by the sensor. Namely, thermal infrared is commonly discarded, but can provide useful hindsight into the properties of exposed soils, arising from the lack of evapotranspiration (due to the removal of vegetation).

Improve estimates of local and regional fire emissions

Currently fire emission estimates for use in global change research generally rely on the parameterization of a simple model, in which the total biomass combusted (and gases emitted) are calculated by area burned × pre-fire fuel load × proportion of fuel combusted within the fire (Kasischke and Bruhwiler 2003; Smith *et al.* 2005*a*). Such an approach relies on localized information of the fuel and fire conditions extrapolated over the extent of area burned. Within the global change community, this approach is known to exhibit considerable uncertainties (Andreae and Merlet 2001; Kasischke and Bruhwiler 2003; French *et al.* 2004), and only the area burned is particularly suited to measurement via satellite sensors. In some studies, the proportion of fuel combusted over very large areas (e.g. Russian boreal forests) has been produced through 'educated guesses' of the likely proportion of fuel combusted (e.g. Conard *et al.* 2002; Zhang *et al.* 2004), which in part might explain the significant discrepancy in carbon emission estimates between Siberia and North America (Wooster and Zhang 2004). Clearly, emission estimates produced using such approaches are not ideal, but to date this has been 'the best tool available for the task'. The present review has highlighted other research efforts, such as the use of the FRP methodology (e.g. Wooster *et al.* 2003; Ichoku and Kaufman 2005; Roberts *et al.* 2005; Smith and Wooster 2005), which might allow (provided sufficient temporal resolution is available) improvements to the above model.

Work with managers to determine the scale of operations and thus, appropriate sensors (and resolutions) to address applied questions

The limitations to remote sensing and associated barriers to more widespread use may include costs, user acceptability, and technical problems. The benefits (expediency, coverage, and reliability of results) must outweigh the technical and logistical costs (costs of equipment, human training, and field data collection). Users must overcome the technology curve associated with the acquisition and processing of large remotely-sensed data sets. In some cases, there are time constraints to the use of remotely sensed data. Fire managers need timely and often real-time answers, not loads of data to process. Researchers can help develop protocols for processing data, and can partner with managers to provide data and interpretations, but their efforts must be sufficiently timely and completed without interfering with the operations of the fire command. Managers are tasked to focus on fuels treatment and fire management in the wildland–urban interface, but they may know relatively little about the effectiveness of management activities there. Researchers need to develop remote sensing products and tools that can address questions that are directly applicable to these highly visible and vulnerable areas. Managers also need standardized procedures for updating vegetation and fuels maps as fires occur, monitoring the effects of post-fire rehabilitation treatments, and modelling post-fire succession. End users must have a firm understanding of the consequences of data use, yet have high confidence in data and products. Users must also accept that there are inherent problems with satellites and aircrafts, such as time intervals between images, clouds obscuring the imagery, topographic relief, and surface variations existing at a scale that the imagery is unable to detect.

Conclusions

When combined with field data, remote sensing can be very helpful in mapping and analyzing both active fire characteristics and post-fire effects. Unfortunately, the inconsistent use of fire descriptors, including fire intensity, fire severity, and burn severity, confuse measurement and interpretation of field and remotely sensed fire effects. The use of qualitative terms such as fire and burn severity has limited utility, given the highly variable nature of fire behavior and subsequent effects, and the dynamic aspect of post-fire recovery. Fire is a stochastic, spatially complex process that is influenced by a multitude of interacting factors, making generalizations from one fire to the next difficult (Morgan *et al.* 2001) unless we understand the underlying processes. Using consistent terminology is an important step in developing a better understanding of the causes and consequences of spatial variability of fire effects.

Remote sensing has great potential for scientists and managers seeking to map, understand, predict, and assess the ecological effects of fires. In addition to these current applications, remote sensing has great potential for detecting and quantifying local and regional fire emissions to improve estimates of fire emissions for use in studies of both air quality and global climate change. Atmospheric emissions from fire increasingly limit the use of prescribed fire, especially near urban areas, which are often in need of burning as part of restoration and fuels reduction treatments. Global climate change research has focused attention on carbon storage, release, and sequestration. Remotely sensed data are useful for quantifying carbon released by fire, and potentially for estimating increases in vegetation growth and carbon sequestration post fire. Remote sensing has made great strides in terms of providing data to address operational and applied research questions, beyond the scope and feasibility that ground-based studies can provide.

Acknowledgements

The present research was supported in part by funds provided by the Rocky Mountain Research Station Forest Service, USDA (JVA 03-JV-11222065-279) and the USDI National Park Service (RM CESU NPS H1200040001), through funding from the USDA/USDI Joint Fire Science Program (Projects 03-2-1-02 and 05-4-1-07). Alistair Smith and Paul Gessler are part of ForestPARC, which is funded by the Upper Midwest Aerospace Consortium, with funding from NASA. The authors would like to thank Mike Bobbitt for his assistance with figures; Caty Clifton, Colin Hardy, Randy McKinley, Annette Parsons, Peter Robichaud, Brian Schwind, Henry Shovic, and Dean Sirucek for participation in the Eleventh Biennial USDA Forest Service Remote Sensing Applications Conference, and the reviewers and editor for their helpful suggestions.

References

Agee JK (1993) 'Fire ecology of Pacific Northwest forests.' (Island Press: Washington, DC)

Albini FA (1976) 'Estimating wildfire behavior and effects.' USDA Forest Service, Intermountain Forestry and Range Experimental Station General Technical Report INT-GTR-30. (Ogden, UT)

Alexander ME (1982) Calculating and interpreting forest fire intensities. *Canadian Journal of Botany* **60**, 349–357.

Al-Rawi KR, Casanova JL, Calle A (2001) Burned area mapping system and fire detection system, based on neural networks and NOAA-AVHRR imagery. *International Journal of Remote Sensing* **22**, 2015–2032. doi:10.1080/01431160152043685

Anderson JE, Romme WH (1991) Initial floristics in lodgepole pine (*Pinus contorta*) forests following the 1988 Yellowstone fires. *International Journal of Wildland Fire* **1**, 119–124. doi:10.1071/WF9910119

Andreae MO, Merlet P (2001) Emission of trace gases and aerosols from biomass burning. *Global Biochemical Cycles* **15**, 955–966. doi:10.1029/2000GB001382

Andreae MO, Atlas E, Cachier H, Cofer WR, III, Harris GW, Helas G, Koppermann R, Lacaux JP, Ward DE (1996) Trace gas and aerosol emissions from savanna fires. In 'Biomass burning and global change: Remote sensing, modelling and inventory development and biomass burning in Africa'. (Ed. JS Levine) pp. 278–295. (MIT Press: Cambridge, MA)

Baltsavias EP (1999) Airborne laser scanning: basic relations and formulas. *ISPRS Journal of Photogrammetry and Remote Sensing* **54**, 199–214. doi:10.1016/S0924-2716(99)00015-5

Barbosa PM, Stroppiana D, Grégoire J-M, Pereira JMC (1999*a*) An assessment of vegetation fires in Africa (1981–1991): Burned area, burned biomass, and atmospheric emissions. *Global Biochemical Cycles* **13**, 933–950. doi:10.1029/1999GB900042

Barbosa PM, Grégoire J-M, Pereira JMC (1999*b*) An algorithm for extracting burned areas from time series of AVHRR GAC data applied at a continental scale. *Remote Sensing of Environment* **69**, 253–263. doi:10.1016/S0034-4257(99)00026-7

Barrett SW, Arno SF, Menakis JP (1997) 'Fire episodes in the Inland Northwest (1540–1940) based on fire history data.' USDA Forest Service, Intermountain Research Station General Technical Report INT-GTR-370. (Odgen, UT)

Beebe GS, Omi PN (1993) Wildland burning: the perception of risk. *Journal of Forestry* **91**(9), 19–24.

Bobbe T, Lachowski H, Maus P, Greer J, Dull C (2001) A primer on mapping vegetation using remote sensing. *International Journal of Wildland Fire* **10**, 277–287. doi:10.1071/WF01029

Bobbe T, Finco MV, Quayle B, Lannom K, Sohlberg R, Parsons A (2003) 'Field measurements for the training and validation of burn severity maps from spaceborne remotely sensed imagery.' USDI Joint Fire Science Program Final Project Report JFSP RFP 2001–2. (Boise, ID)

Borchers JG, Perry DA (1990) Effects of prescribed fire on soil organisms. In 'Natural and prescribed fire in Pacific Northwest forests'. (Eds JD Walstad, SR Radosevich, DV Sandberg) pp. 143–158. (Oregon State University Press: Corvallis)

Bradshaw WG (1988) Fire protection in the urban/wildland interface: who plays what role? *Fire Technology* **24**, 195–203. doi:10.1007/BF01038177

Brauer M (1999) Health impacts of biomass air. In 'Health guidelines for vegetation fire events background papers'. (Eds K-T Goh, D Schwela, JG Goldammer, O Simpson) pp. 186–254. (WHO/UNEP/WMO: Singapore)

Brewer CK, Winne JC, Redmond RL, Opitz DW, Magrich MV (2005) Classifying and mapping wildfire severity: a comparison of methods. *Photogrammetric Engineering and Remote Sensing* **71**, 1311–1320.

Butler BW, Cohen J, Latham DJ, Schuette RD, Sopko P, Shannon KS, Jimenez D, Bradshaw LS (2004) Measurements of radiant emissive power and temperatures in crown fires. *Canadian Journal of Forest Research* **34**, 1577–1587. doi:10.1139/X04-060

Byram GM (1959) Combustion of Forest Fuels. In 'Forest fire: Control and use'. (Ed. KP Davis) pp. 61–89. (McGraw-Hill: New York)

Chappell C, Agee JK (1996) Fire severity and tree seedling establishment in *Abies magnifica* forests, southern Cascades, Oregon. *Ecological Applications* **6**, 628–640. doi:10.2307/2269397

Choromanska U, DeLuca TH (2002) Microbial activity and nitrogen mineralization in forest mineral soils following heating: evaluation of post-fire effects. *Soil Biology & Biochemistry* **34**, 263–271. doi:10.1016/S0038-0717(01)00180-8

Chuvieco E, Congalton RG (1988) Mapping and inventory of forest fires from digital processing of TM data. *Geocarto International* **4**, 41–53.

Chuvieco E, Riano AI, Cocero D (2002) Estimation of fuel moisture content from multitemporal analysis of Landsat Thematic Mapper Reflectance data: applications in fire danger assessment. *International Journal of Remote Sensing* **23**, 2145–2162. doi:10.1080/01431160110069818

Cochrane MA, Souza CM (1998) Linear mixture model classification of burned forests in the Eastern Amazon. *International Journal of Remote Sensing* **19**, 3433–3440. doi:10.1080/014311698214109

Cocke AE, Fule PZ, Crouse JE (2005) Comparison of burn severity assessments using Differenced Normalized Burn Ratio and ground data. *International Journal of Wildland Fire* **14**, 189–198.

Cohen JD (2000) Preventing disaster: home ignitability in the wildland–urban interface. *Journal of Forestry* **98**(3), 15–21.

Cohen JD, Butler BW (1998) Modeling potential ignitions from flame radiation exposure with implications for wildland/urban interface fire management. In 'Proceedings of the 13th conference on fire and forest meteorology'. 27–31 October, Lorne, Victoria, Australia. Fairfield, WA. pp. 81–86. (International Association of Wildland Fire: Montana City, MT)

Conard SG, Ivanova GA (1997) Wildfire in Russian boreal forests – potential impacts of fire regime characteristics on emissions and global carbon balance estimates. *Environmental Pollution* **10**, 267–275.

Conard SG, Sukhinin AI, Stocks BJ, Cahoon DR, Davidenko EP, Ivanova GA (2002) Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia. *Climatic Change* **55**, 197–211. doi:10.1023/A:1020207710195

Cotrell WH (1989) 'The book of fire.' (Mountain Press: Missoula, MT)

Covington WW, Moore MM (1994) South-western ponderosa pine forest structure: changes since Euro-American settlement. *Journal of Forestry* **92**, 39–47.

Crutzen PJ, Andreae MO (1990) Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science* **250**, 1669.

DeBano LF (1981) 'Water repellent soils: A state-of-the-art.' USDA Forest Service Pacific Southwest Forest and Range Experiment Station General Technical Report PSW-46. (Berkeley, CA)

DeBano LF, Rice RN, Conrad CE (1979) 'Soil heating in chaparral fires: effects on soil properties, plant nutrients, erosion and runoff.' USDA Forest Service, Pacific Northwest Forest and Range Experimental Station Research Paper PSW-145. (Berkeley, CA)

DeBano LF, Neary DG, Ffolliott PF (1998) 'Fire's effects on ecosystems.' (John Wiley and Sons: New York)

Dellasala DA, Williams JE, Williams CD, Franklin JF (2004) Beyond smoke and mirrors: a synthesis of fire policy and science. *Conservation Biology* **18**, 976–986. doi:10.1111/J.1523-1739.2004.00529.X

Dennison PE (2006) Fire detection in imaging spectrometer data using atmospheric carbon dioxide absorption. *International Journal of Remote Sensing*, in press.

Dennison PE, Charoensiri K, Roberts DA, Peterson SH, Green RO (2006) Wildfire temperature and land cover modeling using hyperspectral data. *Remote Sensing of Environment* **100**, 212–222. doi:10.1016/J.RSE.2005.10.007

Díaz-Delgado R, Lloret F, Pons X (2003) Influence of fire severity on plant regeneration through remote sensing imagery. *International Journal of Remote Sensing* **24**, 1751–1763. doi:10.1080/01431160210144732

Doerr SH, Shakesby RA, Walsh RPD (2000) Soil water repellency: Its causes, characteristics and hydro-geomorphological significance. *Earth-Science Review* **51**, 33–65. doi:10.1016/S0012-8252(00)00011-8

Drake JB, Dubayah RO, Clark DB, Knox RG, Blair JB, Hofton MA, Chazdon RL, Weishampel JF, Prince S (2002) Estimation of tropical forest structural characteristics using large-footprint lidar. *Remote Sensing of Environment* **81**, 378–392. doi:10.1016/S0034-4257(02)00013-5

Drake NA, White K (1991) Linear mixture modelling of Landsat Thematic Mapper data for mapping the distribution and abundance of gypsum in the Tunisian Southern Atlas. In 'Spatial data

2000: Proceedings of a joint conference of the Photogrammetric Society, the Remote Sensing Society, the American Society for Photogrammetry and Remote Sensing', Christ Church, Oxford. (Ed. I Dowman) pp. 168–177. (Remote Sensing Society: Nottingham)

Drake NA, Mackin S, Settle JJ (1999) Mapping vegetation, soils, and geology in semiarid shrublands using spectral matching and mixture modelling of SWIR AVIRIS imagery. *Remote Sensing of Environment* **68**, 12–25. doi:10.1016/S0034-4257(98)00097-2

Eberhardt KE, Woodard PM (1987) Distribution of residual vegetation associated with large fires in Alberta. *Canadian Journal of Forest Research* **17**, 1207–1212.

Ekstrand S (1994) Assessment of forest damage with Landsat TM: Correction for varying forest stand characteristics. *Remote Sensing of Environment* **47**, 291–302. doi:10.1016/0034-4257(94)90097-3

Epting J, Verbyla D, Sorbel B (2005) Evaluation of remotely sensed indices for assessing burn severity in interior Alaska using Landsat TM and ETM+. *Remote Sensing of Environment* **96**, 328–339. doi:10.1016/J.RSE.2005.03.002

Eva H, Lambin EF (1998*a*) Burnt area mapping in Central Africa using ATSR data. *International Journal of Remote Sensing* **19**, 3473–3497. doi:10.1080/014311698213768

Eva H, Lambin EF (1998*b*) Remote sensing of biomass burning in tropical regions: Sampling issues and multisensor approach. *Remote Sensing of Environment* **64**, 292–315. doi:10.1016/S0034-4257(98)00006-6

Falkowski MJ, Gessler PE, Morgan P, Hudak AT, Smith AMS (2005) Evaluating ASTER satellite imagery and gradient modelling for mapping and characterizing wildland fire fuels. *Forest Ecology and Management* **217**, 129–146. doi:10.1016/J.FORECO.2005.06.013

Falkowski MJ, Smith AMS, Hudak AT, Gessler PE, Vierling LA, Crookston NL (2006) Automated estimation of individual conifer tree height and crown diameter via two-dimensional spatial wavelet analysis of lidar data. *Canadian Journal of Remote Sensing* **32**, 153–161.

Fernandez A, Illera P, Casanova JL (1997) Automatic mapping of surfaces affected by forest fires in Spain using AVHRR NDVI composite image data. *Remote Sensing of Environment* **60**, 153–162. doi:10.1016/S0034-4257(96)00178-2

Fiorella M, Ripple WJ (1993) Analysis of conifer regeneration using Landsat Thematic Mapper data. *Photogrammetric Engineering and Remote Sensing* **59**, 1383–1388.

Flannigan MD, Vonder Haar TH (1986) Forest fire monitoring using NOAA satellite AVHRR. *Canadian Journal of Forest Research* **16**, 975–982.

Flasse SP, Ceccato P (1996) A contextual algorithm for AVHRR fire detection. *International Journal of Remote Sensing* **17**, 419–424.

Fraser RH, Li Z, Cihlar J (2000) Hotspot and NDVI differencing synergy (HANDS): A new technique for burned area mapping over boreal forest. *Remote Sensing of Environment* **74**, 362–376. doi:10.1016/S0034-4257(00)00078-X

Fraser RH, Hall RJ, Landry R, Landry T, Lynham T, Raymond D, Lee B, Li Z (2004) Validation and calibration of Canada-wide coarse-resolution satellite burned maps. *Photogrammetric Engineering and Remote Sensing* **70**, 451–460.

French N, Goovaerts P, Kasischke ES (2004) Uncertainty in estimating carbon emissions from boreal forest fires. *Journal of Geophysical Research* **109**, D14S08. doi:10.1029/2003JD003635

Fuller DO, Fulk M (2001) Burned area in Kalimantan, Indonesia, mapped with NOAA-AVHRR and Landsat TM imagery. *International Journal of Remote Sensing* **22**, 691–697. doi:10.1080/01431160010013504

Garcia-Haro FJ, Gilabert MA, Melia J (2001) Monitoring fire-affected areas using Thematic Mapper data. *International Journal of Remote Sensing* **22**, 533–549. doi:10.1080/01431160050505847

Giglio L, Kendall JD, Justice CO (1999) Evaluation of global fire detection algorithms using simulated AVHRR infrared data. *International Journal of Remote Sensing* **20**, 1947–1985. doi:10.1080/014311699212290

Giovannini G, Lucchesi S (1997) Modifications induced in soil physico-chemical parameters by experimental fires at different intensities. *Soil Science* **162**, 479–486. doi:10.1097/00010694-199707000-00003

Graham RT (2003) 'Hayman fire case study.' USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-114. (Fort Collins, CO)

Gresswell RE (1999) Fire and aquatic ecosystems in forested biomes of North America. *Transactions of the American Fisheries Society* **128**, 193–221. doi:10.1577/1548-8659(1999)128<0193:FAAEIF>2.0.CO;2

Grissino-Meyer HD, Swetnam TW (2000) Century-scale climate forcing of fire regimes in the American South-west. *The Holocene* **10**, 207–214.

Hall DK, Ormsby JP, Johnson L, Brown J (1980) Landsat digital analysis of the initial recovery of burned tundra at Kokolik River, Alaska. *Remote Sensing of Environment* **10**, 263–272. doi:10.1016/0034-4257(80)90086-3

Hann DB, Smith AMS, Powell AK (2003) Technical note: Classification of off-diagonal points in a co-occurrence matrix. *International Journal of Remote Sensing* **24**, 1949–1956. doi:10.1080/01431160210154074

Hardy CC (2005) Wildland fire hazard and risk: Problems, definitions, and context. *Forest Ecology and Management* **211**, 73–82. doi:10.1016/J.FORECO.2005.01.029

Hardy CC, Menakis JP, Long DG, Brown JK, Brunnell DL (1998) Mapping historic fire regimes for the western United States: integrating remote sensing and biophysical data. In 'Proceedings of the 7th biennial Forest Service remote sensing applications conference', 6–9 April 1998, Nassau Bay, TX. pp. 288–300. (American Society for Photogrammetery and Remote Sensing: Bethesda, MD)

Hardy CC, Brunnell DL, Menakis JP, Schmidt KM, Long DG, Simmerman DG, Johnston CM (1999) 'Coarse-scale spatial data for wildland fire and fuel management.' USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. Available at http://www.fs.fed.us/fire/fuelman [Verified 29 June 2006]

Hardy CC, Ottmar RD, Peterson JL, Core JE, Seamon P (2001) 'Smoke management guide for prescribed and wildland fire.' USDA National Wildfire Coordination Group Publication PMS 420-2. (Ogden, UT)

Hartford RA, Frandsen WH (1992) When it's hot, it's hot… or maybe it's not! (Surface flaming may not portend soil heating). *International Journal of Wildland Fire* **2**, 139–144. doi:10.1071/WF9920139

Hely C, Alleaume S, Swap RJ, Shugart HH, Justice CO (2003) SAFARI-2000 characterization of fuels, fire behavior, combustion completeness and emissions from experimental burns in infertile grass savannas in western Zambia. *Journal of Arid Environments* **54**, 381–394. doi:10.1006/JARE.2002.1097

Henry MC, Hope AS (1998) Monitoring post-burn recovery of chaparral vegetation in southern California using multi-temporal satellite data. *International Journal of Remote Sensing* **19**, 3097–3107. doi:10.1080/014311698214208

Henry MC, Yool SR (2002) Characterizing fire-related spatial patterns in the Arizona Sky Islands using Landsat TM data. *Photogrammetric Engineering and Remote Sensing* **68**, 1011–1019.

Holden ZA, Smith AMS, Morgan P, Rollins MG, Gessler PE (2005) Evaluation of novel thermally enhanced spectral indices for mapping fire perimeters and comparisons with fire atlas data. *International Journal of Remote Sensing* **26**, 4801–4808. doi:10.1080/01431160500239008

Hudak AT, Brockett BH (2004) Mapping fire scars in a southern African savanna using Landsat imagery. *International Journal of Remote Sensing* **25**, 3231–3243. doi:10.1080/01431160310001632666

Hudak AT, Lefsky MA, Cohen WB, Berterretche M (2002) Integration of lidar and Landsat ETM plus data for estimating and mapping forest canopy height. *Remote Sensing of Environment* **82**, 397–416.

Hudak AT, Robichaud P, Evans J, Clark J, Lannom K, Morgan P, Stone C (2004) Field validation of Burned Area Reflectance Classification (BARC) products for post-fire assessment. In 'Proceedings of the tenth biennial forest service remote sensing applications conference'. (CD-ROM) (USDA Forest Service RSAC: Salt Lake City, UT)

Hudak AT, Morgan P, Bobbitt M, Lentile LB (2005) Characterizing clearcut harvest and severe fire disturbance patches in a forested landscape: A case study from Cooney Ridge, Montana. In 'Forest disturbance and spatial patterns, GIS and remote sensing approaches'. (Eds M Wulder, S Francis) Chapter 8. (Taylor and Francis–CRC Press: London)

Hudak AT, Crookston NL, Evans JS, Falkowski MJ, Smith AMS, Gessler PE, Morgan P (2006) Regression modeling and mapping of coniferous forest basal area and tree density from discrete-return lidar and multispectral data. *Canadian Journal of Remote Sensing* **32**, 126–138.

Hungerford RD, Babbitt RE (1987) 'Overstory removal and residue treatments affect soil surface, air, and soil temperatures: implications for seedling survival.' USDA Forest Service, Intermountain Research Station Research Paper INT-377. (Ogden, UT)

Ice GG, Neary DG, Adams PW (2004) Effects of wildfire on soils and watershed processes. *Journal of Forestry* **102**(6), 16–20.

Ichoku C, Kaufman YJ (2005) A method to derive smoke emission rates from MODIS fire radiative energy measurements. *IEEE transactions on Geoscience and Remote Sensing* **43**, 2636–2649. doi:10.1109/TGRS.2005.857328

Ichoku C, Kaufman Y, Giglio L, Li Z, Fraser RH, Jin J-Z, Park WM (2003) Comparative analysis of daytime fire detection algorithms, using AVHRR data for the 1995 fire season in Canada: Perspective for MODIS. *International Journal of Remote Sensing* **24**, 1669–1690. doi:10.1080/01431160210144697

Isaev AS, Korovin GN, Bartalev SA, Ershow DV, Janetos A, *et al.* (2002) Using remote sensing to assess Russian forest fire carbon emissions. *Climatic Change* **55**, 235–249. doi:10.1023/A:1020221123884

Jain T, Pilliod D, Graham R (2004) Tongue-tied. *Wildfire* **4**, 22–26.

Jakubauskas ME, Lulla KP, Mausel PW (1990) Assessment of vegetation change in a fire-altered forest landscape. *Photogrammetric Engineering and Remote Sensing* **56**, 371–377.

Justice CO, Malingreau J-P, Setzer AW (1993) Satellite remote sensing of fires: potential and limitations. In 'Fire in the environment.' (Eds PJ Crutzen, JG Goldammer) pp. 77–88. (John Wiley: New York)

Justice CO, Kendall JD, Dowty PR, Scholes RJ (1996) Satellite remote sensing of fires during the SAFARI campaign using NOAA-AVHRR data. *Journal of Geophysical Research* **101**, 23851–23863. doi:10.1029/95JD00623

Justice CO, Giglio L, Korontzi S, Owens J, Morisette JT, Roy D, Descloitres J, Alleaume S, Petitcolin F, Kaufman Y (2002) The MODIS fire products. *Remote Sensing of Environment* **83**, 244–262. doi:10.1016/S0034-4257(02)00076-7

Kasischke ES, Bruhwiler LP (2003) Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998. *Journal of Geophysical Research* **108**, 8146. doi:10.1029/2001JD000461

Kasischke KS, French NHF (1995) Locating and estimating the aerial extent of wildfires in Alaskan boreal forests using multiple-season AVHRR NDVI composite data. *Remote Sensing of Environment* **51**, 263–275. doi:10.1016/0034-4257(93)00074-J

Kaufman YJ, Tucker CJ, Fung I (1990) Remote sensing of biomass burning in the tropics. *Journal of Geophysical Research* **95**, 9927–9939.

Kaufman YJ, Kleidman RG, King MD (1998) SCAR-B fires in the tropics: Properties and remote sensing from EOS-MODIS. *Journal of Geophysical Research* **103**, 31 955–31 968. doi:10.1029/98JD02460

Keane RE, Burgan RE, van Wagtendonk JW (2001) Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. *International Journal of Wildland Fire* **10**, 301–319. doi:10.1071/WF01028

Ketterings QM, Bigham JM (2000) Soil color as an indicator of slash-and-burn fire severity and soil fertility in Sumatra, Indonesia. *Soil Science Society of America Journal* **64**, 1826–1833.

Key CH (2005) Remote sensing sensitivity to fire severity and fire recovery. In 'Proceedings of the 5th international workshop on remote sensing and GIS applications to forest fire management: Fire effects assessment'. (Eds J De la Riva, F Perez-Cabello, E Chuvieco) pp. 29–39. (Universidad de Zaragoza: Spain)

Key CH, Benson NC (2002) Measuring and remote sensing of burn severity. US Geological Survey Wildland Fire Workshop, 31 October to 3 November 2000, Los Alamos, NM. USGS Open-File Report 02-11.

Key CH, Benson NC (2006) 'Landscape assessment: sampling and analysis methods.' USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-164-CD. (Ogden, UT)

Kushla JD, Ripple WJ (1998) Assessing wildfire effects with Landsat Thematic Mapper data. *International Journal of Remote Sensing* **19**, 2493–2507. doi:10.1080/014311698214587

Laes D, Maus P, Lewis S, Robichaud P, Kokaly R (2004) 'Postfire burn-severity classification of the Hayman Fire, CO: Based on hyperspectral data-JFSP RFP 2001–2, Task 1. Project report: Integration of remote sensing.' USDI Joint Fire Sciences Program Report RSAC-0068-RPT1. (Boise, ID)

Lamont BB, Witkowski ETF, Enright NJ (1993) Post-fire litter microsites safe for seeds, unsafe for seedlings. *Ecology* **74**, 501–512. doi:10.2307/1939311

Landmann T (2003) Characterizing sub-pixel Landsat ETM+ fire severity on experimental fires in the Kruger National Park, South Africa. *South African Journal of Science* **99**, 357–360.

Lefsky MA, Harding D, Cohen WB, Parker G, Shugart HH (1999) Surface lidar remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA. *Remote Sensing of Environment* **67**, 83–98.

Lefsky MA, Cohen WB, Harding DJ, Parker GG, Acker SA, Gower ST (2002) Lidar remote sensing of aboveground biomass in three biomes. *Global Ecology and Biogeography* **11**, 393–399. doi:10.1046/J.1466-822X.2002.00303.X

Lefsky MA, Hudak AT, Cohen WB, Acker SA (2005) Geographic variability in lidar predictions of forest stand structure in the Pacific Northwest. *Remote Sensing of Environment* **95**, 532–548. doi:10.1016/J.RSE.2005.01.010

Lenihan HM, Daly C, Bachelet D, Neilson RP (1998) Simulating broad-scale fire severity in a dynamic global vegetation model. *Northwest Science* **72**, 91–103.

Lentile LB (2004) Causal factors and consequences of mixed-severity fire in Black Hills ponderosa pine forests. PhD Thesis, Colorado State University.

Lentile LB, Smith FW, Shepperd WD (2005) Patch structure, fire-scar formation and tree regeneration in a large mixed-severity fire in the South Dakota Black Hills, USA. *Canadian Journal of Forest Research* **35**, 2875–2885. doi:10.1139/X05-205

Lewis SA, Wu JQ, Robichaud PR (2006) Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado. *Hydrological Processes* **20**, 1–16. doi:10.1002/HYP.5880

Li X, Kaufman YJ, Ichoku C, Fraser R, Trishcenko A, Giglio L, Kin J, Yu X (2001) A review of AVHRR-based active fire detection algorithms: principles, limitations, and recommendations. In 'Global and regional vegetation fire monitoring from space: planning and coordinated international effort'. (Eds F Ahern, JG Goldammer, CO Justice) pp. 199–225. (SPB Academic Publishing: The Hague)

Li Z, Nadon S, Chilar J (2000*a*) Satellite-based detection of Canadian boreal forest fires: development and application of the algorithm. *International Journal of Remote Sensing* **21**, 3057–3069. doi:10.1080/014311600050144956

Li Z, Nadon S, Chilar J, Stocks BJ (2000*b*) Satellite-based mapping of Canadian boreal forest fires: evaluation and comparison of algorithms. *International Journal of Remote Sensing* **21**, 3071–3082. doi:10.1080/014311600050144965

Lopez-Garcia MJ, Caselles V (1991) Mapping burns and natural reforestation using Thematic Mapper data. *Geocarto International* **1**, 31–37.

Loveland TR, Merchant JM, Othlen DO, Brown JF (1991) Development of a land-cover characteristics database for the conterminous US. *Photogrammetric Engineering and Remote Sensing* **57**, 1453–1463.

Lutes DC, Keane RE, Caratti JF, Key CH, Benson NC, Sutherland S, Gangi LJ (2006) 'FIREMON: The fire effects monitoring and inventory system.' USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-164-CD. (Fort Collins, CO)

Lyon LJ, Stickney PF (1976) Early vegetal succession following large northern Rocky Mountain wildfires. In 'Proceedings of the Montana tall timbers fire ecology conference and fire and land management symposium' No. 14. 8–10 October, Missoula, MT. pp. 355–375. (Tall Timbers Research Station: Tallahassee, FL)

McHugh C, Kolb TE (2003) Ponderosa pine mortality following fire in northern Arizona. *International Journal of Wildland Fire* **12**, 7–22. doi:10.1071/WF02054

McNaughton SJ, Stronach NRH, Georgiadis NJ (1998) Combustion in natural fires and global emissions budgets. *Ecological Applications* **8**, 464–468. doi:10.2307/2641086

Means JE, Acker SA, Harding DJ, Blair JB, Lefsky MA, Cohen WB, Harmon ME, McKee WA (1999) Use of large-footprint scanning airborne lidar to estimate forest stand characteristics in the Western Cascades of Oregon. *Remote Sensing of Environment* **67**, 298–308. doi:10.1016/S0034-4257(98)00091-1

Means JE, Acker SA, Fitt BJ, Renslow M, Emerson L, Hendrix C (2000) Predicting forest stand characteristics with airborne scanning lidar. *Photogrammetric Engineering and Remote Sensing* **66**, 1367–1371.

Miller JD, Yool SR (2002) Mapping forest post-fire canopy consumption in several overstory types using multi-temporal Landsat TM and ETM data. *Remote Sensing of Environment* **82**, 481–496. doi:10.1016/S0034-4257(02)00071-8

Milne AK (1986) The use of remote sensing in mapping and monitoring vegetational change associated with bushfire events in Eastern Australia. *Geocarto International* **1**, 25–32.

Minshall G, Brock J, Andrews D, Robinson C (2001) Water quality, substratum and biotic responses of five central Idaho (USA) streams during the first year following the Mortar Creek fire. *International Journal of Wildland Fire* **10**, 185–199. doi:10.1071/WF01017

Molina MJ, Llinares JV (2001) Temperature–time curves at the soil surface in maquis summer fires. *International Journal of Wildland Fire* **10**, 45–52. doi:10.1071/WF01001

Morgan P, Bunting SC, Black AE, Merrill T, Barrett S (1996) 'Fire regimes in the Interior Columbia River Basin: Past and Present.' USDA Forest Service, Rocky Mountain Research Station Final Report for RJVA-INT-94913. (Fire Sciences Laboratory: Missoula, MT)

Morgan P, Hardy CC, Swetnam T, Rollins MG, Long LG (2001) Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns. *International Journal of Wildland Fire* **10**, 329–342. doi:10.1071/WF01032

Mottram GN, Wooster MJ, Balster H, George C, Gerrard F, Beisley J (2005) The use of MODIS-derived fire radiative power to characterise Siberian boreal forest fires. In 'Proceedings of the 31st international symposium on remote sensing of environment', 20–24 June 2005. (Saint Petersburg: Russian Federation)

National Wildfire Coordination Group (2005) 'Glossary of wildland fire terminology.' US National Wildfire Coordination Group Report PMS-205. (Ogden, UT)

Neary DG (2004) An overview of fire effects on soils. *Southwest Hydrology* **3**, 18–19.

Neary DG, Klopatek CC, DeBano LF, Ffolliott PF (1999) Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management* **122**, 51–71. doi:10.1016/S0378-1127(99)00032-8

Nelson R, Krabill W, Tonelli J (1988) Estimating forest biomass and volume using airborne laser data. *Remote Sensing of Environment* **24**, 247–267. doi:10.1016/0034-4257(88)90028-4

Nielsen TT, Mbow C, Kane R (2002) A statistical methodology for burned area estimation using multitemporal AVHRR data. *International Journal of Remote Sensing* **23**, 1181–1196. doi:10.1080/01431160110078449

Ottmar RD, Sandberg DV (2003) Predicting forest floor consumption from wildland fire in boreal forests of Alaska – preliminary results. In 'Proceedings of fire ecology 2000: The first national congress on fire ecology, prevention and management'. (Eds KEM Galley, RC Klinger, NG Sugihara) pp. 218–224. Miscellaneous Publication No. 13. (Tall timbers Research Station: Tallahassee, FL)

Parsons A (2003) Burned Area Emergency Rehabilitation (BAER) soil burn severity definitions and mapping guidelines. USDA Forest Service, Forest Service Regional BAER Coordinators 2003 Draft Report. Available at http://fire.r9.fws.gov/ifcc/esr/Remote%20Sensing/soil_burnsev_summary_guide042203.pdf [Verified 29 June 2006]

Parsons A, Orlemann A (2002) Burned Area Emergency Rehabilitation (BAER)/Emergency Stabilization and Rehabilitation (ESR). Burn Severity Definitions/Guidelines Draft Version 1.5. (Remote Sensing Application Center: Salt Lake City) Available at http://gis.esri.com/library/userconf/proc02/pap0431/p0431.htm [Verified 27 July 2006]

Patterson MW, Yool SR (1998) Mapping fire-induced vegetation mortality using Landsat Thematic Mapper data: A comparison of linear transformation techniques. *Remote Sensing of Environment* **65**, 132–142. doi:10.1016/S0034-4257(98)00018-2

Pereira JMC (1999) A comparative evaluation of NOAA/AVHRR vegetation indexes for burned surface detection and mapping. *IEEE Transactions on Geoscience and Remote Sensing* **37**, 217–226. doi:10.1109/36.739156

Pereira JMC (2003) Remote sensing of burned areas in tropical savannas. *International Journal of Wildland Fire* **12**, 259–270. doi:10.1071/WF03028

Pereira JMC, Setzer AW (1996) Comparison of fire detection in savannas using AVHRR's channel 3 and TM images. *International Journal of Remote Sensing* **17**, 1925–1937.

Perez B, Moreno JM (1998) Methods for quantifying fire severity in shrubland-fires. *Plant Ecology* **139**, 91–101. doi:10.1023/A:1009702520958

Picket ST, White PS (1985) Natural disturbance and patch dynamics: an introduction. In 'The ecology of natural disturbance and patch dynamics'. (Eds ST Picket, PS White) pp. 3–13. (Academic Press: New York)

Poth M, Anderson IC, Miranda HS, Miranda AC, Riggan PJ (1995) The magnitude and persistence of soil NO, N_2O, CH_4, and CO_2 fluxes from burned tropical savanna in Brazil. *Global Biochemical Cycles* **9**, 503–513. doi:10.1029/95GB02086

Pozo D, Olmo FJ, Alados Arboledas L (1997) Fire detection and growth monitoring using a multitemporal technique on AVHRR mid-infrared and thermal channels. *Remote Sensing of Environment* **60**, 111–120. doi:10.1016/S0034-4257(96)00117-4

Randriambelo T, Baldy S, Bessafi M, Petit M, Despinoy M (1998) An improved detection and characterization of active fires and smoke plumes in south-eastern Africa and Madagascar. *International Journal of Remote Sensing* **19**, 2623–2638. doi:10.1080/014311698214424

Razafimpanilo H, Frouin R, Iacobillis SF, Somerville RCJ (1995) Methodology for estimating burned area from AVHRR reflectance data. *Remote Sensing of Environment* **54**, 273–289. doi:10.1016/0034-4257(95)00154-9

Reinhardt ED, Keane RE, Brown JK (1997) 'First order fire effects model: FOFEM 4.0, user's guide.' USDA Forest Service, Intermountain Research Station General Technical Report INT-GTR-344. (Ogden, UT)

Reinhardt ED, Keane RE, Brown JK (2001) Modeling fire effects. *International Journal of Wildland Fire* **10**, 373–380. doi:10.1071/WF01035

Riaño D, Chuvieco E, Ustin S, Zomer R, Dennison P, Roberts D, Salas J (2002) Assessment of vegetation regeneration after fire through multitemporal analysis of AVIRIS images in the Santa Monica Mountains. *Remote Sensing of Environment* **79**, 60–71. doi:10.1016/S0034-4257(01)00239-5

Riaño D, Meier E, Allgöwer B, Chuvieco E, Ustin SL (2003) Modeling airborne laser scanning data for the spatial generation of critical forest parameters in fire behavior modeling. *Remote Sensing of Environment* **86**, 177–186. doi:10.1016/S0034-4257(03)00098-1

Richards JA, Jia X (1999) 'Remote sensing digital image analysis: an introduction.' (Springer-Verlag: New York)

Riggan PJ, Tissell RG, Lockwood RN, Brass JA, Pereira JAR, Miranda HS, Miranda AC, Campos T, Higgins R (2004) Remote measurement of energy and carbon flux from wildfires in Brazil. *Ecological Applications* **14**, 855–872.

Roberts G, Wooster MJ, Perry GLW, Drake N, Rebelo L-M, Dipotso F (2005) Retrieval of biomass combustion rates and totals from fire radiative power observations: Part 2 – application to southern Africa using geostationary SEVIRI imagery. *Journal of Geophysical Research* **110**, D24311. doi:10.1029/2005JD006318

Robichaud PR, Beyers JL, Neary DG (2000) 'Evaluating the effectiveness of postfire rehabilitation treatments.' USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-63. (Fort Collins, CO)

Robinson JM (1991) Fire from space: Global fire evaluation using infrared remote sensing. *International Journal of Remote Sensing* **12**, 3–24.

Rollins M, Swetnam TW, Morgan P (2001) Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. *Canadian Journal of Forest Research* **31**, 2107–2123. doi:10.1139/CJFR-31-12-2107

Roy DP, Landmann T (2005) Characterizing the surface heterogeneity of fire effects using multi-temporal reflectance wavelength data. *International Journal of Remote Sensing* **26**, 4197–4218. doi:10.1080/01431160500112783

Roy DP, Giglio L, Kendall JD, Justice CO (1999) Multi-temporal active-fire-based burn scar detection algorithm. *International Journal of Remote Sensing* **20**, 1031–1038. doi:10.1080/014311699213073

Roy DP, Jin Y, Lewis PE, Justice CO (2005) Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data. *Remote Sensing of Environment* **97**, 137–162. doi:10.1016/J.RSE.2005.04.007

Roy DP, Boschetti L, Trigg SN (2006) Remote sensing of fire severity: assessing the performance of the normalized burn ratio. *IEEE Geoscience and Remote Sensing Letters* **3**, 112–116. doi:10.1109/LGRS.2005.858485

Ruiz-Gallardo JR, Castaño S, Calera A (2004) Application of remote sensing and GIS to locate priority intervention areas after wildland fires in Mediterranean systems: a case study from south-eastern Spain. *International Journal of Wildland Fire* **13**, 241–252. doi:10.1071/WF02057

Russell-Smith J, Edwards AC, Cook GD (2003) Reliability of biomass burning estimates from savanna fires: Biomass burning in northern Australia during the 1999 biomass burning and lightning experiment B field campaign. *Journal of Geophysical Research* **108**, 8405. doi:10.1029/2001JD000787

Ryan KC, Noste NV (1985) Evaluating prescribed fires. In 'Proceedings of the symposium and workshop on wilderness fire. 15–18 November 1983, Missoula, MT'. (Eds JE Lotan, BM Kilgore, WC Fischer, RW Mutch) pp. 230–238. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-GTR-182. (Ogden, UT)

Ryan KC, Reinhardt ED (1988) Predicting postfire mortality of seven western conifers. *Canadian Journal of Forest Research* **18**, 1291–1297.

Sa ACL, Pereira JMC, Vasconcelos MJP, Silva JMN, Ribeiro N, Awasse A (2003) Assessing the feasibility of sub-pixel burned area mapping in miombo woodlands of northern Mozambique using MODIS imagery. *International Journal of Remote Sensing* **24**, 1783–1796. doi:10.1080/01431160210144750

Salvador R, Valeriano J, Pons X, Díaz-Delgado R (2000) A semi-automatic methodology to detect fire scars in shrubs and evergreen forests with Landsat MSS time series. *International Journal of Remote Sensing* **21**, 655–671. doi:10.1080/014311600210498

Scholes RJ, Kendall J, Justice CO (1996) The quantity of biomass burned in southern Africa. *Journal of Geophysical Research* **101**, 23 667–23 676. doi:10.1029/96JD01623

Scott DF, Van Wyk DB (1990) The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment. *Journal of Hydrology* **121**, 239–256. doi:10.1016/0022-1694(90)90234-O

Scott JH (1999) NEXUS: A system for assessing crown fire hazard. *Fire Management Notes* **59**(2), 20–24.

Seielstad CA, Queen LP (2003) Using airborne laser altimetry to determine fuel models for estimating fire behavior. *Journal of Forestry* **101**(4), 10–15.

Seielstad CA, Riddering JP, Brown SR, Queen LP, Hao WM (2002) Testing the sensitivity of a MODIS-like daytime active fire detection model in Alaska using NOAA/AVHRR infrared data. *Photogrammetric Engineering and Remote Sensing* **68**, 831–838.

Setzer AW, Pereira AC, Jr (1991) Amazon biomass burnings in 1987 and an estimate of their tropospheric emissions. *Ambio* **20**, 19–22.

Silva JMN, Pereira JMC, Cabral AI, Sa ACL, Vasconcelos MJP, Mota B, Grégoire J-M (2003) An estimate of the area burned in southern Africa during the 2000 dry season using

SPOT-VEGETATION satellite data. *Journal of Geophysical Research* **108**, 8498. doi:10.1029/2002JD002320

Smith AMS (2004) Determining nitrogen volatised within African savanna fires via ground-based remote sensing. PhD Thesis, University of London.

Smith AMS, Hudak AT (2005) Estimating combustion of large downed woody debris from residual white ash. *International Journal of Wildland Fire* **14**, 245–248. doi:10.1071/WF05011

Smith AMS, Wooster MJ (2005) Remote classification of head and backfire types from Modis fire radiative power observations. *International Journal of Wildland Fire* **14**, 249–254. doi:10.1071/WF05012

Smith AMS, Wooster MJ, Powell AK, Usher D (2002) Texture-based feature extraction: application to burn scar detection in Earth Observation satellite imagery. *International Journal of Remote Sensing* **23**, 1733–1739. doi:10.1080/01431160110106104

Smith AMS, Wooster MJ, Drake NA, Perry GLW, Dipotso FM (2005*a*) Fire in African savanna: Testing the impact of incomplete combustion of pyrogenic emission estimates. *Ecological Applications* **15**, 1074–1082.

Smith AMS, Wooster MJ, Drake NA, Dipotso FM, Falkowski MJ, Hudak AT (2005*b*) Testing the potential of multi-spectral remote sensing for retrospectively estimating fire severity in African savanna environments. *Remote Sensing of Environment* **97**, 92–115. doi:10.1016/J.RSE.2005.04.014

Spencer CN, Gabel KO, Hauer FR (2003) Wildfire effects on stream food webs and nutrient dynamics in Glacier National Park, USA. *Forest Ecology and Management* **178**, 141–153. doi:10.1016/S0378-1127(03)00058-6

Spichtinger N, Wenig M, James P, Wagner T, Platt U, Stohl A (2001) Satellite detection of a continental-scale plume of nitrogen oxides from boreal forest fires. *Geophysical Research Letters* **28**, 4579–4582. doi:10.1029/2001GL013484

Stocks BJ, van Wilgen BW, Trollope WSW, McRae DJ, Mason JA, Weirich F, Potgeiter ALF (1996) Fuels and fire behavior on large-scale savanna fires in Kruger National Park, South Africa. *Journal of Geophysical Research* **101**, 23 541–23 550. doi:10.1029/95JD01734

Stronach NRH, McNaughton SJ (1989) Grassland fire dynamics in the Serengeti ecosystem, and a potential method of retrospectively estimating fire energy. *Journal of Applied Ecology* **26**, 1025–1033.

Stroppiana D, Pinnock S, Pereira JMC, Grégoire J-M (2002) Radiometric analysis of SPOT-VEGETATION images for burnt area detection in Northern Australia. *Remote Sensing of Environment* **82**, 21–37. doi:10.1016/S0034-4257(02)00021-4

Tian X, Mcrae DJ, Shu L, Wang M, Li H (2005) Satellite remote-sensing technologies used in forest fire management. *Journal of Forestry Research* **16**, 73–78.

Trigg S, Flasse S (2000) Characterising the spectral-temporal response of burned savanna using in situ spectroradiometry and infrared thermometry. *International Journal of Remote Sensing* **21**, 3161–3168. doi:10.1080/01431160050145045

Trigg S, Flasse S (2001) An evaluation of different bi-spectral spaces for discriminating burned shrub-savanna. *International Journal of Remote Sensing* **22**, 2641–2647.

Trollope WSW, Potgieter ALF (1985) Fire behavior in the Kruger National Park. *Journal of the Grassland Society of South Africa* **2**, 17–22.

Trollope WSW, Trollope LA, Potgieter ALF, Zambatis N (1996) SAFARI-92 characterisation of biomass and fire behaviour in the small experimental burns in Kruger National Park. *Journal of Geophysical Research* **101**, 23 531–23 540. doi:10.1029/96JD00691

Turner MG, Romme WH (1994) Landscape dynamics in crown fire ecosystems. *Landscape Ecology* **9**, 59–77. doi:10.1007/BF00135079

Turner MG, Hargrove WW, Gardner RH, Romme WH (1994) Effects of fire on landscape heterogeneity in Yellowstone National Park, Wyoming. *Journal of Vegetation Science* **5**, 731–742. doi:10.2307/3235886

Turner MG, Romme WH, Gardner RH, Hargrove WW (1997) Effects of fire size and pattern on early succession in Yellowstone National Park. *Ecological Monographs* **67**, 411–433. doi:10.2307/2963464

Turner MG, Romme WH, Garner RH (1999) Prefire heterogeneity, fire severity, and early post-fire plant reestablishment in subalpine forests of Yellowstone National Park, Wyoming. *International Journal of Wildland Fire* **9**, 21–36. doi:10.1071/WF99003

Vafeidis AT, Drake NA (2005) A two-step method for estimating the extent of burnt areas with the use of coarse-resolution data. *International Journal of Remote Sensing* **26**, 2441–2459. doi:10.1080/01431160500034102

van Wagtendonk JW, Root RR, Key CH (2004) Comparison of AVIRIS and Landsat ETM+ detection capabilities for burn severity. *Remote Sensing of Environment* **92**, 397–408. doi:10.1016/J.RSE.2003.12.015

Ventura JMP, Mendes-Lopes JMC, Ripado LMO (1998) Temperature–time curves in fire propagating in beds of pine needles. *Proceedings of the Conference on Fire and Forest Meteorology* **14**, 699–711.

Viedma O, Melia J, Segarra D, Garcia HJ (1997) Modeling rates of ecosystem recovery after fires by using Landsat TM data. *Remote Sensing of Environment* **61**, 383–398. doi:10.1016/S0034-4257(97)00048-5

Vieira NKM, Clements WH, Guevara LS, Jacobs BF (2004) Resistance and resilience of stream insect communities to repeated hydrologic disturbances after a wildfire. *Freshwater Biology* **49**, 1243–1259. doi:10.1111/J.1365-2427.2004.01261.X

Wan S, Hui D, Luo Y (2001) Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: a meta-analysis. *Ecological Applications* **11**, 1349–1365. doi:10.2307/3060925

Wells CG, Campbell RE, DeBano LF, Lewis CE, Fredriksen RL, Franklin EC, Froelich RC, Dunn PH (1979) 'Effects of fire on soil, a state-of-knowledge review.' USDA Forest Service, Washington Office General Technical Report WO-7. (Washington, DC)

Wessman CA, Bateson CA, Benning TL (1997) Detecting fire and grazing patterns in tallgrass prairie using spectral mixture analysis. *Ecological Applications* **7**, 493–511. doi:10.2307/2269515

Whelan RJ (1995) 'The ecology of fire.' (Cambridge University Press: Cambridge)

White JD, Ryan KC, Key CC, Running SW (1996) Remote sensing of forest fire severity and vegetation recovery. *International Journal of Wildland Fire* **6**, 125–136. doi:10.1071/WF9960125

Wilson RA, Hirsch SN, Madden FH, Losensky BJ (1971) 'Airborne infrared forest fire detection system: final report.' USDA Forest Service, Intermountain Forest and Range Experiment Station Research Paper INT-93. (Ogden, UT)

Wondzell SM, King JG (2003) Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. *Forest Ecology and Management* **178**, 75–87. doi:10.1016/S0378-1127(03)00054-9

Wooster MJ (2002) Small-scale experimental testing of fire radiative energy for quantifying mass combusted in natural vegetation fires. *Geophysical Research Letters* **29**, 2027. doi:10.1029/2002GL015487

Wooster MJ, Zhang YH (2004) Boreal forest fires burn less intensely in Russia than in North America. *Geophysical Research Letters* **31**, L20505. doi:10.1029/2004GL020805

Wooster MJ, Shukiv B, Oertel D (2003) Fire radiative energy for quantitative study of biomass burning: Derivation from the BIRD experimental satellite and comparison to MODIS fire products. *Remote Sensing of Environment* **86**, 83–107. doi:10.1016/S0034-4257(03)00070-1

Wooster MJ, Roberts G, Perry GLW, Kaufman YJ (2005) Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release. *Journal of Geophysical Research* **110**, D24311. doi:10.1029/2005JD006318

Wyant JG, Omi PN, Laven RD (1986) Fire-induced tree mortality in a Colorado ponderosa pine/Douglas-fir stand. *Forest Science* **32**, 49–59.

Yokelson RJ, Griffith DWT, Ward DE (1996) Open-path FTIR studies of large-scale laboratory biomass fires. *Journal of Geophysical Research* **101**, 21 067–21 080. doi:10.1029/96JD01800

Yokelson RJ, Bertschi IT, Christian TJ, Hobbs PV, Ward DE, Hao WM (2003) Trace gas measurements in nascent, aged, and cloud-processed smoke from African savanna fires by airborne Fourier transform infrared spectroscopy (AFTIR). *Journal of Geophysical Research* **108**, 8478. doi:10.1029/2002JD002322

Zhang Y-H, Wooster MJ, Tutabalina O, Perry GLW (2003) Monthly burned area and forest fire carbon emission estimates for the Russian Federation from SPOT VGT. *Remote Sensing of Environment* **87**, 1–15. doi:10.1016/S0034-4257(03)00141-X

Zhang Y-C, Rossow WB, Lacis AA, Oinas V, Mishchenko MI (2004) Calculation of radiative fluxes from the surface to top-of-atmosphere based on ISCCP and other global data sets: Refinements of the radiative transfer model and the input data. *Journal of Geophysical Research* **109**, D19105. doi:10.1029/2003JD004457

Zhukov B, Lorenz E, Oertal D, Wooster MJ, Roberts G (2006) Spaceborne detection and characterization of fires during the bi-spectral infrared detection (BIRD) experimental small satellite mission (2001–2004). *Remote Sensing of Environment* **100**, 29–51. doi:10.1016/J.RSE.2005.09.019