CSIRO PUBLISHING

International Journal of Wildland Fire **2017**, *26*, 930–943
https://doi.org/10.1071/WF17023

Multidecadal trends in area burned with high severity in the Selway-Bitterroot Wilderness Area 1880–2012

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Abstract. Multidecadal trends in areas burned with high severity shape ecological effects of fires, but most assessments are limited to ~30 years of satellite data. We analysed the proportion of area burned with high severity, the annual area burned with high severity, the probability areas burned with high severity and also the area reburned (all severities and high burn severity only) over 133 years across 346 265 ha within the Selway-Bitterroot Wilderness (SBW) Area in Idaho, United States. We used burn severity class inferred from digitised aerial photography (1880–2000) and satellite imagery (1973–2012). Over this long record, the proportion burned with high severity did not increase, despite extensive area burned in recent decades. Much greater area burned with high severity during the Early (1880–1934) and Late (1975–2012) periods than during the Middle period (1935–1974), paralleling trends in area burned. Little area reburned with high severity, and fires in the Early period limited the extent of fires burning decades later in the Late period. Our results suggest that long-term data across large areas provides useful context on recent trends, and that projections for the extent and severity of future fires must consider prior fires and fire management.

Additional keywords: fire ecology, fire regimes, fire severity, remote sensing.

Received 5 February 2017, accepted 8 August 2017, published online 25 October 2017

Introduction

The degree of ecological change resulting from fire, referred to as burn severity (Morgan *et al.* 2001, 2014*b*; Lentile *et al.* 2006; Keeley 2009*b*), influences vegetation response, erosion potential, wildlife habitat and other values (Turner *et al.* 1997; Lentile *et al.* 2007; Keeley *et al.* 2009; Romme *et al.* 2011; Hutto *et al.* 2016), yet we know little about long-term trends in burn severity. Burn severity can be inferred from satellite imagery, enabling analysis of trends for large areas. Assessing temporal trends in burn severity is an active area of research. For example, whereas some have concluded that burn severity has increased in the Sierra Nevada (Miller *et al.* 2009; Miller *et al.* 2012*a*, 2012*b*; Mallek *et al.* 2013), others have concluded this is not the case (Collins *et al.* 2009; Hanson and Odion 2014). Dillon *et al.* (2011) documented that burn severity increased in the southern Rocky Mountains but not in four other ecoregions in the western United States (US). It may be that these studies are often conflicting and inconsistent because the time series is relatively short (~30 years) and prior fires could alter effects of recent fires. The Landsat Thematic Mapper (TM) record upon which most remotely-sensed burn severity assessments are based began in 1984 (Dillon *et al.* 2011). Given changing climate and land management and historical fire return intervals in many forest ecosystems that exceed that of the satellite record, many temporal trend assessments are hampered by a time series that is short. Consequently, longer time series over large areas will help to refine our understanding of temporal changes in proportion of area burned with high severity (Cansler and McKenzie 2014) and provide context for evaluating the effects of recent large fires and expected future fires.

Although underutilised, aerial photography can be used to infer fire perimeters and patch dynamics (Minnich and Chou 1997; Hessburg *et al.* 2000, 2007) and to extend the temporal range beyond what is available from satellite data. We used both historical aerial photography and satellite imagery to examine trends in areas burned with high severity from 1880 to 2012.

This time period coincides with highly variable decadal fire activity and changing fire management (Morgan *et al.* 2008) and climate (Higuera *et al.* 2015). In the western US, wildfires have burned extensive areas in recent decades. More large fires are likely in the future, especially in forests of the US northern Rockies (Littell *et al.* 2009; Westerling 2016). As more area burns, more area burns with high severity (Holden *et al.* 2012), but if the proportion burned with high severity has increased, this could represent a shift in fire regime and the ecological effects of fire.

Areas burned with high severity concern policy makers, scientists and managers. They are ecologically important (Hutto *et al.* 2016).

Repeat fires, hereafter reburns, occur when a previously burned area burns again over the time period of interest (van Wagtendonk *et al.* 2012). Because previous fires often affect the extent and burn severity of subsequent fires (Collins *et al.* 2009; Teske *et al.* 2012; Parks *et al.* 2014; Harvey *et al.* 2016; Holsinger *et al.* 2016; Stevens-Rumann *et al.* 2016), the probability of reburn likely depends on several factors, such as geography, topography, fire regime characteristics, climatic variability (especially extreme weather) and vegetation response to the initial fires. Most reburn assessments are conducted using ~30 years of satellite imagery; a longer time frame encompassing varying climate, fire management and prior fire history will help inform our understanding of the degree to which fires are self-regulating (Stevens-Rumann *et al.* 2016). To the extent that prior fires influence the extent and burn severity of subsequent fires, projections for increased area burned under a changing climate need to incorporate this feedback (Prichard *et al.* 2017).

Historical area burned in the Selway-Bitterroot Wilderness has been well studied. Extensive area burned before 1935 (Early period) and after 1974 (Late period), but little area burned in the middle 1900s (Middle period, Morgan *et al.* 2008, 2014*a*). Fire management varied (Rollins *et al.* 2001; Haire *et al.* 2013) as did climate (Morgan *et al.* 2008; Higuera *et al.* 2015). In the Early period, fires typically burned without suppression because it was difficult to detect and suppress fires in the remote, rugged montane terrain. During the Middle period, fire suppression was effective given improved technology and the large number of firefighters, including smoke jumpers. The US *Wilderness Act of 1964* established the Selway-Bitterroot Wilderness Area with the goal of having an area that is managed to reflect the forces of nature (McCloskey 1966). Consequently, fires were managed to play a more natural role in the Late period, but only under carefully defined conditions (Frost 1982; Rollins *et al.* 2001). Fires have the potential to become quite large in wilderness and other remote areas when they are managed to accomplish resource benefits or when they are being suppressed but are low priority during periods of widespread fire activity (Steelman and McCaffrey 2011; North *et al.* 2012; Morgan *et al.* 2014*a*). Extensive fires in Idaho in 1910 and again in 1934 and 2000 (and other years) have greatly influenced national fire management policy (Pyne 2016). Climate has an important and changing influence on area burned (Morgan *et al.* 2008; Higuera *et al.* 2015) in the surrounding region. Morgan *et al.* (2008) and Higuera *et al.* (2015) found that drought was more pronounced Early and Late than in the Middle period when both springs and summers were relatively cool. Morgan *et al.* (2008) attributed the lower area burned in the Middle period to both climate and fire management, as a cooler/wetter climate facilitated effective fire suppression compared with the Early and Late periods.

Our objectives were to:

1) Evaluate if burn severities inferred from historical aerial photographs and satellite imagery are similar
2) Examine annual trends in a) area burned with high severity, b) proportion burned with high severity, and c) annual probability of burning with high severity. We evaluated if these increased in time and how they varied for three time periods reflecting different past fire management (Rollins *et al.* 2001; Haire *et al.* 2013; Morgan *et al.* 2014*a*) and climate (Morgan *et al.* 2008; Higuera *et al.* 2015), and how these were all influenced by time period and time since previous fire (Parks *et al.* 2014, 2015*a*)
3) Quantify the correlation between area and proportion burned with high severity across multiple decades
4) Quantify the area reburned in all burn severity classes and then compare observed to expected extent of area burned with high severity.

We expected to find that the relative lack of fire in the mid-20th century due to both climate (Heyerdahl *et al.* 2008; Morgan *et al.* 2008, 2014*a*; Higuera *et al.* 2015) and fire suppression (Rollins *et al.* 2001) would be followed by an increase in recent decades in area burned with high severity and proportion burned with high severity reflecting the extensive area burned in recent decades (Morgan *et al.* 2014*a*). We expected area burned with high severity, but not proportion burned with high severity, to be correlated with total annual area burned across multiple decades as both Dillon *et al.* (2011) and Birch *et al.* (2014) found. We expected that relatively little area reburned, as previous fires limit the extent and severity of subsequent fires even through many decades. We focus on temporal trends here, though we fully recognise that changing climate, previous fires, topography and vegetation influence fires and fire effects (Morgan *et al.* 2008; Dillon *et al.* 2011; Mallek *et al.* 2013; Parks *et al.* 2014; Stevens-Rumann *et al.* 2016; Prichard *et al.* 2017). In this large wilderness area, we can study the temporal patterns of high burn severity with few confounding effects such as grazing, roads and timber harvest. Our 133-year fire record extends well before the recent decades commonly assessed with satellite imagery.

Methods

Study area

We analysed area burned from 1880 to 2012 for 346 265 ha within the Selway River Watershed within the Selway-Bitterroot Wilderness (SBW) (Fig. 1). With elevations ranging from 550 m to 3050 m, the climate in the SBW varies widely (Finklin 1983). This is an inland-maritime climate (Finklin 1983). Mean temperatures from 1931 to 2012 ranged from −10°C to −1°C in January and from 8°C to 21°C in July in the central mountains of Idaho (www.ncdc.noaa.gov/cag/time-series/us, accessed 28 June 2017). Most of the precipitation falls as snow, and snowpack in the upper elevations usually persists through late June (Finklin 1983). January is typically the wettest month with

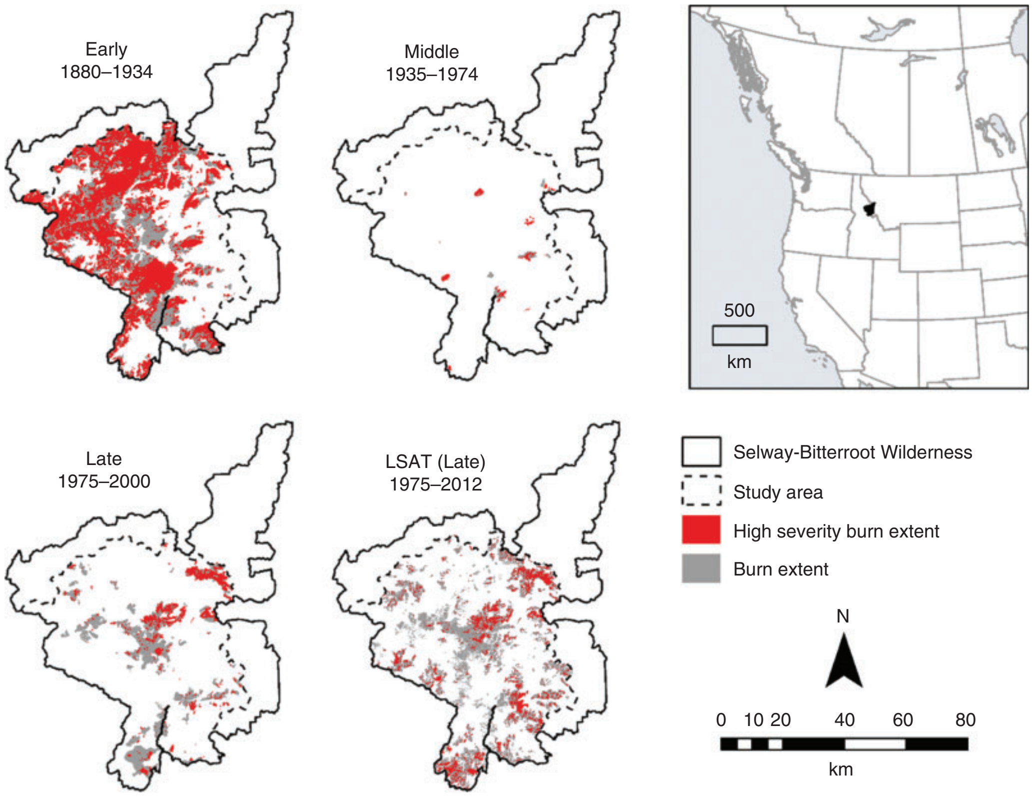

Fig. 1. The Selway-Bitterroot Wilderness Area (SBW) on the border of Idaho and Montana. Our study area (the SBW watershed) encompasses 346 265 ha within the Selway-Bitterroot Wilderness. Red areas represent the high severity burn portion of total burn area, with moderate and low severities indicated in grey. All maps illustrate HAPS data except map at lower right that is based on 1975–2012 LSAT data. Our two data sources are HAPS [historical aerial photograph severity, inferred from historical aerial photos and other historical data for fires from 1880 to 2000 (P. Green, unpubl. data)] and LSAT [Landsat satellite-inferred burn severity for fires from 1973 to 2012 (Parks *et al.* (2015*b*)].

~75–250 mm falling as snow, summer months are the driest with only 20–30 mm falling as rain (Finklin 1983).

The forests of the study area vary with topography (Habeck 1972). Cold forests are found at high elevations (Morgan *et al.* 2014*a*). These subalpine forests cover nearly 70% (Rollins *et al.* 2001) of the area in the SBW. They primarily consist of subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), lodgepole pine (*Pinus contorta* Douglas ex Loudon), Engelmann spruce (*Picea englemannii* Parry ex Englem.), whitebark pine (*Pinus albicaulis* Douglas) and subalpine larch (*Larix lyallii* Parl.). On drier sites at lower elevations, the forests are dominated by ponderosa pine (*Pinus ponderosa* Lawson and C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Morgan *et al.* 2014*a*). Mesic forests are dominated by grand fir, western redcedar (*Thuja plicata* Donn ex D. Don.) and western hemlock (*Tsuga heterophylla* [Raff.] Sarg.) (Morgan *et al.* 2014*a*).

Two burn severity datasets, for 1880–2000 and 1973–2012

We used fire perimeters and burn severities from two datasets (Fig. 1). For 1880–2000, we used burn severity polygons inferred from aerial photography; hereafter historical aerial photograph severity (HAPS). We obtained satellite-inferred burn severity for all fires ≥20 ha that occurred from 1973–2012 from Parks *et al.* (2015*b*); hereafter LSAT. In this latter dataset, burn severity was inferred using Multi-Spectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors using the delta Normalized Differenced Vegetation Index (dNDVI) derived from pre- and post-fire image pairs. The dNDVI isn't as commonly applied in burn severity studies as the delta Normalized Burn Ratio (dNBR), but NDVI can be calculated from all three Landsat sensors whereas MSS lacks the short-wave infrared channel needed to calculate NBR.

HAPS data consisted of fire year, fire perimeter and burn severity class (unburned, low, moderate and high) interpreted from fire atlases and aerial photographs as part of another study (P. Green, unpublished). Green, a fire ecologist with extensive experience in field and aerial photo interpretation in the study area, used fire atlases from the Nez Perce and Bitterroot National Forests to digitise fire perimeters onto 1:24 000 orthophoto topographic maps, and then used aerial photographs to refine fire boundaries and delineate burn severity classes within the fire perimeters. She used the earliest aerial photographs available, which were taken from 1932 to 1939, and supplemented them with more recent aerial photographs from 1948, 1954, 1970, 1980, 1985, 1991, 1994 and 1995; photograph scales varied from 1:12 000 to 1:24 000. Green also drew upon visual interpretation of Landsat TM images from 1996 and 2000 and other historical documents, including the USDA Forest Service (1910–1940) Nez Perce National Forest fire perimeter map, the Survey of the Bitterroot Forest Preserve 1898 (Leiberg 1899), USDA Forest Service (1914) Selway National Forest Land Classification, the Report on the Forestal Conditions and Possibilities of the Clearwater National Forest (Shattuck 1910), and Habeck's (1972) Report on Fire Ecology Investigations in the Selway-Bitterroot Wilderness. Burn severity classes were assigned based upon percent mortality of overstory trees, with low burn severity classified as less than 30% mortality, moderate as 30–70% mortality and high burn severity as greater than 70% mortality, based on snags and percentages of forest openings (Morrison and Swanson 1990).

To infer high severity with LSAT, we used the HAPS data to train a burn severity classification of the 1973–2012 LSAT dNDVI values, based on fires recorded in both datasets during the 1973–2000 period of overlap (see Appendix 1). We used a classification and regression tree (CART) algorithm (Breiman *et al.* 1984) to identify dNDVI thresholds that best fit the HAPS high burn severity classification (see Appendix 1). The CART was based on an analysis of variance (ANOVA) of the dNDVI distribution, using the rpart package of R (R Development Core Team 2014).

HAPS burn severity polygons were rasterised at 30 m to match the spatial resolution of LSAT. For both HAPS and LSAT datasets, we removed patches <1 ha; this eliminated 15% of the HAPS patches (352 ha cumulative area) and 18% of the LSAT patches (33 ha cumulative area). We applied this minimum mapping unit to make the two datasets more comparable and to eliminate very small patches that were numerous, not as ecologically significant and largely indistinguishable from mapping errors.

To address objectives 1 and 2, we used generalised linear mixed models (GLMMs) to analyse each of the responses of 1) annual area burned; 2) annual area burned with high severity; 3) annual proportion burned with high severity and 4) annual binary response indicating a) the probability of a burn and b) the probability of a high severity burn. For the response of annual proportion burned with high severity, only years with annual area burned greater than zero were considered. We used GLMMs to model non-normal distributions, variance heterogeneity and potential temporal response dependence. All models included period (Early, Middle, or Late) and source (LSAT or HAPS) as predictors. Source was included in all models as a fixed effect to control for any difference in means between the two sources, regardless of the significance of the difference between means. We also included a random effect for source in order to account for any differences in residual variation. The inclusion of source in the models was not intended to address the hypotheses involving period, but source was instead included in order to offer a properly specified model that takes into account 1) differences in variation and 2) mean level of source in order to better isolate the only effect of interest which is period. Prior to fitting models, tests for variance heterogeneity were run in order to assess variance differences between LSAT and HAPS during the overlap years of 1973–2000. Annual area burned and annual area burned with high severity were modelled using a lognormal distribution and a first-order autoregressive (AR(1)) covariance structure on the residuals. In order to include zero responses, we used the transformation described by Stahel (2002). We modelled the annual proportion of area burned with high severity with a beta distribution and a one-dimensional spatial power function on residual covariance in time because non-zero burn years were irregular and the residual correlation was a function of time between event years. In order to include values of zero for years where fires were recorded but not at high severity, we transformed the values as described by Smithson and Verkuilen (2006). Burn probability was modelled using a binomial distribution and an AR(1) covariance structure on the residuals. In order to prevent inflated Type I error rates due to multiple comparisons, we used the Games and Howell (1976) method that properly adjusts for differences in variation and sample size between treatment levels. We further adjusted the pairwise *P*-values using a stepdown procedure that increases the test power by assuring that a *P*-value will not be declared significant unless all smaller *P*-values are also declared significant. All GLMM analyses were done using SAS 9.4, PROC GLIMMIX (SAS Institute Inc. 2014). To determine if both annual proportion burned with high severity and annual area burned with high severity were correlated with annual area burned, we used a block-bootstrapped Spearman's Rho, $\hat{\rho}$, a rank-based measure of association. Rank transformations are widely used to mitigate the influence of outliers (e.g. Montgomery 2012). We chose this instead of a regression approach which would inappropriately imply a predictor-response relationship. We used $\alpha = 0.05$ to judge statistical significance for all tests.

To address objective 3, we calculated the annual area burned with low, moderate and high severity. We then calculated the correlation between annual values of area burned with high severity and proportion burned with high severity. The block-bootstrapped Spearman correlations ($\hat{\rho}$) and associated *P*-values are based on only non-zero burn years. We block bootstrapped in order to remedy serial correlation in the observations. Both this and the previous block-bootstrap analyses were done using R version 3.1.2 (R Core Team 2016) and the boot package (Canty and Ripley 2016; Davison and Hinkley 1997).

To address objective 4 about reburn, we calculated observed extent of areas reburned each year. We then compared the observed extent reburned with high severity to the expected value that we calculated as the product of total area burned with high severity (152 763 ha), the probability of reburn (0.22) and the probability that one fire in a reburn burns with high severity (0.58, calculated as 44 874 ha reburned with high severity at least once divided by the 76 951 ha that reburned).

Results

HAPS and LSAT are similar enough for analysing long-term trends

The CART classification effectively aligned the LSAT dNDVI data with the HAPS classification, making the HAPS and LSAT records similar enough to analyse trends while accounting for source (Fig. 2). The CART using the HAPS burn severity calls to train the classification of dNDVI based on 1906 polygons common to both the HAPS and LSAT datasets (Table A1) was highly significant ($P < 0.0001$) but had an overall accuracy of only 55%. Classification errors were due to considerable overlap

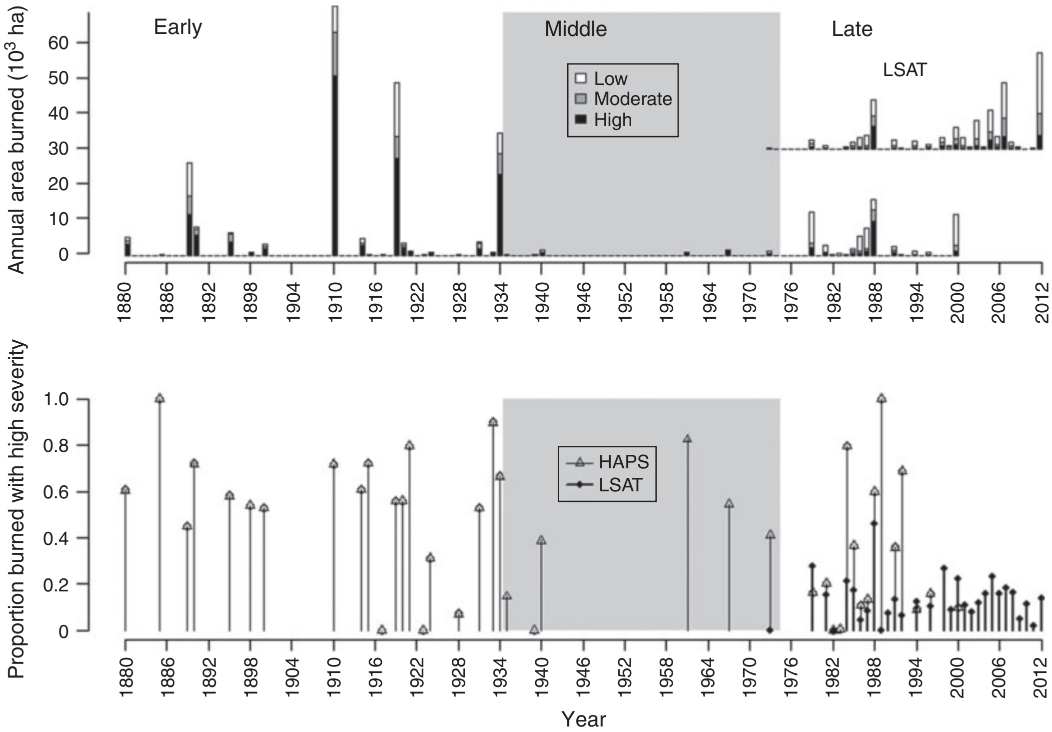

Fig. 2. Annual area burned through time, by burn severity class (low, moderate and high), as classified from HAPS (1880–2000) and LSAT (1973–2012) (top), and proportion of area burned with high severity as recorded in both datasets (bottom) for 346 265 ha in the Selway-Bitterroot Wilderness Area.

in dNDVI values between low and moderate, and between moderate and high severities (Fig. A1), which manifested as overprediction of low severity and underprediction of high severity (Table A2). This suggests that our long-term trends in area burned with high severity are conservative. In other words, if we had used the Key and Benson (2006) dNBR thresholds, commonly applied to identify areas burned with high severity from Landsat satellite data, and in this study converted to dNDVI using simple linear regression (Eqn. A1), we would have had less low severity and more area burned with high burn severity from LSAT.

For the 28 years (1973–2000) of overlapping records, we found no significant differences in variances of annual area burned ($P = 0.708$), annual area burned with high severity ($P = 0.592$), the probability of a burn ($P = 1.000$) or the probability of a high severity burn ($P = 1.000$). However, variance for proportion of area burned with high severity differed between HAPS and LSAT ($P = 0.012$), largely because years with poor agreement between HAPS and LSAT (i.e. 1973, 1984, 1989 and 1992) for this response were also years with little burning (Fig. 2, Table A1). Thus, we added a random effect for data source to all generalised linear mixed models.

Across all years, 1880–2012, neither annual area burned nor annual area burned with high severity differed significantly ($P = 0.185$ and 0.528) between HAPS and LSAT (Table 1). Neither the probability of a burn nor the probability of a burn with high severity differed between data sources ($P = 0.091$ and 0.242, Table 1). Annual proportion burned with high severity differed significantly ($P < 0.0001$) between sources, with the HAPS record of this attribute over twice as high on average compared with LSAT (Table 1). For the years with annual area burned >0 by either HAPS or LSAT, the area burned was greater for HAPS than LSAT in 11 of 14 years (Fig. 2).

Most of the area burned severely did so in just a few years

Of the 346 265-ha study area, 76% (262 788 ha) burned at least once from 1880 to 2012, and 44% (152 763 ha) burned with high severity while 43% (150 510 ha) burned with low or moderate severity. Annual area burned in the Early, Middle and Late periods averaged 4122 ± 1769, 141 ± 71 and 3087 ± 816 ha (sample means with standard errors). Annual area burned at high severity in the Early, Middle and Late periods averaged 2301 ± 1042, 60 ± 29 and 611 ± 169 ha. Fires were recorded in 56 years of the 133-year record; 38% of these years ($n = 21$) occurred in the Early period, 11% ($n = 6$) in the Middle period and 52% ($n = 29$) in the Late period (Figs 1 and 2). Both annual area burned with high severity and proportion of area burned with high severity varied considerably from year to year (Fig. 2). Most (87%) of the area burned with high severity did so in just 9% of the years.

Annual area burned with high severity did not increase through time

Annual area burned was high in both the Early and Late periods, and lowest in the Middle period (Tables 2 and 3). Annual area burned with high severity followed the same pattern between periods, and differences were similarly significant between the

Table 1. Comparison of HAPS [historical aerial photograph severity, inferred from historical aerial photos and other historical data from 1880 to 2000 (P. Green, unpublished)] versus LSAT [Landsat satellite-inferred from 1973 to 2012 (Parks *et al.* (2015*b*)] burn severity datasets for the five response variables

Backtransformed estimates from generalised linear mixed models (GLMM) of the median annual area burned, median annual area burned with high severity, mean probability of burn, mean probability of high severity burn based on all years (1880–2012, including years with zero fires recorded) and mean proportion of area burned with high severity based on only years with recorded fires over the same period. *P*-values indicate significance of the effect of data source (HAPS *v.* LSAT). Numbers in parentheses are 95% confidence bounds. Bold type for $P < 0.05$.

Compared attribute	HAPS	LSAT	*P*
Annual area burned (ha)	98.00 (61, 156)	235.00 (87, 638)	0.185
Annual area burned with high severity (ha)	29.00 (18, 46)	46.00 (17, 129)	0.528
Probability of burn (0–1)	0.34 (0.24, 0.46)	0.58 (0.34, 0.80)	0.091
Probability of high severity burn (0–1)	0.30 (0.21, 0.41)	0.45 (0.24, 0.68)	0.242
Proportion of area burned with high severity (0–1)	0.40 (0.30, 0.50)	0.16 (0.11, 0.24)	**<0.0001**

Table 2. Back-transformed estimates from generalised linear mixed models (GLMM) of median annual area burned, median annual area burned with high severity, mean probability of burn, mean probability of high severity burn based on all years (1880–2012, including years with zero fires recorded) and mean proportion of area burned with high severity based on only years with recorded fires over the same period

GLMM models include and account for differences in HAPS and LSAT data sources. Numbers in parentheses are 95% confidence bounds.

Compared attribute	Early period (1880–1934)	Middle period (1935–1974)	Late period (1975–2012)
Annual area burned (ha)	186.00 (77, 450)	55.00 (22, 139)	345.00 (185, 641)
Annual area burned with high severity (ha)	53.00 (22, 131)	14.00 (5, 35)	68.00 (36, 129)
Probability of burn (0–1)	0.48 (0.29, 0.69)	0.24 (0.10, 0.47)	0.68 (0.53, 0.79)
Probability of high severity burn (0–1)	0.40 (0.23, 0.60)	0.15 (0.06, 0.35)	0.63 (0.49, 0.75)
Proportion of area burned with high severity (0–1)	0.39 (0.26, 0.54)	0.19 (0.09, 0.37)	0.23 (0.18, 0.28)

Table 3. Significance of paired differences of mean burn attributes between three time periods in the 1880–2012 burn record, after including the effect of data source (HAPS or LSAT)

Annual area burned, annual area burned with high severity, probability of burn, and probability of high severity burn are based on all years (1880–2012), while proportion of area burned with high severity is based on only burn years over the same period. Adjusted *P* is the Games and Howell (1976) adjustment for multiple comparisons.

Compared attribute	Compared periods	tValue	Adjusted *P*
Annual area burned	Early *v.* Middle	2.450	0.018
	Early *v.* Late	−1.180	0.243
	Middle *v.* Late	−3.280	0.005
Annual area burned with high severity	Early *v.* Middle	2.670	0.018
	Early *v.* Late	−0.530	0.600
	Middle *v.* Late	−2.830	0.018
Probability of burn (0–1)	Early *v.* Middle	1.960	0.056
	Early *v.* Late	−1.530	0.133
	Middle *v.* Late	−3.140	0.008
Probability of high severity burn (0–1)	Early *v.* Middle	2.240	0.030
	Early *v.* Late	−1.850	0.070
	Middle *v.* Late	−3.580	0.002
Proportion of area burned with high severity	Early *v.* Middle	1.910	0.124
	Early *v.* Late	2.010	0.124
	Middle *v.* Late	−0.460	0.647

Middle and Early (Adj. $P = 0.018$) and Middle and Late (Adj. $P = 0.018$) periods (Tables 2 and 3). The probability of a burn differed significantly between the Middle and Late periods (Adj. $P = 0.008$) and nearly significantly between the Middle and Early periods (Adj. $P = 0.056$), while the probability of a high severity burn significantly differed between the Middle and Early (Adj. $P = 0.030$), Middle and Late (Adj. $P = 0.002$) periods and nearly significantly between the Early and Late

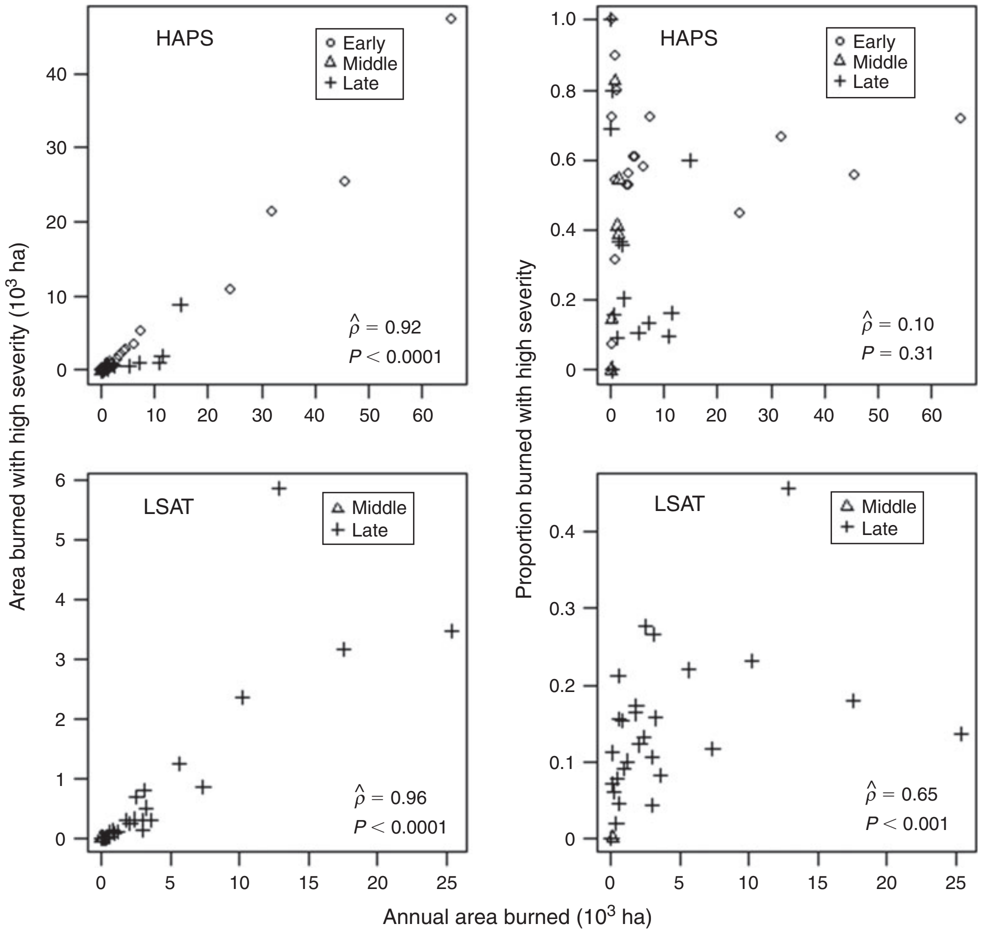

Fig. 3. Annual area burned *v.* annual area burned with high severity from HAPS and LSAT (left); annual area burned *v.* proportion of area burned with high severity from HAPS and LSAT (right). The plotted data, block-bootstrapped Spearman correlations ($\hat{\rho}$) and associated *P*-values are based on only non-zero burn years.

periods (Adj. $P = 0.070$) (Table 3). Proportion of area burned with high severity did not differ significantly between any two periods (Table 3).

Proportion burned with high severity was not correlated with area burned

Annual area burned with high severity was highly correlated with area burned for HAPS and LSAT ($\hat{\rho} = 0.92$ and 0.96, $P < 0.0001$ for both, Fig. 3). In contrast, the proportion of area burned with high severity was weakly correlated with area burned; this correlation was significant for the LSAT record ($\hat{\rho} = 0.65$, $P < 0.001$), but not the longer HAPS record ($\hat{\rho} = 0.10$, $P = 0.31$, Fig. 3).

Little area reburned

Late period fires largely appear to have burned outside of areas that burned in the Early period (Fig. 1). Reburns occurred on 22% (76 951 ha) of the study area; only 4% (13 551 ha) of the study area burned three or more times. Areas that initially burned at low severity were more likely to reburn, and areas that initially burned at moderate or high severity were less likely to reburn at high severity (Fig. 4). High severity reburns occurred on only 4% (5515 ha) of areas already burned with high severity (152 763 ha), while 58% (44 874 ha) of the reburned area burned severely at least once. We found that 21 091 ha that initially burned at low or moderate severity reburned with high severity, while a nearly equal area (19 394 ha) that first burned with high severity reburned at low or moderate severity.

Discussion

Proportion burned with high severity did not increase overall

Neither annual area burned with high severity nor annual proportion burned with high severity have increased over the 133-yr time span, as these values did not differ for Early and Late periods (Tables 2 and 3). Relative to the Middle 1900s, annual area burned and annual area burned with high severity have both increased in recent decades (Tables 2 and 3, Fig. 2). This is likely in response to changing climate and fire management (Morgan *et al.* 2008, 2014*a*) since the middle 20th century when many fires were aggressively suppressed (Rollins *et al.* 2001) and the cooler summers and springs were conducive to fire suppression

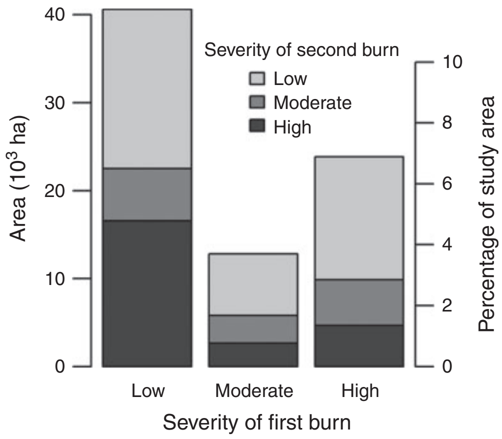

Fig. 4. Area and severity of reburned areas.

(Morgan *et al.* 2008). Increases in area burned did not translate into a higher proportion of area burned with high severity as these values are poorly correlated (Fig. 3). Given that area burned with high severity did not differ for the Late and Early periods, even as the climate has warmed and fire seasons are longer in Idaho (Klos *et al.* 2015) in the Late period, our results suggest both previous fires and fire management are important influences. However, climate, topography and other factors also likely influence proportion burned with high severity (Cansler and McKenzie 2014).

Possible explanations for multi-decadal patterns in areas burned with high severity

There are multiple possible reasons that extensive area burned with high severity in the Early and Late periods but not during the Middle period. First, as we did not find an increase in proportion burned with high severity, annual area burned with high severity logically follows the temporal pattern that Morgan *et al.* (2008, 2014*a*) documented for annual area burned throughout the forests of the US northern Rockies. They attributed the relative lack of fire during the Middle period to climate, including cool and wet springs and summers, and to aggressive fire suppression efforts. They attributed the increase in area burned in the Late period (compared with the Middle period) to changing fire management and also to climate, consistent with Higuera *et al.* (2015)'s findings that changing climate influenced fire extent in forests of the US northern Rockies 1902–2008. Fire suppression was difficult in the Early period but became more aggressive and successful in the Middle period aided by technology and conducive climate (Morgan *et al.* 2008). In the Late period, climate favoured widespread fires in regional fire years (Morgan *et al.* 2008, 2014*a*) and many wildfires were managed with limited suppression as fire policy changed in 1974, starting with fires in the Selway-Bitterroot Wilderness (Steelman and McCaffrey 2011). The extensive fires in the Early period and the management of many wildfires for resource benefits, or at least with limited suppression in the Late period, may mean that our findings are unique to this area and should not be used to generalise temporal severity patterns in other landscapes. Therefore we suggest similar analyses elsewhere. Second, Early period fires influenced the extent and burn severity of subsequent fires over many decades as others have found in these and other nearby wilderness areas for the past ~30 yr (Teske *et al.* 2012; Parks *et al.* 2014, 2015*a*, 2016*a*). Extensive Early period fires contributed to few extensive fires in the Middle period, and the relative lack of fires in the Middle period contributed to more extensive fires in the Late period. However, the degree to which subsequent fires burn differently due to prior fires varies from place to place, and depends on what vegetation comes back after the prior fire and also on the climate and wind at the time of the subsequent fire (Collins *et al.* 2009; Holsinger *et al.* 2016). Further, Early period fires could have influenced Late period fires given the relatively low historical fire frequencies in the cold forests and moist mixed conifer forests common to the SBW (Schoennagel *et al.* 2004). The effect of previous fire on subsequent burn severity can last for decades (Miller *et al.* 2012*c*; Parks *et al.* 2014). Third, climate, topography and vegetation conditions influence burn severity (Haire and McGarigal 2009; Cansler and McKenzie 2014; Birch *et al.* 2015), but we did not analyse those factors here. Further research of these data and their patch dynamics will improve understanding of how burn severity varied with time since fire, vegetation, topography and climate. Although these factors clearly influence area burned (Haire and McGarigal 2009; Teske *et al.* 2012; Haire *et al.* 2013; Parks *et al.* 2015*a*; Cansler and McKenzie 2014), their relative influence on burn severity is not well understood, but see the useful conceptual model from Cansler and McKenzie (2014) and findings of Kane *et al.* (2015).

Fire in the SBW has been self-limiting for both fire extent and burn severity

The probability of reburning is low (22% of the study area reburned with high, moderate or low severity within 133 years) compared with the probability of burning once (76% of the study area burned once within 133 years) regardless of burn severity of prior or subsequent fires. This suggests that fire extent is self-limiting. Similarly, area burned with high severity is self-limiting, for the observed area reburned with high severity (5515 ha) is only 28% of the value expected (19 493 ha) if there were no effect of prior burns. Also, the probability of a reburn (0.22) is much greater than the probability of reburn with two or more high severity fires (0.016), suggesting that high severity fires strongly limit the occurrence of subsequent high severity fires. Note that for these calculations we used the HAPS area for early and middle periods and the LSAT data for late period. Indeed, that fires are self-limiting is qualitatively evident from the maps, as most of the fires that burned in the Late period burned outside of areas that burned in the Early period (see Fig. 1).

Previous fires can affect the burn severity (Miller *et al.* 2012*a*, 2012*b*; Parks *et al.* 2014; Harvey *et al.* 2016; Stevens-Rumann *et al.* 2016) and extent of fires by limiting fuels for subsequent fires (Collins *et al.* 2009; Teske *et al.* 2012; Parks *et al.* 2015*a*, 2016*a*), although there is a high level of complexity and variability of these fire-on-fire interactions geographically, with climate and weather, and with prior fire effects and recovery (Harvey *et al.* 2016; Holsinger *et al.* 2016; Parks *et al.* 2016*b*). Teske *et al.* (2012) found that 15% of the SBW burned in recent years (1984–2007) with only 1% of the area burning twice within those 24 years. Parks *et al.* (2014) found that previous fires moderated the severity of subsequent fires for >20 years in the adjacent Frank Church – River of No Return Wilderness using satellite data available for fires occurring from 1984 to 2008, and Miller *et al.* (2012*a*, 2012*b*) showed a similar effect in California that also lasted decades. We conclude that the extensive area burned with high severity in Early years had a lasting effect on later fires in the SBW. This has major implications for fire managers faced with managing large fires, as they may be able to take advantage of the 'footprint' of earlier fires. Projections for the extent and severity of future large fires must consider the feedback effects of previous fires (Collins *et al.* 2009; Parks *et al.* 2015*a*; Stevens-Rumann *et al.* 2016; Prichard *et al.* 2017).

Data limitations and their implications

Our conclusions hinge on similar burn severity inferences from HAPS and LSAT, while noting that burn severity inferences from either source are challenging (Morgan *et al.* 2014*b*). The trends in annual area burned and annual area burned with high severity show very similar patterns from 1973 to 2000 when the HAPS and LSAT records coincide (see Fig. 2). The agreement between the two records during this period is notably worse with regard to the proportion burned with high severity (see Fig. 2), highlighting that this can be an unstable metric in years with little area burned. The highly significant difference in this metric between HAPS and LSAT (Table 1) points to lower detectability of lower severity fires in the HAPS record. The LSAT proportion burned with high severity would have to be ~2.5 times our reported values to equal the HAPS proportion burned with high severity (Table 1). On the other hand, after correcting for source effect, the overall trend in proportion burned with high severity is still generally decreasing (Fig. 2, Table 2). Thus, our conclusion that the proportion of area burned with high severity has not significantly changed over 133 years is conservative (Table 3). Moreover, the high ratio of omission/commission errors in classifying high burn severity show the LSAT predictions were ~2.5 times less likely than the HAPS observations to indicate high burn severity in 659 burn severity polygons common to both datasets (Table A2).

That the probability of burning and the probability of burning with high severity did not differ for the two datasets in the 28 years of overlap (Table 1) is reassuring, as these responses are less subject to mapping errors. We focused on patches burned with high severity, because the accuracy, though unknown, likely is higher for inferring high severity than for moderate or low severity burns (Hudak *et al.* 2007; Miller and Thode 2007). From aerial photographs, the burn severity was of necessity inferred long after fires, especially for fires occurring before the 1930s. We mitigated this by relying on a local expert familiar with the ecosystems, who also consulted other historical records while interpreting the aerial photographs. Nevertheless, long temporal gaps could result in overestimating the burn severity, particularly where second-order fire effects such as insect-induced tree mortality and windthrow may have reduced surviving trees with time, though this would have to be pronounced to change burn severity class calls. Although tree regrowth may hinder our ability to assign burn severity accurately, it is less likely to do so in the cold forests that dominate 70% of the study area; such cold forests are low productivity and likely to burn with high severity.

Other limitations would have the opposite effect of underestimating burn severities. Burn severity classifications based on satellite image-derived spectral indices (e.g. NBR, NDVI) may be more sensitive than aerial photographs to soils and other sources of background reflectance, making burn severity inferences less reliable from LSAT. However, burn severity inferences from LSAT are mostly influenced by overstory trees rather than underlying surface reflectance (Hudak *et al.* 2007). It is difficult to map reburns well as it is difficult to separate the effects of older fires from more recent fires, but only 22% of the area burned two or more times, and we often had aerial photographs or other records between repeated fires. Despite these limitations, we highlight the spatially explicit long-term perspective that our data provide, and their value in bridging palaeoecological and contemporary data through changing fire management and climate.

A unique temporal and spatial context for recent large fires, with important ecological implications

Evaluations of burn severity using the relatively short Landsat record can potentially result in conclusions that are not representative of long-term trends. This could potentially explain some of the contradictions and inconsistencies among previous studies that used only ~30 years of satellite-inferred burn severity data (e.g. Dillon *et al.* 2011; Miller *et al.* 2012*a*, 2012*b*; Hanson and Odion 2014), as could the effects of earlier fires. Here, we conclude that both the area burned with high severity and the proportion burned with high severity have not increased in recent decades. However, had we analysed only the last 30 years of data, our results would have showed an increase over time in area burned with high severity (Tables 2 and 3, Fig. 2). This said, our findings could be unique to our study area in which fires are often allowed to burn under less than extreme weather conditions. Other regions with policies of strong fire suppression in both Middle and Late periods may have increasing burn severity trends since most fires in recent decades are burning under extreme weather conditions and have abundant fuel (Stephens and Ruth 2005; North *et al.* 2009) with forest conditions favouring contagious spread of fires (Hessburg *et al.* 2000, 2007). Clearly, more research is needed to evaluate long-term (>100 years) trends in burn severity and their causes.

We have only just begun to explore the potential of these long-term spatially explicit data from diverse terrain over a large area to inform our understanding of burn severity. Compared with fire extent and frequency, burn severity is a less understood aspect of fire regimes (Morgan *et al.* 2014*b*) despite the importance for ecological processes (Turner *et al.* 1997; Lentile *et al.* 2007; Keeley 2009*b*; Hutto *et al.* 2016). Areas burned with high severity were extensive in the 20th century and are likely to be extensive in the future, both within and outside wilderness (Haire *et al.* 2013; Parks *et al.* 2016*a*). Here in the Selway-Bitterroot Wilderness, extensive fires have altered the extent and patch dynamics of recent fires; continued burning will likely influence the effects of future fires. Thus, understanding burn severity is crucial in the face of predictions for a future of increased area burned (Littell *et al.* 2009). In particular, the implications of interacting influences on burn severity of prior fire, vegetation and associated fuels, topography, land management and climate need to be understood if we are to predict fire effects under future novel conditions. Clearly, long-term spatially explicit data from large landscapes are valuable.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

We sincerely thank the staff at Nez Perce National Forest for supporting Patricia Green, then Fire Ecologist there, during her careful interpretation of burn severity from aerial photographs. Donovan Birch, Kerry Kemp, Camille Stevens-Rumann and Philip Higuera assisted with analysis and graphics. This research was supported by the National Aeronautics and Space Administration award NNX11AO24G, USDA Forest Service agreements 09-JV-11221637–270 and 12-JV-11221637–136, and by the University of Idaho. Jeffrey A. Hicke, Alistair M.S. Smith and anonymous reviewers helped us to improve the manuscript.

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Appendix 1

We intersected HAPS burn severity polygons with the LSAT-derived fire perimeters, which resulted in 2828 polygons mapped as burned within the years of overlap between the two datasets. Area burned was recorded in 14 of the 28 overlapping years. We calculated mean dNDVI and dNBR within these polygons, which provided an empirical basis for selecting dNDVI thresholds based on the HAPS classification. After eliminating polygons of unknown severity, that lacked dNDVI data or had negative mean dNDVI values, or sliver polygons due to spatial mismatches and other small polygons that were <1 ha in area, we were left with 1906 polygons for comparative analysis (Table A1). The two burn severity indices showed very similar trends as they were highly correlated with each other (Fig. A1).

Table A1. Year and number of burned polygons included in both the HAPS and LSAT data in the years of overlap (fires were recorded in 14 of the 28 years of overlap)
Data in these years were used to calibrate LSAT dNDVI values to the HAPS burn severity classification.

Year	Number of burned polygons
1973	42
1979	438
1981	69
1982	4
1984	7
1985	76
1986	252
1987	189
1988	427
1991	141
1992	9
1994	32
1996	45
2000	175
TOTAL	1906

We developed a CART based on ANOVA of the dNDVI distribution to identify dNDVI thresholds that best fit the HAPS burn severity classification for the 1906 polygons common to both the HAPS and LSAT datasets. The best fit of the dNDVI data to the HAPS burn severity classes produced burn severity class breaks at dNDVI of 297.5 between the High and Moderate burn severity classes and at dNDVI of 196.5 between the Moderate and Low burn severity classes (Table A2). Given the high correlation between dNBR and dNDVI (Fig. A1), we developed a simple linear model to predict dNBR from dNDVI:

$$\text{dNBR} = 1.88832 \times \text{dNDVI} - 14.76278 \qquad (\text{A1})$$

The model R^2 is 0.90 based on $n = 1353$ polygons. Key and Benson (2006) reported a dNBR unburn/burn threshold of 100, which by Eqn 1 equates to a dNDVI value of 60.775; thus, an unburned/low severity class threshold of 60.5 was added to the CART (Table A2). For comparison with other published work using the Key and Benson (2006) dNBR thresholds of

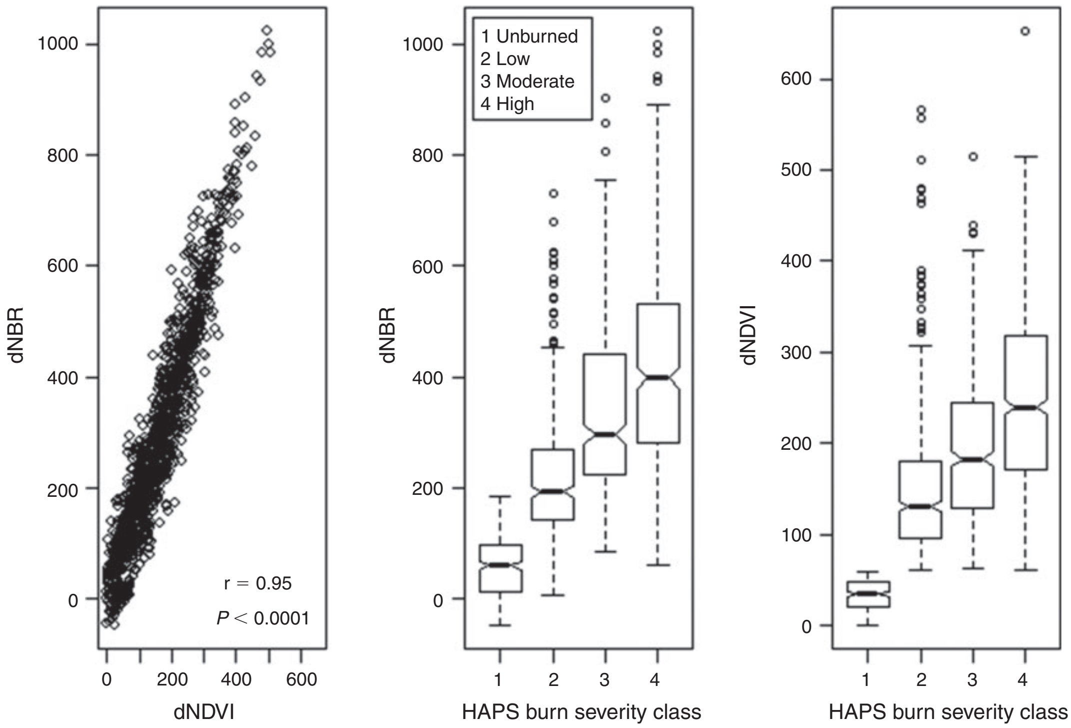

Fig. A1. Scatterplot of mean dNBR versus mean dNDVI (left), both calculated from 1984–2000 Landsat TM imagery within HAPS burn severity polygons ($n = 1353$); box and whisker plots of dNBR (middle, $n = 1353$) and dNDVI (right, $n = 1906$) by HAPS burn severity class.

Table A2. LSAT dNDVI classification confusion matrix and statistics. Burn severity class thresholds were as follows: unburned: dNDVI <60.5; low: dNDVI > = 60.5 and <196.5; moderate: dNDVI > = 196.5 and <297.5; and high: dNDVI > = 297.5
Overall accuracy was 0.55% with a No Information Rate of 35%, Kappa = 0.40, and $P < 0.0001$.

		LSAT polygons				Total predicted	Commission error (%)	User's accuracy (%)
		Unburned	Low	Moderate	High			
HAPS Polygons	Unburned	260	0	0	0	260	0	100
	Low	0	450	244	213	907	50	50
	Moderate	0	84	143	243	470	70	30
	High	0	27	39	203	269	26	74
Total observed		260	561	426	659	1906		
Omission error (%)		0	20	66	69			
Producer's accuracy (%)		100	80	34	31			

270 (low-moderate) and 659 (moderate-high), the low-moderate and moderate-high dNDVI thresholds predicting these thresholds by Eqn A1 are 150.8 and 356.8.

There is a high degree of overlap between severity classes in the HAPS data, with the exception of the unburned and low severity classes according to dNDVI (Fig. A1, right). This is a consequence of the unburned/burned threshold being empirically derived from Eqn A1, which also resulted in the unburned class being perfectly classified by the CART (Table A2). If the unburned class is omitted from the CART, then the overall accuracy drops to 48%, the No Information Rate increases to 40%, and the Kappa decreases to 0.23, yet the CART remains highly significant ($P < 0.0001$).