

## Global patterns in fire leverage: the response of annual area burnt to previous fire

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**Abstract.** Prescribed fire is practiced around the world to reduce the effect of unplanned fire, but we hypothesise that its effectiveness is proportional to the mean annual area burnt by unplanned fire, which varies among biomes. Fire history mapping was obtained for six global case studies from a range of biomes: Portugal, Spain (both Mediterranean), Alberta (boreal Canada), Sequoia and Kings Canyon National Parks (montane USA), the Sandy Desert (arid Australia) and Kruger National Park (South African savanna). Leverage is the unit reduction in unplanned fire area resulting from one unit of previous fire as measured at a regional scale over a long period. We calculated leverage for each case study using statistical modelling of annual area burnt, controlling for annual climatic variation. We combined the six leverage values with those from four previously published cases to conduct a global test of our hypothesis. Leverage was high in Portugal (~0.9) and moderate in the Sandy Desert (~0.3). However, the other case studies showed no evidence of leverage: burnt area was not influenced by past fire. In all regions, climatic variation had more influence than past area burnt on annual area burnt. The global analysis revealed a positive relationship between mean area burnt and leverage but only when outlying cases were removed. In biomes with low fire activity, prescribed fire is unlikely to reduce unplanned fire area at all, while for many others, the return for effort is likely to be low. Lessons derived from one biome cannot necessarily be applied to another.

**Additional keywords:** fire management, fire risk, prescribed fire, unplanned fire, wildfire.

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### Introduction

Prescribed burning is practiced around the world as a means of reducing the extent and effect of unplanned fires on natural or human values (Penman *et al.* 2011), though the degree to which this actually works is often assumed rather than quantified (Fernandes and Botelho 2003; Price and Bradstock 2010). Just as importantly, the effectiveness of prescribed burning is sometimes assumed to be the same among biomes with substantially different fire regimes (Sneeuwjagt *et al.* 2013). Quantifying the biome-specific effectiveness of prescribed burning is important because without it we cannot be sure whether a desired fire regime (either for public risk reduction

or for ecological sustainability) is achievable or whether the vast sums of public money spent on treatment are being used wisely.

There is now a growing body of research that quantifies the effect of prescribed fire on various aspects of fire behaviour, including fire spread (McArthur 1967; Price and Bradstock 2010) and severity (Pollet and Omi 2002; Safford *et al.* 2009; Bradstock and Price 2010; Price and Bradstock 2012). This includes several studies examining the effectiveness of prescribed fire at reducing the area of subsequent unplanned fire. Empirical and simulation studies suggest that this measure of effectiveness is strongly positively related to the mean annual extent of unplanned fire (Price and Bradstock 2011; Price *et al.* 2012a; Price *et al.* 2012b)

and is also related to the rate of fuel recovery, fire size and treatment design (Pausas and Paula 2012; Price 2012). Most of these parameters vary around the world, so it is predicted that prescribed fire effectiveness also varies. Indeed, the few empirical studies have found regions where treatment is highly effective (tropical savannas (Price *et al.* 2012a)), has no measureable effect (southern California (Price *et al.* 2012b)) and where it is somewhat effective (Australian eucalypt forest (Boer *et al.* 2009; Price and Bradstock 2011)). Recognition of this inter-biome variation is important because it means that fire management experiences gained in one biome cannot easily be applied in another. For example, it has been shown that fire-derived greenhouse gas emissions can be reduced in Australian tropical savannas by increasing prescribed burning levels (and hence reducing unplanned fire area) (Russell-Smith *et al.* 2013). However, such a benefit is unlikely to work in southern Australian forests because prescribed burning is less effective at reducing unplanned fire area (Bradstock *et al.* 2012a). It follows that in southern Australia, fire regimes are less amenable to manipulation to produce desirable outcomes for biodiversity or hazard reduction.

Past research is helpful for building a global model that can be used to predict the effectiveness of prescribed fire in any region. However, to improve this model, it is necessary to examine more empirical case studies that sample a greater range of parameter space. Among other things, the model will aid in the estimation of cost effectiveness from prescribed fire treatments in different regions and how much extra treatment may be required to counter the effects of climate change on unplanned fire activity.

In this study, we collate data from six regions around the world and calculate leverage: the unit reduction in unplanned fire area resulting from one unit of previous fire. This definition of leverage was first coined by Loehle (2004) in a simulation study and has subsequently been applied to empirical studies (e.g. Boer *et al.* 2009; Price 2012). Leverage can be calculated empirically from fire history mapping as the negative of the slope of the relationship between area burnt each year (dependent variable) and area burnt in past years (predictor variable), where the duration of the past fire window is chosen to give the best predictive power to the relationship. Ideally, the predictor would be the past area burnt by prescribed fire, but because in most biomes prescribed fire is a small component of the overall fire regime (typically <10%), it is more practical to detect a leverage for all past fire (prescribed and unplanned). This assumes that for the purpose of inhibiting fire spread, prescribed and unplanned fires are functionally the same. This is unlikely the case in forests because prescribed fires consume less fuel than unplanned fires, so leverage calculated in this way can be considered to be maximum potential leverage: what it would be if prescribed fires were as effective as unplanned fires. The estimation of leverage is improved by including annual weather variables to control for inter-annual variation in burnt area caused by climatic patterns.

Leverage has been calculated in this way in five studies for four regions: two for Australian tropical savannas; two for Australian eucalypt forests (one in the west and one on the east of the continent); and one in southern California. In the tropical savannas, Gill *et al.* (2000) used 10 years of Landsat-derived fire

mapping from Kakadu National Park to determine that the leverage of early dry season fires (prescribed) on late dry season fires (unplanned) of the same year was 1. Price *et al.* (2012a) studied 19 years of Landsat-derived data for the neighbouring West Arnhem Land, subdivided into 60 400 km<sup>2</sup> blocks and derived a very similar value (0.9). In eucalypt forests of Western Australia, Boer *et al.* (2009) used 52 years of manual fire history mapping to identify a non-linear leverage effect with a magnitude of ~0.25. Price and Bradstock (2011) used 30 years of manual fire history mapping for eucalypt forests in the Sydney region, subdivided into four regions of 5000 km<sup>2</sup> and controlling for annual variation in weather to derive a leverage value of 0.3. That method was applied to 29 years of manual fire mapping for seven counties in the Mediterranean region of southern California where no leverage effect was detected, mostly because the annual area burnt in the region is low (~2%) (Price *et al.* 2012b).

Several simulation studies have also produced a leverage value. Although simulation is sensitive to the accuracy of the fire spread models used, it has the advantage over empirical studies that experimental treatment strategies can be explored over long periods. A simulation for eucalypt forests gave very similar results to the empirical study (leverage = 0.25) (Bradstock *et al.* 2012b). A study in button-grass moorland in Tasmania gave a value of ~0.04 (25 ha treated to reduce unplanned area by 1 ha) (King *et al.* 2006) and an Australian desert example gave a value of 0.09 (King *et al.* 2013). An explicit exploration of the drivers of leverage using percolation models (Price 2012) concluded that the mean area burnt by unplanned fire is the primary driver of leverage. This is because the encounter rate between prescribed and subsequent unplanned fire increases with increasing area burnt (Price 2012): the more unplanned fire there is, the more chance that a particular prescribed burning patch will be encountered by it. Price (2012) also found that leverage has a linear rather than threshold-type relationship with both annual mean area burnt and prescribed treatment level and also that spatial strategies such as linear treatments give higher leverage values than random treatments (as also predicted by Finney (2007)). The empirical data to date supports this hypothesised relationship between leverage and annual area burnt: where the mean annual area burnt is higher, so is leverage. Approximately 30% of the tropical savanna burns each year (leverage = 1), compared with 5% of eucalypt forest (leverage = 0.25) and 2% of California chaparral (leverage = 0). Among other things, it remains to be demonstrated whether there is any place in the world where leverage greater than 1 can be obtained. At any value less than 1, increased treatment also increases the total area burnt. This has major consequences for biodiversity management and socioeconomic considerations (such as smoke management and carbon sequestration).

The hypothesis for our study is that leverage is proportional to mean area burnt, as suggested by the previous empirical and simulation studies. We use the results from the six case studies together with previously published values to test this hypothesis. Hence, we predict a positive relationship among the cases between mean area burnt and leverage. If the hypothesis is supported, it means that lessons learned in one biome about prescribed burning effectiveness cannot reliably be applied to another biome where the mean area burnt is different.

## Materials and methods

Fire history data were obtained for six case studies around the world: Portugal, Spain, Alberta (Canada), Sequoia and Kings Canyon National Parks in western USA, Kruger National Park in South Africa and the Sandy Desert in Western Australia (Fig. 1). In each case, the study area was divided into regions (administrative or environmental), and the area burnt in each region in each year was calculated as the percentage of burnable area (excluding urban area, open water and agricultural land). The regions were selected to be independent from the perspective of fire occurrence as all were larger than the 99.9th percentile fire size in each case study. The case studies differed in the number of regions used and number of years of data, as well as climatically and in the annual area burnt (Table 1).

Inter-annual variation in area burnt is mediated by many factors, of which rainfall over the previous period of months or years and the occurrence of severe fire weather are two important factors. In order to control for these sources of variation, rainfall and additional weather data were also sourced for each case study, though the exact variables differed among the case studies (see Table 2). Where possible, weather was sourced from a different weather station for each region, but for two of the case studies only one weather station was used. We considered this acceptable because we were using annualised weather variables that are unlikely to show different inter-annual patterns between

locations within the two affected case studies (e.g. inter-annual variation in rainfall is similar across the Great Sandy Desert).

### Case studies

Alberta is primarily boreal forest that experiences rare but large stand-renewing, high-intensity crown fires ignited by lightning and burning 0.56% of the available area each year (Flannigan and Wotton 2001; Stocks *et al.* 2002). Annual area burnt is positively correlated with mean and maximum temperature (Flannigan *et al.* 2005). We used 12 ecoregions based on the classification system developed by the Ecological Stratification Working Group (Anon 1995), national fire mapping data for years 1991–2010 and weather data for each region from Alberta Environment and Sustainable Development, as described in Tymstra *et al.* (2007).

Sequoia and Kings Canyon National Parks are in the Sierra Nevada in central California (Collins *et al.* 2007), where the vegetation grades from chaparral shrublands and oak woodlands at lower elevation through a variety of conifer forest types to largely unvegetated alpine peaks. Instead of regions, the analysis used six mapped forest vegetation types (Haultain 2007) because fire regimes vary markedly according to altitudinal vegetation zones. Hence, there is less separation and more intermingling of sampling units than in the other case studies, which use discrete regions. However, the use of vegetation types

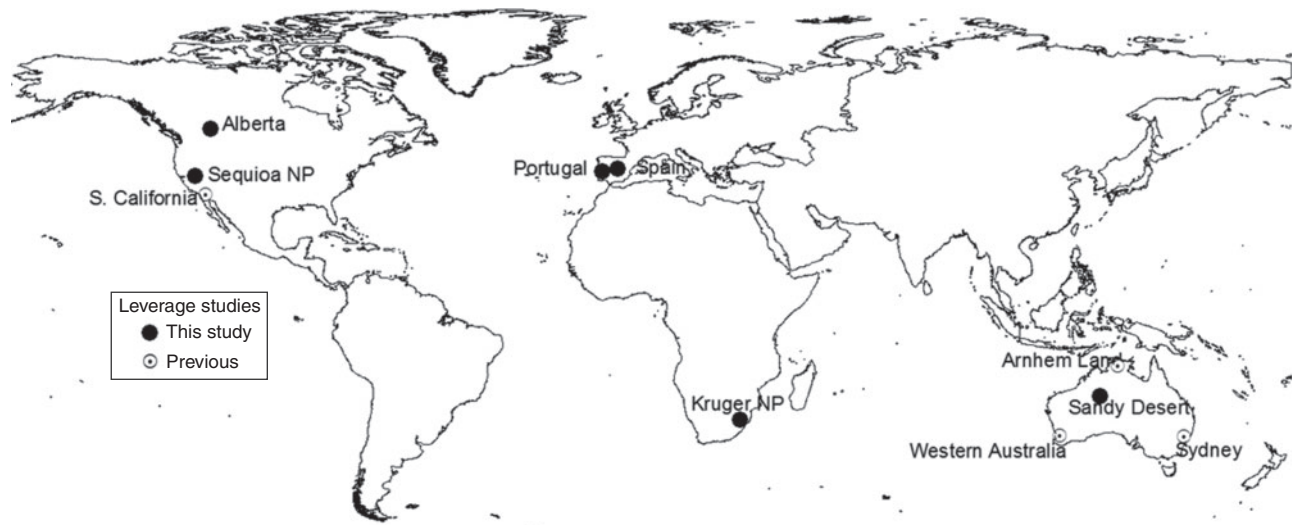


Fig. 1. The location of study sites and sites where leverage values have previously been calculated.

Table 1. The six regions ordered by mean area burnt (as a percentage of burnable vegetation)

*N* is the sample size for analysis, area burnt region range is the minimum and maximum across the regions of the mean annual area burnt

Case study	Area (km <sup>2</sup> )	Climate	Number of regions	Year range	<i>N</i>	Annual rainfall (mm)	Mean area burnt	Range area burnt	Leverage
Alberta	365 000	Boreal	12	1991–2010	240	273	0.56	0.02–1.76	None
Sequoia	741	Mediterranean/Alpine	6	1945–2011	402	871	0.59	0.12–0.84	None
Spain	259 000	Mediterranean/Temperate	13	1976–2007	416	677	0.67	0.14–2.10	None
Portugal	89 000	Mediterranean	12	1998–2011	156	850	3.62	0.66–6.81	0.896
Sandy Desert	46 000	Semiarid	12	2000–2010	120	361	9.23	7.48–11.6	0.337
Kruger NP	18 000	Monsoonal/Savanna	4	1957–2012	220	500	20.7	16.8–25.1	–0.172

**Table 2. Variables used in the analysis**  
FFBPS, Canadian Forest Fire Behaviour Prediction System

Variable	Description	Case studies
Area burnt	The dependant variable: percentage of the burnable area of each region burnt each year	All
Pastfire 1, 2, 5 or 8 years	Mean percentage area burnt per past year (calculated from Area Burnt)	All
Rainfall	Annual rainfall for each region (absolute value or deviation from mean (Standardised Precipitation Index))	All
Pastrain 1	Annual rainfall in previous year	All
Pastrain 2	Annual rainfall in previous two years (including current)	All
Rainfall quarter 1, 2, 3 or 4	Rainfall from each quarter of the current year	Sequoia
Evapo-transpiration	Actual evapo-transpiration (combination of annual rainfall and solar radiation)	Spain
DC	Annual 95th percentile of daily Drought Code (from FFBPS)	Portugal, Alberta
FFMC	Annual 95th percentile of daily Fine Fuel Moisture Content (from FFBPS)	Portugal, Alberta
ISI	Annual 95th percentile of daily initial spread index (from FFBPS)	Portugal, Alberta
FWI	Annual 95th percentile of daily Fire Weather Index (from FFBPS)	Portugal, Alberta
Meantemp	Annual mean of monthly mean temperature	Sequoia, Spain
Maxtemp	Annual value of the warmest month mean temperature	Sequoia, Spain
Dry season temperature	Annual mean of daily maximum temperature April–October	Sandy, Kruger
September temperature	Annual mean of daily maximum temperature September	Kruger
Year	Year as a continuous variable	All
Group	Regions (forest types for Sequoia) grouped into two classes with low and high mean area burnt	All

did result in higher spatial autocorrelation than for the regional case studies (see analysis, below). These forest classes have surface fire regimes (Thode *et al.* 2011) and comprise 91% of the forest and 28% of the total vegetated area of the park. Fire mapping from 1945 to 2011 was used (NPS 2013), which revealed very low mean annual area burnt in these forests, varying from 0.11% per year for lodgepole pine (*Pinus contorta*) to 0.96% for interior live oak (*Quercus wislizeni*). Following many decades of fire suppression, management shifted in 1968 to generally allowing natural lightning ignitions to burn freely and applying prescribed fire (Nesmith *et al.* 2011). Consequently the average area burnt area has increased from 0.10% across the six forest types before 1968 to 1.04% post-1968, including 0.48% of prescribed fire. Monthly rainfall and mean monthly values of the daily maximum temperature were obtained for one weather station (Grant Grove, National Climate Data Center station number 043551, 36°44'N, 118°58'W, elevation 1958 m, downloaded from <http://www.ncdc.noaa.gov>, March 2012).

Spain spans a range of climates from dry Mediterranean (in the south-east) to temperate (in the north-west) and the vegetation is dominated by a mosaic of shrublands and low-stature forests that mostly burn in crown fires. The dataset comprises fire information for 13 administrative regions between 1968 and 2007 with an average annual burnt of 0.67%, and weather data for each region from the Agencia Española de Meteorología (AEMET = Spanish Meteorological Agency). The data are explained in more detail in Pausas and Paula (2012). In drier regions fires are mainly driven by fuel whereas in moister regions with denser vegetation, fires are more driven by drought. Land abandonment and the associated increase in fuel amount and continuity are the main drivers of recent changes in fire activity (Pausas 2004; Pausas and Fernández-Muñoz 2012).

Portugal's 12 ecoregions span gradients in elevation and climate (from Mediterranean to temperate), with complementary patterns of vegetation type and spatial arrangement, human

settlement and fire activity (Marques *et al.* 2011). Forests and shrublands occupy two-thirds of Portugal's area, and consist of predominantly managed forests of maritime pine and eucalypt, and woodlands of cork oak. Fire patterns are known to respond to temperature, rainfall, atmospheric circulation patterns and socioeconomic factors (Pereira *et al.* 2005; Costa *et al.* 2011), and in particular, the Canadian Fire Weather Index system (Van Wagner 1987) is a useful predictor of area burnt (Carvalho *et al.* 2008), which averages 1.2% per year (Oliveira *et al.* 2012). We used fire data from the Portuguese Forest Service and weather data for each region from the Portuguese Weather Service (IPMA, Instituto Português do Mar e da Atmosfera) for the years 1987 to 2011. The data are explained in more detail in Vilén and Fernandes (Vilén and Fernandes 2011).

The Sandy Desert dataset is drawn from the study by Bliege Bird *et al.* (2012). The Sandy Desert in Australia is a dune system dominated by spinifex tussock grass in a transition zone between the monsoonal savannas to the north and the true desert to the south. The very sparse aboriginal population lead a semi-traditional life, which includes active fire management. The mean annual area burnt is 9.23%, which occurs predominantly in the dry season corresponding to the monsoonal dry season (April–October) (Table 1). The dominant source of fires is either traditional aboriginal occupants or lightning. However, since causes are not recorded, we used all fire as the dependent variable in this analysis. The study area of 46 000 km<sup>2</sup> was divided into a grid of 12 regions, each 60 × 60 km, and fires were mapped from Landsat TM imagery from 1999–2010. There is only one weather station in the study area (Telfer Aero, BOM Station number 13030, 21°43'S, 122°14'E) from which data were used for all regions.

Kruger National Park (NP) is an 18 000-km<sup>2</sup> protected area in the north-east corner of South Africa, comprising an open-wooded savanna, with a diverse flora dominated by trees in the genera *Acacia*, *Combretum*, *Sclerocarya* and *Colophospermum*

(Govender *et al.* 2012). The mean annual rainfall is 500 mm and the mean annual area burnt is 21% (Table 1). Kruger NP has undergone several changes of fire management since the 1920s including periods referred to by Govender *et al.* (2012) as *laissez-faire* (1926–1956), fixed rotational (1957–1980), flexible rotational (1981–1991), lightning only (1992–2001) and integrated fire management (2002–present). Kruger NP is divided into four biogeographic regions according to rainfall and geology and the fire data spanned the years 1957–2012. Weather data were sourced from a separate South African Weather Service station for each region (Punda Maria (22°41'S, 31°02'E) for Far North, Letaba (23°51'S, 31°35'E) for North, Satara (24°24'S, 31°46'E) for Central and Skukuza (24°59'S, 31°36'E) for South Region).

### Analysis

The objective of the analysis was to measure the slope of the relationship between annual area burnt by unplanned fire (dependent variable) and past area burnt (predictor variable). For the predictor variable, we use all past fire rather than past prescribed fire because in most case studies prescribed burning rates are low, which makes the identification of a leverage signal difficult. Thus, we assume that prescribed and unplanned fires have the same effect in terms of leverage. The analysis is complicated for a variety of reasons, including the choice of a time window for past fire, the choice of covariates to control for non-fire effects on area burnt, regional variation in area burnt and the repeated-measures nature of the data. Past fire is likely to be most effective at stopping the spread of fire when the burnt areas are recent but because the annual area burnt is low, this effect is often hard to detect statistically using only fires from the past year. However, burnt areas have some (diminishing) effect for several years. In order to best capture the leverage effect, four possible window lengths were analysed (the mean area burnt over 1, 2, 5 and 8 years). Most case studies used 2, 5 and 8 years, but the 8-year window was not possible for the Sandy Desert due to the short duration of the fire data, and a 1-year window was used instead (i.e. 1, 2 and 5 years). To address inter-region variation in area burnt within each case study, the regions were classified into two region-groups according to their mean area burnt (High, greater than all-region mean; Low, less than all-region mean). It is expected that regions with more fire activity are more likely to show a leverage effect, and this variable ensured that this effect was not masked by regions with low fire activity. The full set of predictor variables is listed in Table 2.

Statistical analysis was undertaken as a generalised linear mixed-model with annual area burnt as the dependent variable and region as a random variable to account for repeated measurements of the same region, and a normal error distribution. Analyses were conducted using the NLME package in the R statistical software (Pinheiro *et al.* 2014). The analysis comprised five steps, identifying (1) the best rainfall variable (or sets of variables); (2) the best ambient weather or fire danger rating variables; (3) the best past fire variable; (4) the best combined model and (5) checking for non-linearity, time trends and outliers and comparing different past fire windows. Step 4 used all of the variables identified in Steps 1–3, plus the additional variables year and region-group. Year was included

to identify and control for any trend in area burnt that could mask the leverage effect. In Step 4 the interaction between the past fire variable and each of the other variables was also tested. For each step, the best combination of variables was identified by fitting all variable combinations and selecting the model with the lowest Akaike's Information Criteria (AIC) value (Burnham and Anderson 2002). Supported alternative models (with  $\Delta AIC < 2$ ) were also identified, but only the variables in the best model were used as candidates for the full model (Step 4). In Step 5, non-linearity was tested by adding the square of the past fire variable and by using the log of the past fire variable; the influence of outliers was explored by repeating the entire analysis without the year with greatest fire activity; and any possible bias caused by cases with very little or no fire activity was tested by repeating the analysis without cases with less than 0.1% burnt. The residuals from the final models were checked for normality by visual interpretation (histograms and q-q plots). The five-step approach allowed us to compare the strength of influence of the different drivers (rainfall, weather, past fire and other factors) and to fully explore dependencies among the drivers (i.e. whether the past fire effect is apparent only under certain conditions). The final model was tested for spatial autocorrelation by plotting the variogram for the model residuals and fitting a spheroid model to it, and also by calculating Moran's *I* for the residuals using the R packages *gstat* (Pebesma 2004) and *ape* (Paradis *et al.* 2004).

After analysing each of the case studies, we conducted a global analysis by combining the six leverage values calculated here with the values from four previous empirical studies to begin to examine the global pattern of leverage. These were from Australian tropical savannas (Price *et al.* 2012a), eucalypt forests from Western Australia (Boer *et al.* 2009) and Sydney (Price and Bradstock 2011), and for Mediterranean California (Price *et al.* 2012b). We plotted leverage against mean area burnt and fitted a linear model through the 10 points.

## Results

### Case studies

All six case studies revealed a relationship between annual area burnt and both rainfall and weather, but only four of them showed any indication of a relationship with past fire (as judged by the AIC values, Table 3). In all cases, the relationship with past fire was weaker than the relationship with weather (Table 3). In the final models, where weather, time trends and regional differences were controlled for, only three case studies included a past fire term. Of these, Portugal showed strong leverage (0.896) with an 8-year past fire window and the Sandy Desert showed moderate leverage (0.337) with a 5-year window. Kruger NP showed a positive (but non-significant) slope (0.172), meaning negative leverage or fire is more likely following previous fire.

None of the case studies showed evidence of non-linearity in the leverage relationship. The analysis was repeated excluding cases with burnt area  $< 0.1\%$  for three case studies (Sequoia/Kings Canyon, Spain and Kruger NP) but not for the other three, for which such cases were less than 10% of the sample. For these three, the removal of those cases did not alter the final models in a material way: that is, they did not reveal a leverage effect

**Table 3. Generalised linear mixed-models for annual area burnt for each case study**

The table shows the best final model and supported alternatives along with the  $\Delta AIC$  (Akaike's Information Criterion compared with a null model) for each step of the analysis (i.e. developing models for rainfall variables, ambient weather variables and fire variables). The table also includes pseudo- $r^2$  value for the final model and the statistical significance of the fire term in the model for the three case studies with a fire term

Case study	Model	$\Delta AIC$ rain	$\Delta AIC$ weather	$\Delta AIC$ fire	$\Delta AIC$ final	Model $r^2$	Fire term $P$	Alternatives
Alberta	$-0.338 + 0.0626*FWI - 0.752*GrouP = LOW$	-4.92	-8.74	0	-15.53	0.781	NA	
Spain	$52.89 + 0.0012*PastRain1 + 0.0941*Maxtemp - 0.015*Evapo-transpiration$ $-0.0271*Year - 0.947*GrouP = LOW$	-24.14	-12.18	-2.04	-62.71	0.160	NA	+ Rainfall
Sequoia/ Kings Canyon	$-29.374 - 0.293*GrouP = LOW + 0.014*Year + 0.188*Meantemp$ $-0.0217*Sumtemp - 0.00035*Pastrain1$	-10.50	-17.49	-13.78	-46.77	0.132	NA	
Portugal	$-108 - 0.896*Pastfire8 + 0.00116*Rainfall + 1.127*FFMC - 6.13*GrouP = LOW$	-6.67	-10.21	-0.60	-31.19	0.222	0.0005	
Sandy Desert	$-79.86 - 0.337*Pastfire2 + 9.134*Spi5\ mean + 2.894*DS\_Temp$	-16.66	-4.72	0	-29.75	0.258	0.0002	
Kruger NP	$-2.835 + 0.033*Rainfall + 0.172*Pastfire5$	-69.08	-7.67	-7.31	-69.27	0.309	0.144	- Pastfire5

where none were present with the full data, or vice versa. Portugal and Spain experienced single outlier years with very extensive unplanned fires (respectively in 2003 and 1994). Removing these years made no material difference to the model for Spain, but for Portugal, it reduced the estimated leverage from 0.896 to 0.446. We concluded that leverage was present only in Portugal and the Great Sandy Desert.

None of the case studies displayed any spatial autocorrelation in the residuals of the final models. In all cases, the variogram showed no obvious spatial structure, the fitted model was a flat line (Fig. 2), and the Moran's  $I$  was non-significant (Table 4).

*Global analysis*

When the 10 known leverage values (four previous and six from this study) were fitted against the mean area burnt, the relation was not significant (Fig. 3,  $P = 0.173$ ,  $r^2 = 0.121$ ). Portugal and Kruger NP were obvious outliers, with Portugal having higher, and Kruger NP lower, than expected leverage. When these two studies were excluded, the fit was much improved ( $P < 0.001$ ,  $r^2 = 0.92$ ). The slope of this line was 0.039, meaning that leverage increases by 0.039 for each 1% increase in mean area burnt.

**Discussion**

This multi-country comparison has shown that leverage (an inhibitory effect of past fire on subsequent fire area) is not a universal phenomenon and only occurs in biomes with high rates of fire activity.

Leverage is proximally driven by the encounter rate: how likely it is that an unplanned fire encounters a previously burnt area that has sufficiently reduced fuel to form a barrier or substantially slow fire spread. Encounter itself has two components: how much burnt area is present (the annual area burnt); and how long a burnt area remains a barrier to fire spread (fuel recovery rate). Therefore, leverage should be positively correlated with the product of annual area burnt and the fuel recovery period, which is essentially the proportion of the landscape at any time that is in a fuel-reduced state.

However, these two components are negatively linked as rapid fuel recovery is one of the drivers of high annual area burnt. Therefore, we expect leverage to be highest in regions where area burnt is high despite long recovery periods; that is, where drivers other than fuel dynamics are responsible for high levels of fire activity (many large fires). These other potential drivers are drought, fire weather, barriers to spread and ignition rates. Regular drought makes fuel available to burn and hence fires will tend to be large. Likewise severe fire weather leads to large fires. Barriers may be due to topographic relief (cliffs and steep slopes), water bodies, roads or vegetation clearing, and in flat and undeveloped regions we may expect fires to be larger. Ignition is required for all fires so it follows that, in the absence of saturation, higher ignition rates will lead to a larger area burnt.

Among the cases studied, only Portugal and the Sandy Desert displayed a leverage effect. Our global analysis including previously published estimates of leverage suggested that there may be a strong relationship between leverage and the mean annual area burnt, but only when Portugal and Kruger NP are excluded. Since we have no strong justification for removing

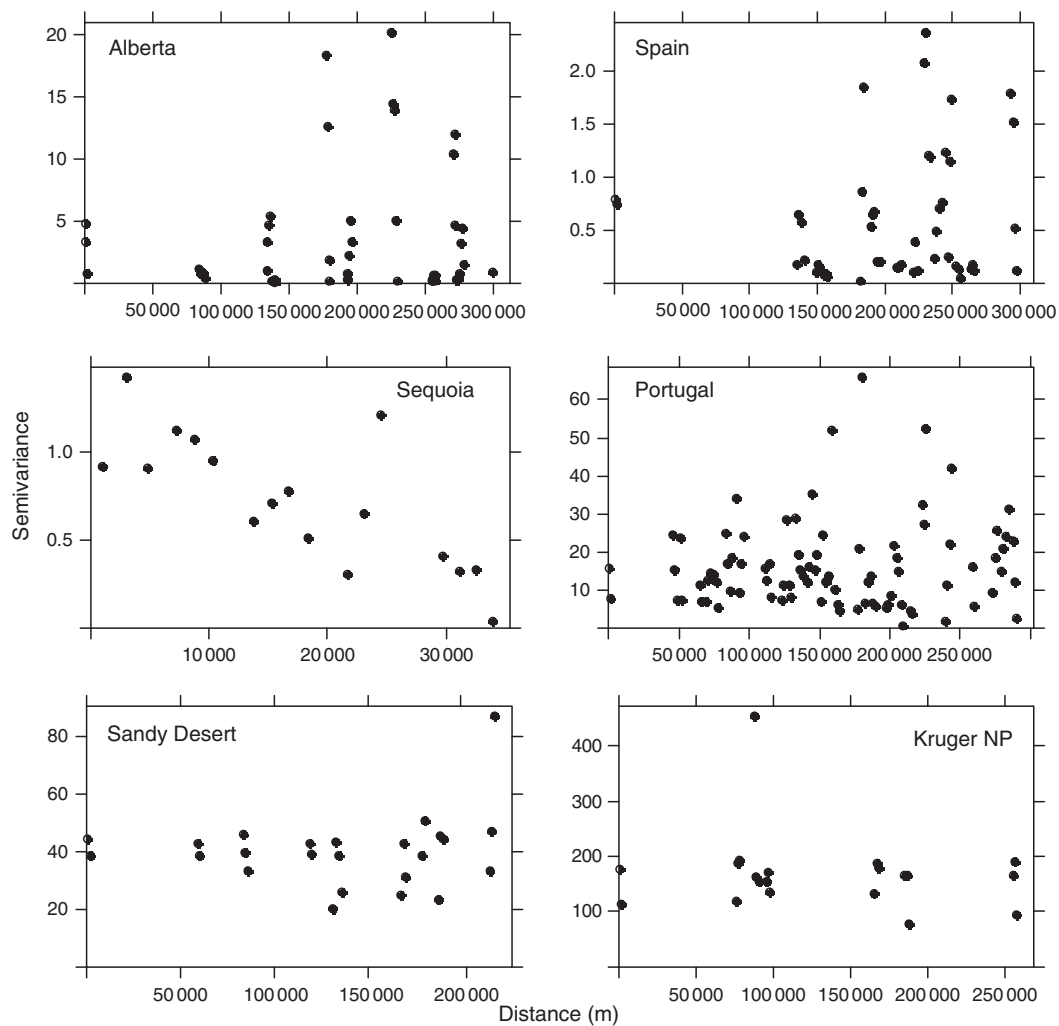


Fig. 2. Variograms for the six case studies (distance in metres).

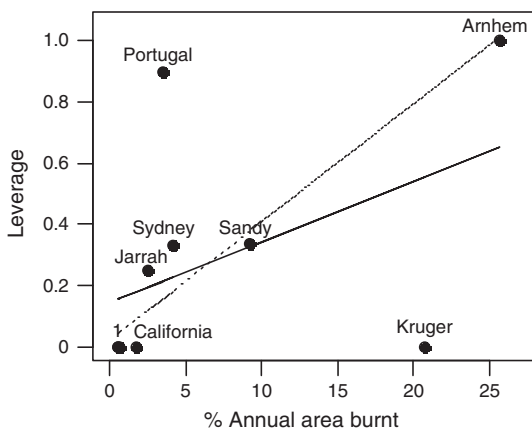
Table 4. Moran's  $I$  test for spatial autocorrelation for the six case studies

Case study	Moran's $I$	$P$
Alberta	-0.025	0.390
Sequoia	0.0045	0.462
Spain	-0.0387	0.039
Portugal	-0.050	0.212
Sandy Desert	-0.013	0.924
Kruger NP	-0.013	0.674

these cases, our hypothesis received qualified support. The lack of fit for these two studies may be because fuel recovery period was not included in this global analysis. This would have been desirable, but unfortunately values are not available for the case study regions. There has been work on fuel accumulation rates (Raison *et al.* 1983; Keifer *et al.* 2006; Russell-Smith *et al.* 2009) and hazard of burning (Diaz-Delgado *et al.* 2004; Fernandes *et al.* 2012) in some of these regions, but neither method quite captures the important attribute that is the

relationship between fire spread and fuel age. The lack of fit for Portugal and Kruger NP may also be due to the other drivers mentioned above, and a more detailed discussion is warranted.

The lack of leverage in Kruger NP is particularly surprising given that leverage is strong in Arnhem Land (Australia), which also has a savanna fuel type with high fire activity (Price *et al.* 2012a). This difference may reflect a variety of effects, but note that the Arnhem Land leverage effect was largely driven by previous fires within the same year and if these were not considered, leverage was much lower ( $\sim 0.2$ , authors' unpubl. data). It was not possible to distinguish previous fires from the same year in the Kruger NP dataset, so direct comparison between the two study regions was not possible. In both regions, vigorous grass growth in the wet season allows for annual fires. Differences between the two study areas include lower annual rain (500 mm cf. 1300), much higher herbivore biomass and fewer trees in Kruger NP, all of which suggest that fuel loads may be more determined by rainfall and herbivores than by recent fires. Indeed, Van Wilgen *et al.* (2004) found that fire activity is largely driven by antecedent rainfall over 2 years, which is highly variable. Thus it seems likely that rapid fuel recovery following annual rains



**Fig. 3.** The currently known global set of leverage values plotted against annual area burnt. The point labelled 1 near the origin represents three different studies: Sequoia and Kings Canyon NP, Spain and Alberta. The continuous line is the regression line for all points:  $\text{leverage} = 0.145 + 0.020 * \text{Burntarea}$ ,  $r^2 = 0.121$ ,  $P = 0.121$ . The dotted line is with Kruger NP and Portugal excluded:  $\text{leverage} = 0.0222 + 0.039 * \text{Burntarea}$ ,  $r^2 = 0.920$ ,  $P < 0.001$ .

inhibits leverage. It is also possible that the encounter rate is low despite high mean annual area burnt, which is a likely consequence of the rotational fire management practiced for much of Kruger NP's history so that fires were unlikely to encounter previous patches for at least 3 years.

The Portuguese leverage value is higher than would have been predicted from our global analysis. This is particularly surprising given that bordering Spain has no leverage. The Portuguese regions with the highest area burnt are in the north and the Spanish region of Galicia, which is on Portugal's northern border, has the highest area burnt of the Spanish regions (2.1%). However, this is still much lower than the bordering Portuguese regions (5–6%) and when analysed on its own, Galicia showed no leverage. It seems likely that the factors governing the fire regime are different in Spain and Portugal, and this may also explain why leverage is higher than predicted. The burnable vegetation in Portugal is often fragmented or occurs in complex, dissected terrain that constrains fire spread. Ignition rates in Portugal exceed those of Spain by a factor of five and are among the highest in the world (Carvalho *et al.* 2008). Leverage would be higher than expected if fires were spatially biased, tending to burn the same places regularly, which results in a higher effective mean area burnt in the affected areas. Re-burns (areas burnt at least twice between 1975 and 2008) corresponded to 51.3% and 23.2% of the total area burnt in the high- and low-region groups of Portugal during 1975–2008 (authors' unpubl. data), indicating this effect is relevant at least in part of the country. Similarly, the fact that removing the outlier year had a large influence on the leverage value suggests a problem with the method: leverage is sensitive to the particular run of years included. This is a particular problem for the Portuguese case study because data were available from only a short period (14 years).

It is perhaps surprising that the boreal forests in Alberta showed zero leverage because they remain impervious to fire for up to 25 years (Schimmel and Granstrom 1997). This means the

percentage of the landscape that has an effective recent burn may be between 5 and 10%. Even at this level only a small proportion of unplanned fires would encounter a significant area of recent burning so we might expect leverage to be relatively low, but still detectable. It is likely that the method we used is not able to detect small leverage effects because the data are dominated by points at the origin (zero past and zero subsequent fire). There is some evidence for leverage from regions with low mean area burnt, from simulation studies that are able to simulate centuries of fire over large areas (King *et al.* 2013).

The absence of a strong leverage effect for the Sierra Nevada is also surprising. There are several possible reasons for this. Management post-1968 has tended to favour prescribed burning and allowing natural fires to burn in years of below-average fire activity and conversely to suppress natural fires in years of above-average activity (T. Caprio, pers. comm.). This artificial balancing of fire acts to negate leverage. Management (both suppression and prescribed fire) is also spatially non-random, being focussed on protecting infrastructure and certain groves of large sequoias (T. Caprio, pers. comm.), which could produce a positive relationship between past and subsequent area burnt (at least locally). The change in management in 1968 may have affected the analysis, though analysis to detect whether the relationship of past fire on unplanned area burnt changed after this year found no significant difference. The other possibility is that multi-year weather patterns such as the El Niño–La Niña cycle cause positive relationships. Our use of annual weather data is an attempt to control for this effect, but our crude measures can only partly account for weather variation. It should also be noted that recent fire activity (as in the data used) is much lower than natural fire activity due to the effectiveness of fire suppression in the 20th century (Stephens and Ruth 2005). Under natural fire regimes (which may be up to 10% mean area burnt in some mixed conifer forest types), leverage may well occur (Collins *et al.* 2009). Taking all of these factors into account, it seems that although a leverage type effect has been found at fine scales in intensively managed areas (Collins *et al.* 2009), the low level of fire activity across the full extent of the park means that there is little or no leverage effect at this larger scale. In other words, high levels of treatment are required at landscape scales to affect wildfire areas across the park.

The fact that some of the case studies do not fit perfectly with predictions means that more research is required in order to fully understand global variation in leverage. Priorities are gathering more global case studies and improving our understanding of the interaction between mean area burnt and the rate of fuel recovery. Global analysis using MODIS area burnt data could prove useful for the former, since it has been used to investigate the drivers of burnt area (Krawchuk *et al.* 2009; Archibald *et al.* 2013; Pausas and Ribeiro 2013). However, the coarse resolution and low fire detection accuracy could potentially mask the leverage effect.

In all six case studies, the weather variables out-performed the past fire variables (higher pseudo- $r^2$ ), which implies that weather has a bigger influence on annual area burnt than does past fire. This is an important result given that the relative role of weather and fuel treatment is the subject of debate around the world. These results are consistent with previous leverage studies (Price and Bradstock 2011; Price *et al.* 2012b) and with



other studies that argue that fire patterns are more strongly governed by variation in weather than fuel management (Keeley and Fotheringham 2001; Cary *et al.* 2009).

In conclusion, we found that leverage is positively related to the mean annual area burnt and cases where leverage occurs that is sufficient to effectively reduce area burnt by unplanned fire are rare. Generally leverage occurs and is stronger where annual burnt area is high and also if fuel recovery periods are long. In biomes where the annual burnt area is low, it is unlikely that past fire inhibits subsequent fire area due to low encounter rates. In forested ecosystems, leverage for prescribed fires is likely to be even lower than the maximum leverage we have calculated here because prescribed fires remove less fuel than unplanned fires. The cases studied to date are not sufficient to confidently predict leverage for a biome based solely on annual burnt area and fuel recovery rates. Nevertheless, we have shown that leverage is related to area burnt and that it is not valid to predict prescribed fire effectiveness in one biome based on its effectiveness in another, as some studies have attempted to do (Sneeuwjagt *et al.* 2013). Our results also highlight the need to focus the large sums of money spent on prescribed burning to regions where it will be most effective.

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