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Fire intensity, fire severity and burn severity: a brief review and suggested usage

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Abstract. Several recent papers have suggested replacing the terminology of *fire intensity* and *fire severity*. Part of the problem with *fire intensity* is that it is sometimes used incorrectly to describe fire effects, when in fact it is justifiably restricted to measures of energy output. Increasingly, the term has created confusion because some authors have restricted its usage to a single measure of energy output referred to as fireline intensity. This metric is most useful in understanding fire behavior in forests, but is too narrow to fully capture the multitude of ways fire energy affects ecosystems. Fire intensity represents the energy released during various phases of a fire, and different metrics such as reaction intensity, fireline intensity, temperature, heating duration and radiant energy are useful for different purposes. *Fire severity*, and the related term *burn severity*, have created considerable confusion because of recent changes in their usage. Some authors have justified this by contending that fire severity is defined broadly as ecosystem impacts from fire and thus is open to individual interpretation. However, empirical studies have defined fire severity operationally as the loss of or change in organic matter aboveground and belowground, although the precise metric varies with management needs. Confusion arises because fire or burn severity is sometimes defined so that it also includes ecosystem responses. *Ecosystem responses* include soil erosion, vegetation regeneration, restoration of community structure, faunal recolonization, and a plethora of related response variables. Although some ecosystem responses are correlated with measures of fire or burn severity, many important ecosystem processes have either not been demonstrated to be predicted by severity indices or have been shown in some vegetation types to be unrelated to severity. This is a critical issue because fire or burn severity are readily measurable parameters, both on the ground and with remote sensing, yet ecosystem responses are of most interest to resource managers.

Additional keywords: BAER, dNBR Landsat Thematic Mapper, soil burn severity.

Introduction

In recent papers dealing with post-fire studies, there has been a disturbing number that have acknowledged problems in terminology associated with fire intensity and fire severity (e.g. Simard 1991; Parsons 2003; Jain *et al.* 2004; Lentile *et al.* 2006). These problems are perceived to be sufficiently problematical that alternative terminology has been proposed. Jain *et al.* (2004) suggested that these categories might best be replaced with a continuum of post-fire changes, along the lines of Simard's (1991) space–time continuum of fire issues. It has also recently been suggested that fire intensity and severity be replaced with new categories such as 'active fire characteristics' and 'post-fire effects' (Lentile *et al.* 2006).

The present paper is prompted because of strong agreement about the problems in this terminology, but here I argue for retention of the original terminology as a valuable organizational tool. I believe that much of the confusion can be alleviated by clarification of the original operational definition of these terms and suggest a model that may help clarify the phenomena under consideration (Fig. 1). The emergence of remote imaging technology and its application to fire issues has contributed to some of the problems, in part because the speed of technology development has not always been in sync with our ability to relate it to useful purposes. The basis of some of the problems has been the more recent introduction of the term burn severity and the extension of this term to include not just fire severity, but what are here termed *ecosystem responses* (Fig. 1). A long-standing need by resource managers has been how to utilize different patterns of fire intensity as predictive tools for anticipating post-fire effects. As fire intensity is often not known for most wildfires, fire and burn severity measures are usually the currency for such predictions. Much confusion has arisen because severity is increasingly being measured by a multitude of fire effects that have very different relationships to fire intensity. As discussed below, there is considerable value in keeping fire or burn severity metrics separate from ecosystem responses.

Fire intensity

Fire intensity describes the physical combustion process of energy release from organic matter. Thus, it would be logical to consider the usage of the term 'intensity' in the field of physics,

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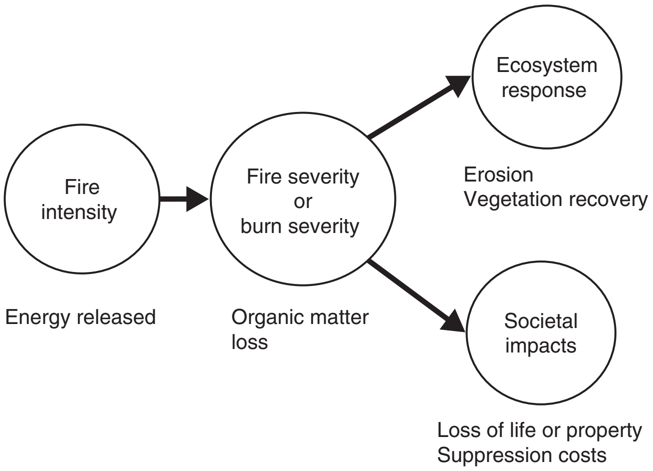

Fig. 1. Schematic representation relating the energy output from a fire (fire intensity), the impact as measured by organic matter loss (fire or burn severity), and ecosystem responses and societal impacts. One of the central themes of the current paper is recognizing the importance of separating fire or burn severity from ecosystem responses. A similar argument could be posed for separating severity and societal impacts but that is not discussed here.

where it is defined as a measure of the time-averaged energy flux or, in other words, the energy per unit volume multiplied by the velocity at which the energy is moving; the resulting vector has the units of $W\,m^{-2}$. Rothermel's (1972) reaction intensity, which represents the heat source in his firespread model, is consistent with this definition. However, fire science, like many other fields, has found a need for a much broader use of the term 'intensity'.

One alternative is fireline intensity, which is the rate of heat transfer per unit length of the fireline ($kW\,m^{-1}$) (Byram 1959). This represents the radiant or convective energy in the flaming front and is an important characteristic for propagation of a fire, and thus is critical information for fire suppression activities and has been incorporated into fire danger rating calculations (Salazar and Bradshaw 1986; Hirsch and Martell 1996; Weber 2001). Increasingly, fireline intensity is presented in the literature as the only appropriate measure for fire intensity (e.g. Johnson 1992; Michaletz and Johnson 2003; Chatto and Tolhurst 2004; Sugihara *et al.* 2006), but this is misleading because it fails to acknowledge that, for many fire scientists, other measures of energy release from fires provide more useful metrics.

Fireline intensity is most frequently used in forested ecosystems as there is a well-developed literature showing a relationship between fireline intensity or flame length and scorching height of conifer crowns and other biological impacts of fire. However, some fire effects are more closely tied to different fire intensity metrics. For example, modeling soil duff consumption requires (among other things) understanding smoldering combustion, which is more related to temperatures at the soil surface and the duration of heating than to fireline intensity (Ryan and Frandsen 1991; Hartford and Frandsen 1992; Valette *et al.* 1994; Miyanishi 2001). Even with tree mortality, fireline intensity often cannot explain mortality patterns because mortality may be more a function of total heat output reflected in flame residence time or a function of smoldering combustion in the duff after the flame front passes (Wade 1993; Sackett *et al.* 1996). Also, the development of non-wettable layers in soil may be more closely related to duration of soil heating (DeBano 2000), and survival of seed banks or rhizomes may be closely tied to duration of heating as well as maximum soil temperatures (Beadle 1940; Flinn and Wein 1977; Auld and O'Connell 1991; Bradstock and Auld 1995; Brooks 2002). Measurements of these other metrics are often required because fireline intensity may be weakly correlated with maximum temperature or heating duration (Bradstock and Auld 1995; Keeley and McGinnis 2007). This should be no surprise as very little radiant or convected heat from combustion of aerial fuels may be transferred to the soil, and often soil temperatures are more dependent on consumption of fine fuels on the surface (Bradstock and Auld 1995). Although fireline intensity provides information for fire managers involved in fire containment, temperature and duration of heating (residence time) may be far more critical information for managers concerned with prescribed burning conditions required to retain sensitive ecosystem components. In addition, the future for fire science will be heavily influenced by remote imaging technologies and these may not always scale with fireline intensity (Smith *et al.* 2005). Other metrics, such as radiative energy appear to be a more readily measurable metric for fire intensity in remote imaging studies of fire impacts (Wooster *et al.* 2003; Dennison *et al.* 2006).

Another reason for not discounting other metrics of fire intensity is that fireline intensity has important limitations, particularly in how it is measured and the ability to make cross-ecosystem comparisons. Byram's fireline intensity assumes that available fuel weight reflects fuels entirely consumed during the flaming phase of combustion as the flame front passes. This metric excludes glowing combustion or post-frontal smoldering, which may continue for many hours or even days after the front passes. Thus, fireline intensity requires that one distinguish fuels consumed by the flaming front from the total fuel consumption. However, fuel consumption usually is estimated as the difference between pre- and post-fire fuel inventories, and this inflates estimates of fireline intensity (Alexander 1982; Scott and Reinhardt 2001). Because of these difficulties, the majority of papers reporting fireline intensity do not measure it directly; rather they use surrogate measures that are assumed to be allometrically related. Typically, flame length is used and much work has gone into methodology development for making such measurements (Ryan 1981; Finney and Martin 1992). Empirical studies show there is a significant relationship between flame length and fireline intensity in forest and shrubland ecosystems (Andrews and Rothermel 1982; Johnson 1992; Wade 1993; Burrows 1995; Fernandes *et al.* 2000). However, in vegetation with a mixture of fine fuels and woody fuels such as palmetto understoreys or grasslands and savanna forests, the relationship is not always reliable (Nelson and Adkins 1986; Catchpole *et al.* 1993; Keeley and McGinnis 2007). Cheney (1990) found that fireline intensity is system-dependent and fires of identical intensities in different fuel beds will have very different flame lengths. Thus, flame length is primarily applicable to fuel types with the same fuel structure characteristics.

In summary, fire intensity represents the energy released during various phases of the fire and no single metric captures all of the relevant aspects of fire energy. Different metrics, including

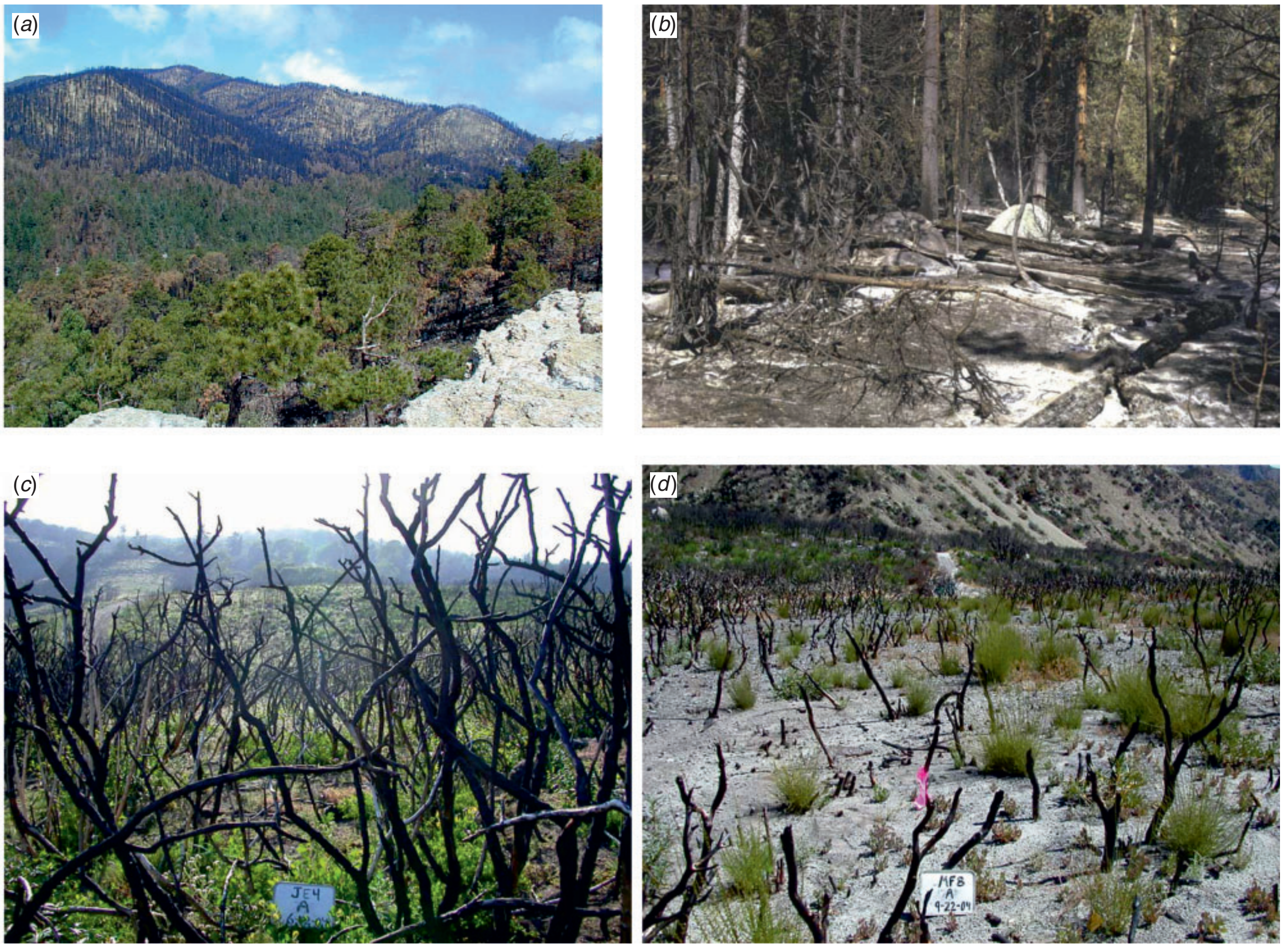

Fig. 2. (*a*) Arizona ponderosa pine forest illustrating different degrees of fire severity; entire scene burned, foreground mostly low severity with patches of scorched canopy of moderate severity and background high severity; (*b*) soil burn severity assessment with characteristics of high severity, including heavy white ash deposition indicating loss of substantial levels of organic matter and loose unstructured soil; (*c*) chaparral shrublands with large shrub skeletons retaining small twigs indicative of low fire severity; and (*d*) high fire severity.

reaction intensity, fireline intensity, temperature, residence time, radiant energy and others are useful for different purposes.

Fire severity

The term fire severity was born out of the need to provide a description of how fire intensity affected ecosystems, particularly following wildfires where direct information on fire intensity was absent and effects are often quite variable within and between different ecosystems (Fig. 2). Some definitions of fire severity have been rather general statements about broad impacts of fires, e.g. the degree of environmental change caused by fire (e.g. White and Pickett 1985; Simard 1991; Jain *et al.* 2004; NWCG 2006), and consequently have not lent themselves to operationally useful metrics. However, most empirical studies that have attempted to measure fire severity have had a common basis that centers on the loss or decomposition of organic matter, both aboveground and belowground. Aboveground metrics such as crown volume scorch used in forests or twig diameter remaining on terminal branches used in forests and shrublands are indicators of biomass loss (e.g. van Wagner 1973; Moreno and Oechel 1989; Tolhurst 1995; Dickinson and Johnson 2001). Soil characteristics include the loss of the litter and duff layers and ash characteristics, all of which reflect to varying degrees the level of organic matter consumed (Wells *et al.* 1979; Stronach and McNaughton 1989; Neary *et al.* 1999; Ice *et al.* 2004).

One of the first metrics for fire severity that captured the essence of how it subsequently has been used empirically was that proposed by Ryan and Noste (1985). They maintained that any metric for fire severity needed to consider the immediate impacts of heat pulses aboveground and belowground, which they noted were directly related to fire intensity. They developed an index that comprised a matrix of vegetation and soil impacts reflecting the degree of organic matter consumed, which in most studies has been simplified to categories of fire severity (Table 1). They, and others (e.g. Cram *et al.* 2006), have found that this index captures the fire intensity signal, and appears to be a function of fireline intensity, residence time (heating duration) and soil and plant dryness (Chatto and Tolhurst 2004). Of course, other factors such as pre-fire species composition, stand age, topography, substrate, and climate will all have some effect on how fire intensity translates into fire severity.

Table 1. The matrix originally proposed by Ryan and Noste (1985) that related changes in aboveground vegetation and soil organic matter to fire severity has generally been simplified to a table such as that below; modified from Ryan (2002) and Turner *et al.* (1994)

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

Many studies that report fire severity have used an index similar to that in Table 1 or at least an index based on the concept of organic matter loss, such as crown volume scorch or tree mortality, and these have been shown to be correlated with measures of fire intensity (Buckley 1993; Williams *et al.* 1998; Catchpole 2000). Depending on the focus of the study, they may report only on vegetation or on soils. For example, the BAER (Burned Area Emergency Response) assessment, which is conducted by USA federal (and some state) government agencies, has traditionally focussed on soil changes induced by fire and has often referred to this as the *soil burn severity* assessment (see Burn severity section). In these soil assessments, the metric is largely based on loss of soil organic matter or deposition of ash from the aboveground combustion of biomass (Lewis *et al.* 2006). Other parameters that are sometimes included in this assessment of fire severity impacts to soils include changes in soil structure, increased hydrophobicity, and iron oxidation, many of which are indirectly tied to organic matter decomposition as well. Of course, the purpose of such assessments is not because of any perceived need to determine organic matter loss, but rather because it is presumed that these are keys to other impacts (discussed under Ecosystem response). Whether or not studies have used the Ryan and Noste (1985) index in its entirety, most have used metrics that depend on loss of organic matter and in that respect share the same functionality as that index.

Remote sensing studies have found a good correlation between LANDSAT measures, particularly the Normalized Difference Vegetation Index (NDVI), and fire severity estimates based on biomass loss (e.g. Turner *et al.* 1994; Conard *et al.* 2002; Miller and Yool 2002; Chafer *et al.* 2004). Much of this work has been done in forests and woodlands, and studies that have sampled more broadly have found that the vegetation type markedly influences the detection of fire severity (Hammill and Bradstock 2006).

Plant mortality, which is also a measure of biomass loss, is often included in fire severity metrics, or sometimes the fire severity metric is based entirely on mortality (e.g. Chappell and Agee 1996; Larson and Franklin 2005), and numerous studies have shown it is correlated with fire intensity (e.g. Wade 1993; McCaw *et al.* 1997). Tree mortality has been widely used as a measure of fire severity in conifer forests in North America that historically have been exposed to low-severity or mixed-severity fire regimes where normally there is substantial tree survival. In these forests, the dominant trees are non-sprouting species, so that aboveground mortality reflects mortality of the entire genet. One limitation to using mortality is that it sometimes is not evident for a year or more after a fire event. Where the use of mortality becomes problematical is when it is applied to understorey species in many forest types or to dominant species in crown-fire ecosystems such as shrublands. In these species, the aboveground ramets are nearly always killed, but some percentage survives belowground. Several problems are encountered when the degree of resprouting is incorporated into the fire or burn severity index (e.g. Key and Benson 2006). Many species are innately incapable of resprouting (Keeley 1981) and in these species failure to resprout is clearly unrelated to fire intensity. As communities differ substantially in the proportion of sprouting to non-sprouting species, this would need to be considered in using sprouting capacity as a measure of fire severity. Also, within resprouting species there is substantial variation in resprouting capacity that is related to species-specific differences (Vesk and Westoby 2004) and plant age (Keeley 2006*a*). Considering these factors, it is suggested that resprouting should not be included as a measure of fire severity, and, as discussed below, is best viewed as an ecosystem response variable.

In summary, fire severity refers to the loss or decomposition of organic matter aboveground and belowground. Metrics for this parameter vary with the ecosystem. Including mortality is consistent with the definition of fire severity as a loss of organic matter; however, it is only advisable when dealing with forest trees that lack any resprouting capacity. Fire severity is correlated with fire intensity.

Burn severity

The term *burn severity* has gained popularity in recent years, but it has caused some confusion because it is often used interchangeably with fire severity, and often is based on metrics similar to fire severity measurement (e.g. White *et al.* 1996; Turner *et al.* 1999; Rogan and Franklin 2001). In the US BAER assessments, the term burn severity has replaced fire severity, although the metric is very similar and is largely based on loss of organic matter in the soil and aboveground organic matter conversion to ash. In the recent 'Glossary of Wildland Fire Terminology', the term burn severity is restricted to the loss of organic matter in or on the soil surface (NWCG 2006), and in this respect represents what BAER assessments term 'soil burn severity' (Parsons 2003).

Remote sensing applications to assess burned areas typically use the term burn severity rather than fire severity, and as remote sensing has increased in burned area assessments, so has the use of the term burn severity. In some of the initial studies of remote sensing applications to burned area assessments, the term burn severity was used for the index calculated from the satellite sensors (van Wagtendonk *et al.* 2004). Various remote sensors (e.g. MODIS, AVIRIS) have been tested for their ability to match field measurements of severity and the Landsat Thematic Mapper sensor is widely accepted as most appropriate for this task (van Wagtendonk *et al.* 2004; Brewer *et al.* 2005; Cocke *et al.* 2005; Epting *et al.* 2005; Chuvieco *et al.* 2006; but cf. Roy *et al.* 2006; Kokaly *et al.* 2007). These remote-sensing data are used to generate an index known as the differenced Normalized Burn Ratio (dNBR), which is a preferable term over burn severity as it keeps separate the remote imaging index from surface measurements of the burned site.

BAER assessments are now commonly expedited by the use of satellite sensing data that usually, but not always, use the dNBR index to produce a burn severity map of conditions on the ground, and this is termed the Burned Area Reflectance Classification (BARC). There appears to be a reasonably good correlation between these BARC map categories and field assessments of fire severity (Bobbe *et al.* 2004; Robichaud *et al.* 2007*b*); however, because the assessments must be done very soon after the fire, it is not always possible to coordinate satellite pass-over with clear skies.

In many remote sensing studies, field validation of the method has used metrics of fire severity, i.e. organic matter loss through combustion or mortality with regards to the approach used by Ryan and Noste (1985), although sometimes using the term burn severity (White *et al.* 1996; Rogan and Franklin 2001; Miller and Yool 2002; Chafer *et al.* 2004; Hammill and Bradstock 2006; Roldán-Zamarrón *et al.* 2006).

In recent studies using remote-sensing indices, field validation has used the term burn severity in a way that diverges from the concept of fire severity as a measure of just organic matter loss; rather, in these studies, burn severity defines a much broader collection of attributes that include both fire severity and ecosystem responses (van Wagtendonk *et al.* 2004; Cocke *et al.* 2005; Epting *et al.* 2005; Chuvieco *et al.* 2006). This approach uses a measure called the *composite burn index* (CBI) designed to provide a single index to represent many different phenomena of interest to land managers (Key and Benson 2006). The CBI combines fire severity metrics and ecosystem responses that include resprouting of herbs, shrubs and hardwood trees, and seedling colonization. Recent studies of several major fires in southern California raise concerns about the value of combining fire severity and ecosystem responses into a single 'composite' index (Box 1). These studies show that although dNBR is significantly correlated with field measurements of fire severity, this signal is not necessarily a good predictor of ecosystem responses. This is critical because the remote sensing signal is most important to land managers only as far as it is a predictor of ecosystem responses. The potential for remote-sensing techniques to contribute to post-fire management has not yet been fully realized and it is suggested that this will develop best if we parse out the separate contributions of fire severity and ecosystem response (Fig. 1).

In summary, when the term burn severity is used interchangeably with fire severity, it may lead to some minor confusion but this is not a significant problem. However, where the term has been defined to include fire severity and ecosystem responses, it may lead to a significant amount of confusion as it has the potential for confounding factors with different effects. It is recommended that fire (or burn) severity and ecosystem responses be evaluated separately.

Ecosystem response

Fire intensity, fire severity and burn severity are operationally tractable measures, but they are largely of value only so far as they can predict ecosystem responses such as soil erosion or natural revegetation. In predicting ecosystem responses, fire scientists may take one of two approaches: the descriptive approach or the process-based approach (Johnson and Miyanishi 2001; Michaletz and Johnson 2003). The former yields statistical descriptions of relationships between, for example, fire intensity and fire severity, or fire severity and ecosystem responses, and this is often the only approach available when studying impacts of wildfires. Under more controlled experimental conditions, one can use the process-based approach that studies the direct path from measures of fire intensity to fire severity or from fire intensity to ecosystem response variables, and tests underlying mechanisms. Regardless of the path studied, it is clear that many biotic and abiotic factors also enter into the relationship between fire intensity and ecosystem response (e.g. Peterson and Ryan 1986; Neary *et al.* 1999; Moody and Martin 2001; Pérez-Cabello *et al.* 2006).

Statistical studies show correlations between fire intensity and fire severity metrics (e.g. McCaw *et al.* 1997) and between different measures of fire severity and ecosystem responses. For example, in forests it has been shown that fire severity is tied to forest recovery and alien plant invasion (Turner *et al.* 1999; Wang and Kemball 2003) and belowground changes in fauna and flora (Neary *et al.* 1999). In forests and shrublands prone to crown fires, increased fire severity has been correlated with decreased resprouting of herbs and shrubs (Flinn and Wein 1977; Keeley 2006*a*). Fire severity has also been correlated with ecosystem responses such as species richness and patterns of seedling recruitment (Whelan 1995; Bond and van Wilgen 1996; Ryan 2002; Keeley *et al.* 2005; Johnstone and Chapin 2006). In some shrublands, high fire severity is correlated with reduced alien plant invasion (Keeley 2006*b*; Keeley *et al.* 2008). In Canadian boreal forests, fire severity may be correlated with long-lasting impacts on forest regeneration and carbon storage (Lecomte *et al.* 2006). However, some ecosystems responses such as vegetative recovery or resprouting after

Box 1. Interpreting the Landsat differenced Normalized Burn Ratio (dNBR) signal in terms of fire severity and ecosystem response in crown-fire chaparral shrublands

In late October 2003, five large wildfires burned more than 200 000 ha in southern California. A total of 250 0.1-ha plots were sampled in these burned areas to assess fire severity and vegetation recovery (Keeley *et al.* 2008). Fire severity was assessed using the twig diameter method commonly used in crown fire ecosystems (Moreno and Oechel 1989; Perez and Moreno 1998) on multiple samples of the same shrub (*Adenostoma fasciculatum*) at all sites. Vegetation recovery was based on plant cover in the first spring following fires. The early assessment dNBR data were provided by EROS data center (US Geological Survey, Sioux Falls, SD).

The Landsat TM index was strongly correlated with field measurement of fire severity (Fig. 3*a*), explaining over a third of the variation between these 250 sites. However, if dNBR is then used to predict ecosystem response variables, there is little or no relationship. Total vegetative recovery (Fig. 3*b*) was very weakly related to dNBR and explained only ~1% of the variation, and there was no significant relationship with woody cover ($P = 0.94$, not shown), or percentage of the pre-fire *Adenostoma fasciculatum* population resprouting (Fig. 3*c*). These results argue against the concept of a composite burn index that mixes fire severity and ecosystem responses, even if such composites generate significant relationships with dNBR. For example, a standardized index that includes fire severity (Fig. 3*a*) and the two ecosystem impact variables (Fig. 3*b*, *c*) was created, and it did generate a highly significant relationship with dNBR ($P < 0.000$), but clearly this 'composite index' is driven by the fire severity response variable (Fig. 3*a*) and the dNBR index is not conveying information about ecosystem responses.

Further complications arise with composite indices when adding in terms that have species-specific differences in the direction of response. For example, in this dataset, fire severity was slightly negatively correlated with log seedling recruitment of facultative-seeding shrubs, whereas fire severity was positively correlated with obligate seeding shrub recruitment. These shrublands may be an example in which remote-sensing data can provide some information on fire severity but has limited predictive ability for ecosystem impacts, thus requiring coupling of remote-sensing data with field studies (e.g. Ludwig *et al.* 2007).

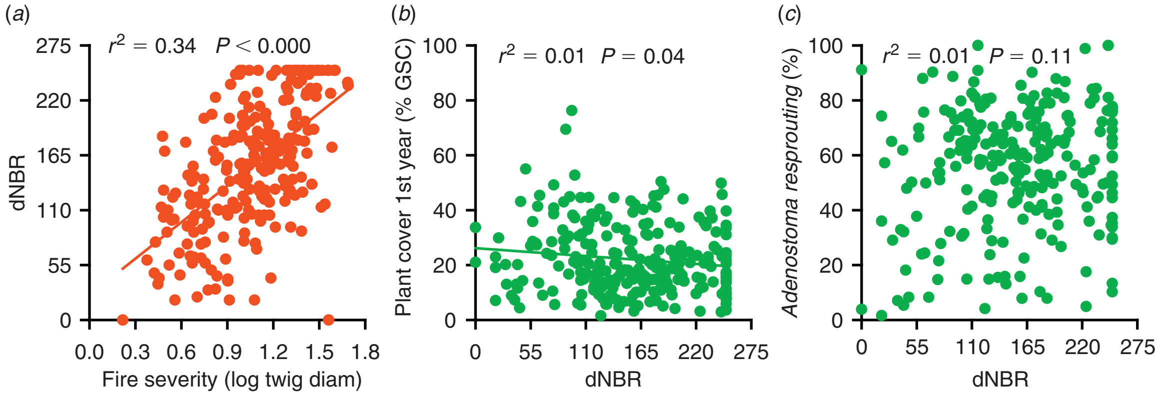

Fig. 3. Relationship of Landsat TM differenced Normalized Burn Ratio (dNBR) based on spectral analysis of Landsat TM sensing data taken in the first growing season after the fall (autumn) 2003 wildfires in southern California chaparral (scaled from 0 to 250) to (*a*) field measurement of fire severity and the extent to which dNBR can predict ecosystem response variables of (*b*) first-year plant cover and (*c*) resprouting percentage of the common shrub *Adenostoma fasciculatum*, for 250 sites distributed across the Otay, Cedar, Paradise, Old and Grand Prix fires (Landsat imagery from the US Geological Survey, Earth Resources Observation Systems Center; field data from Keeley *et al.* 2008).

fire are not correlated with fire severity measures on the ground or with remote-sensing indices (Box 1).

Process-based studies can provide a mechanistic basis for translating fire intensity measures directly into fire severity impacts such as tree mortality as well as ecosystem responses such as erosion. One of the clearest examples is the use of heat transfer models of the flame and plume heat into a plant to account for tree mortality patterns (Gill and Ashton 1968; Dickinson and Johnson 2001). Mercer *et al.* (1994) demonstrated that seed survival in woody fruits was predicted by a mathematical model that used heat-flow equations with time-dependent temperature inputs and used this model to predict seed survival in the field. Temperature response curves for seed survival, when coupled with field measures of fire intensity, also provide predictive models for subsequent seedling recruitment (Keeley and McGinnis 2007).

A major reason for post-fire assessments of fire or burn severity is because it is believed to be an important indicator of the potential for water runoff and erosion (Robichaud *et al.* 2000; Wilson *et al.* 2001; Ruiz-Gallardo *et al.* 2004; Lewis

Table 2. Summary of fire terminology and metrics

	Fire intensity	Fire severity	Burn severity	Ecosystem responses
Appropriate usage	Energy output from fire.	Aboveground and belowground organic matter consumption from fire.	Aboveground and belowground organic matter consumption from fire. Sometimes subdivided into 'vegetation burn severity' and 'soil burn severity'.	Functional processes that are altered by fire including regeneration, recolonization by plants and animals and watershed hydrology processes altered by fire.
Metrics	Strictly speaking it is the time-averaged energy flux in W m^{-2}, but more broadly can be measured as fireline intensity, temperature, residence time, radiant energy and other.	Aboveground measures include tree crown canopy scorch, crown volume kill, bole height scorch, skeleton twig diameter. Belowground and soil measures include ash deposition, surface organic matter, belowground organic matter contributing to soil structure, degree of hydrophobicity, and heat-induced oxidation of minerals. Mortality is a common measure that is best applied to non-sprouting trees in surface fire regimes. In crown fire regimes, aboveground mortality may be useful when fires are patchy.	Often used interchangeably with fire severity. Usually the term is applied to soils and designated 'soil burn severity'. In the USA, it is the preferred term used in post-fire Burned Area Emergency Response assessments and is considered to be the relative change due to fire, i.e. two soils with poor structure and low organic matter content may be rated differently if one was in that condition before the fire and another was not. Degree of severity may be influenced by socio-political concerns such as values at risk.	Vegetative cover, seedling recruitment, plant community composition and diversity, and plant and animal recolonization are important biotic parameters. Watershed hydrological processes such as dry ravel, erosion, and debris flows are the more important abiotic processes.
Inappropriate usage	Should never be used to describe fire effects such as those described under any of the remaining columns.	Should not include ecosystem responses. Also, in shrubland ecosystems, complete above- and belowground mortality should not be considered here because it depends on vegetation composition and the proportion of sprouting and non-sprouting species.	Should not include ecosystem responses. Also, this term should be restricted to field measurements and not be used to name remote-sensing indices because the interpretation of remote data is dependent on ground-truthing with field measurements of burn severity; calling both measures burn severity is circular.	Correlations between severity and ecosystem responses demonstrated in one system should not be considered universal for all ecosystems.

et al. 2006). Indeed, it is sometimes stated that these severity measurements are indicators of changes in soil hydrologic function (Parsons 2003; Ice *et al.* 2004). Conceptually, this inference is logical based on various types of indirect evidence. For example, loss of aboveground biomass exposes more soil surface, which increases the kinetic force of precipitation on the soil surface and that can increase overland flow (Moody and Martin 2001). Also, loss of soil organic matter alters the binding capacity of soil and results in other structural changes that can affect erosional processes (Hubbert *et al.* 2006). Post-fire increases in soil water repellency due to hydrophobic soil layers are tied, albeit sometimes weakly, to fire severity (Robichaud 2000; Lewis *et al.* 2006), although in some ecosystems, soil hydrophobicity is unrelated to fire severity (Cannon *et al.* 2001; Doerr *et al.* 2006).

In general, there is little direct evidence that fire severity measurements are a reliable indicator of specific changes in hydrologic or other ecosystem functions (Robichaud *et al.* 2000; González-Pelayo *et al.* 2006), and some even suggest that fire severity classifications are unsuitable for predicting fire impacts on soil hydrological responses (Doerr *et al.* 2006). The primary reason is that ecological responses such as erosion, overland water flow and debris flows are affected as much by topography, soil type, rates of weathering, fire-free interval, and precipitation as they are by fire severity (Cannon *et al.* 2001; Moody and Martin 2001; Nearing *et al.* 2005). In short, the factors responsible for hydrologic responses to fire are multi-factorial and until we have better mechanistic models explaining these phenomena, it would be prudent to keep separate the metric for fire or burn severity from inferred ecosystem responses. Applied efforts focussed on this include the Erosion Risk Management Tool (ERMiT) (Robichaud *et al.* 2007*a*).

Ecosystem responses include those processes that are differentially affected by fire intensity, measured either directly, or indirectly with fire severity metrics, and include erosion, vegetation regeneration, faunal recolonization, restoration of community structure and a plethora of other response variables. Predicting how fire intensity or severity will affect these responses is critical to post-fire management.

Conclusions

A summary of the appropriate and inappropriate use of these terms is presented in Table 2. Fire intensity is the energy output from fire and should not be used to describe fire effects. Fire severity and burn severity have been used interchangeably and operationally have generally emphasized degrees of organic matter loss or decomposition both aboveground and belowground. Both are positively correlated with fire intensity. Significant confusion has arisen from rather broad definitions for fire or burn severity that include ecosystem responses. Another source of confusion has arisen by using these terms for remote-sensing indices, and separate terms such as BARC or dNBR are preferable. Ecosystem responses include vegetative regeneration and faunal recolonization as well as abiotic watershed hydrologic processes. Some of these have been directly correlated with fire intensity and others indirectly with fire or burn severity metrics. It is important to recognize that ecosystem responses may be positive, negative or neutral in their response to fire intensity and severity.

The present approach has value for resource managers because it emphasizes the distinction between measures of severity after a fire and the resource impact of the fire. Most managers are not specifically interested in severity measures *per se*, but rather the extent to which they reflect potential ecosystem responses. Metrics that combine burn severity and measures of vegetative recovery can provide misinformation when those measures are not correlated (Box 1). It is recommended that field measurements of severity be restricted to measures of organic matter loss, such as canopy scorch or ash deposition and these be analyzed separately from measures of ecosystem response such as vegetative regeneration. Mortality needs to be evaluated with consideration of species-specific traits. Mortality is a straightforward measure in most conifer-dominated forests but in other ecosystems, it can only be evaluated in the context of pre-fire community composition because of species-specific differences in resprouting capacity.

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