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Assessing the susceptibility of semiarid rangelands to wildfires using Terra MODIS and Landsat Thematic Mapper data

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Abstract. In order to monitor wildfires at broad spatial scales and with frequent periodicity, satellite remote sensing techniques have been used in many studies. Rangeland susceptibility to wildfires closely relates to accumulated fuel load. The normalised difference vegetation index (NDVI) and fraction of photosynthetically active radiation (fPAR) are key variables used by many ecological models to estimate biomass and vegetation productivity. Subsequently, both NDVI and fPAR data have become an indirect means of deriving fuel load information. For these reasons, NDVI and fPAR, derived from the Moderate Resolution Imaging Spectroradiometer on-board Terra and Landsat Thematic Mapper imagery, were used to represent prefire vegetation changes in fuel load preceding the Millennial and Crystal Fires of 2000 and 2006 in the rangelands of south-east Idaho respectively. NDVI and fPAR change maps were calculated between active growth and late-summer senescence periods and compared with precipitation, temperature, forage biomass and percentage ground cover data. The results indicate that NDVI and fPAR value changes 2 years before the fire were greater than those 1 year before fire as an abundance of grasses existed 2 years before each wildfire based on field forage biomass sampling. NDVI and fPAR have direct implication for the assessment of prefire vegetation change. Therefore, rangeland susceptibility to wildfire may be estimated using NDVI and fPAR change analysis. Furthermore, fPAR change data may be included as an input source for early fire warning models, and may increase the accuracy and efficiency of fire and fuel load management in semiarid rangelands.

Additional keywords: biomass burning, fPAR, fuel loads, Idaho, NDVI, remote sensing.

Introduction

Rangelands refer to expansive, mostly non-cultivated, non-irrigated and non-forested lands that include grasslands, savannas and shrublands where livestock grazing is a common land use. Rangelands cover ~40% of the Earth's terrestrial surface and play an important role in global ecosystem productivity (Breman and de Wit 1983; Huntsinger and Hopkinson 1996). Wildfires are common in rangelands worldwide and have significant effects on rangeland ecosystem balance, with the most obvious effect being direct effect on vegetation communities (Mutch 1970; Pierson *et al*. 2002; West and Yorks 2002; Taylor 2003). In a wildland fire, fuel is composed nearly entirely of vegetation and severe fires can leave entire landscapes devoid of vegetative cover, resulting in numerous significant climatic, ecological and hydrologic hazards (Pierson *et al*. 2002; Hilty *et al*. 2004; Collins *et al*. 2006). In addition, biomass burning is recognised as an important source of trace gases to the atmosphere, such as carbon dioxide, methane, carbon monoxide, nitrogen dioxide and non-methane hydrocarbons (Crutzen *et al*. 1979; Greenberg *et al*. 1984). These trace gas compounds may trap the heat radiated by the earth and contribute to the greenhouse effect (e.g. average annual CO_2 emissions from fires in the lower 48 states of USA were ~213 Tg CO_2 year^{-1} from 2002 to 2006) (Houghton 1992; Wiedinmyer and Neff 2007; EPA 2008). Furthermore, following a fire, vegetation communities may transition to a very different community type due to invasions by non-native species, resulting in a variety of propagated indirect effects (Thomas and Davis 1989; Hilty *et al*. 2004).

Satellite remote sensing is an evolving technology providing regional and global imagery that has been used for many wildfire studies (Fernandez *et al*. 1997; Miller and Yool 2002; Wooster *et al*. 2003; Lentile *et al*. 2006; Weber *et al*. 2008*b*). These studies include both observational and modelled data and have been conducted on active fires and for detecting post-fire burn extent. For example, National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) imagery has been used to detect and map fire growth (Kennedy *et al*. 1994; Fernandez *et al*. 1997; Pozo *et al*. 1997; Siegert and Hoffmann 2000). MODIS (Moderate Resolution Imaging Spectroradiometer) imagery provides thermal anomalies and fire products to meet the requirements of understanding the timing and spatial distribution of fires at various regional and global scales (Wooster *et al*. 2003; Li *et al*. 2004; Morisette *et al*. 2005). In addition, Landsat-5 Thematic Mapper (TM) and the Landsat-7 Enhanced Thematic Mapper Plus (ETM+) have been used to determine fire

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perimeter and burn severity of the Cerro Grande Fire, New Mexico, USA. (Miller and Yool 2002). Similarly, post-fire field observations coupled with Satellite Pour l'Observation de la Terre 5 (SPOT 5) imagery have been used for fire-severity modelling of sagebrush steppe rangelands in south-eastern Idaho (Weber *et al*. 2008*b*).

Recently, satellite-based wildfire studies have focussed on post-fire factors (i.e. severity and perimeter mapping), with emphasis on forested ecosystems (Chuvieco and Congalton 1989; Fernandez *et al*. 1997; Fraser and Li 2002; Giglio *et al*. 2003). Many reflectance indicators derived from various remotely sensed data have been tested to assess forest fire effects including the normalised difference vegetation index (NDVI) (Illera *et al*. 1996; Leblon *et al*. 2001; Aguado *et al*. 2003; Chuvieco *et al*. 2004), spectral indices retrieved by Tasseled Cap (Mbow *et al*. 2004), and normalised difference water index (NDWI) (Maki *et al*. 2004; Verbesselt *et al*. 2006). In addition, in order to calculate burn severity, the Normalised Burn Ratio (NBR; Key and Benson 1999), which incorporates near- and mid-infrared bands, and the differenced Normalised Burn Ratio (dNBR), which is the result of differenced pre- and post-fire NBR models, have been widely applied (Epting *et al*. 2005; Escuin *et al*. 2008). NBR and dNBR are key indicators of burn severity and can be used to infer many post-fire effects such as fire extent (Holden *et al*. 2005) and fire severity classification (Brewer *et al*. 2005; Smith *et al*. 2005). For example, incorporating Classification Tree Analysis (CTA) techniques and post-fire field survey data, NBR along with various other band ratios was used to assess the severity of fire occurring in rangelands of Idaho (Weber *et al*. 2008*b*). Furthermore, these reflectance indicators derived from remotely sensed data were widely used for fire studies in savannahs and semiarid environments (Smith *et al*. 2005; Fisher *et al*. 2006; Weber *et al*. 2008*a*).

Many studies indicate that wildfire danger is directly linked to fuel properties (e.g. fuel load, fuel size, fuel moisture content and fuel type) and many of these fuel properties can be assessed using remotely sensed data (West and Yorks 2002; Westerling *et al*. 2003). For example, estimates of forest biomass have been used to reveal changes in crown fuels (Nelson *et al*. 1988; Means *et al*. 1999; Franklin, *et al*. 2003). In addition, surface fuel type has been characterised using vegetation classification maps derived from various remotely sensed data (Keane *et al*. 2001; Riano *et al*. 2002; Van Wagtendonk and Root 2003), including various vegetation indices (e.g. NDVI) that have been related to fuel moisture content and fire potential (Paltridge and Barber 1988; Chuvieco *et al*. 2002; Danson and Bowyer 2004; Dennison *et al*. 2008).

Fire danger conditions are related to, although not entirely attributable to accumulated fuel load, which in turn is related to vegetation cover, type, biomass, phenology and various fuel properties such as moisture content. Rangeland susceptibility to wildfire is determined by the combined effect of these characteristics, many of which can be accurately estimated based on empirical relationships with remotely sensed imagery. NDVI and fPAR are two important indicators of these vegetation variables, and global or regional scale NDVI and fPAR have been derived through satellite remote sensing (Chuvieco *et al*. 2002; Chen *et al*. 2008). Because NDVI and the fraction of photosynthetically active radiation (fPAR) represent canopy greenness and are closely related to biomass, vegetation type, leaf area index (LAI) and primary productivity, they represent an indirect way to derive fuel load (Van Wagtendonk and Root 2003) in conjunction with field data. NDVI leverages the ratio of reflectance in the red band (where chlorophyll makes notable absorption of incoming sunlight) of a sensor to that of the near-infrared band (where considerable reflectance is made by a plant's spongy mesophyll leaf structure) of the sensor, and is closely related to the quantity of green vegetation on the landscape (Tucker 1979). NDVI is easy to calculate and can be considered a basic index from which many subsequent vegetation variables can be calculated or deduced (i.e. LAI, vegetation cover, biomass) (Chen and Cihlar 1996; Boelman *et al*. 2003; Hill and Donald 2003). fPAR is the fraction of available radiation in specific photosynthetically active wavelengths of the electromagnetic spectrum (i.e. 0.4–0.7 μm) that a canopy absorbs (Chen 1996; Myneni *et al*. 1999; Chen *et al*. 2008). In many ecosystem models, fPAR has been used as a modelling input across several biomes (Bonan 1995; Hély *et al*. 2003). In addition, after accounting for atmospheric effects and background contributions to the signal, linear relationships have been established between fPAR and NDVI.

Although both fPAR and NDVI respond to pixel heterogeneity, background noise and atmospheric effects and exhibit similar responses to vegetation percentage cover, leaf area, leaf orientation, solar zenith angle and atmospheric optical depth, they respond differently to soil reflectance and leaf optical properties (Daughtry *et al*. 1983; Myneni and Williams 1994). In the present study, both NDVI and fPAR were used as indicators to evaluate wildfire danger in semiarid rangelands. MODIS- and TM (Thematic Mapper)-derived fPAR and NDVI data were chosen to represent vegetation status and to detect changes in fuel load. Incorporating monthly precipitation, monthly mean temperature, field-based measurements of ground cover and measures of biomass at numerous sites, variation in fuel load across the semiarid rangelands of Idaho, USA, was evaluated.

Materials and methods

Study area

The Big Desert study area lies ~71 km north-west of Pocatello, ID, and the centre of the study area is ~113°4′18.68″W and 43°14′27.88″N (Fig. 1). The study area is located on the land managed by the US Department of the Interior Bureau of Land Management (USDI BLM). The area is a semiarid sagebrush-steppe ecosystem with a high proportion of bare ground (bare ground >17%), and the area consists primarily of native and non-native grasses, forbs and many shrub species including sagebrush (*Artemisia tridentata*) and rabbit brush (*Chrysothamnus nauseosus*). The elevation of the study area ranges from 1349 to 2297 m above sea level, and annual precipitation is 230 mm, with 40% of the precipitation falling from April through June (Yanskey *et al*. 1966). Cattle and sheep grazing is the primary anthropic disturbance to the study area with deferred, rest-rotation and continuous and seasonal grazing systems used on allotments ranging in size from 1100 to over 125 000 ha. The stocking rate is low across the study area, ~19 ha per animal unit (AU), and is considered a semi-extensive

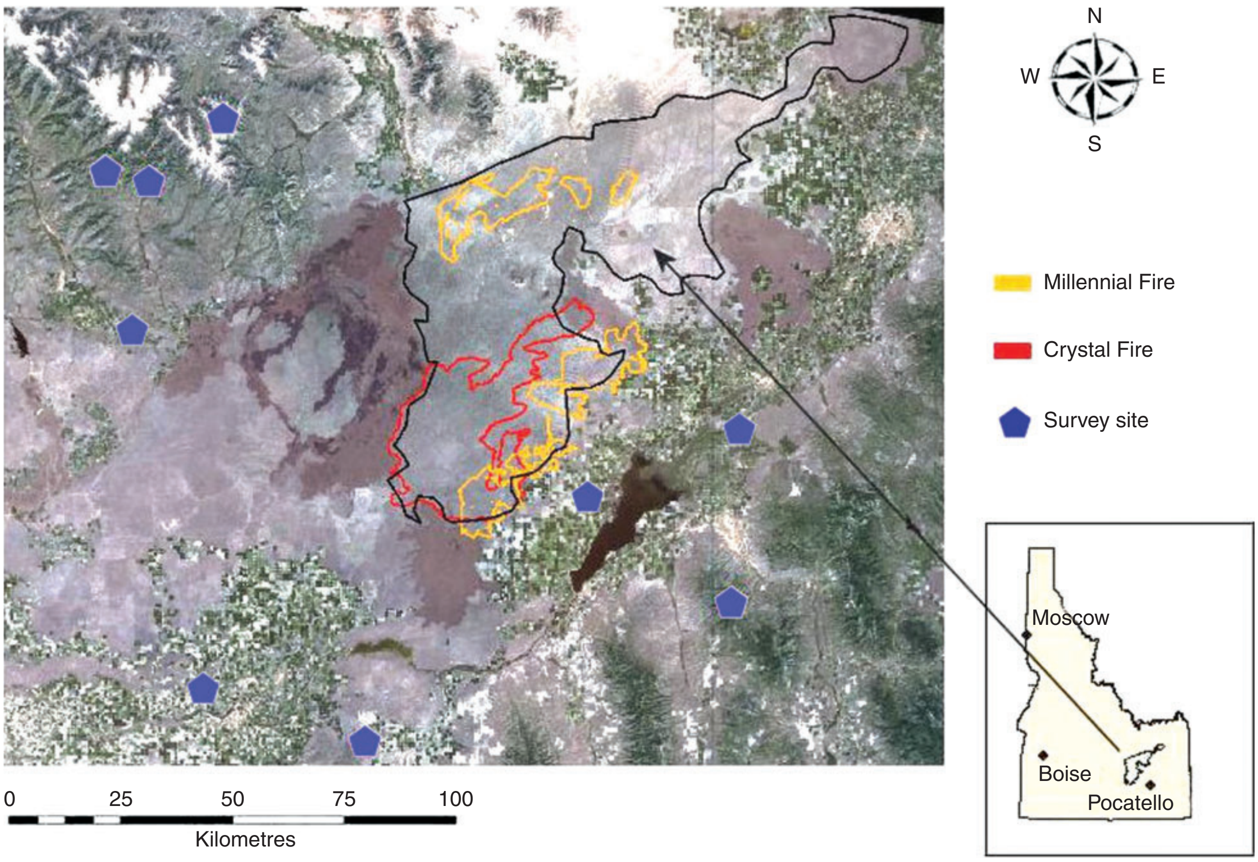

Fig. 1. Location and general characteristics of the Big Desert in south-eastern Idaho. The true colour composite of Landsat-5 TM: band 3 = red, band 2 = green, band 1 = blue.

Table 1. Dates and numbers of field sample plots used for validation

Year	Sampling date	Number of sample plots
2004	1 June to 30 June	154
2005	1 June to 15 July	88
2006	5 June to 10 July	175

grazing regime. Wildfire is another common disturbance and 39% of the study area has burned in the past 10 years.

Sample design and field measurements

A total of 417 sample points were randomly generated across the study area. Each point met the following criteria: (1) >70 m from an edge (road, trail or fence line), and (2) <750 m from a road. Table 1 details four field campaigns from 2004 to 2006. Each plot centre location was recorded using a Trimble GPS (Sunnyvale, CA, USA) receiver and all points were post-processed differentially corrected (±1 m (2004), ±0.70 m (2005) and ±0.20 m (2006) after post-processing with a 95% confidence interval, CI). The sample points were then projected into Idaho Transverse Mercator NAD 83 (Gnieting *et al.* 2005).

Ground vegetation cover and biomass are two variables that closely relate to wildfire fuel load. For this reason, ground cover and biomass were estimated in the field survey. This study sought to characterise vegetation cover and biomass at the time of maximum primary production in June, but was not intent on relating field measurements directly to pixel data. Ground-cover estimations were made within 10 × 10-m square plots centred over each sample point with the edges of the plots aligned in cardinal directions. The percentage cover of five vegetation classes (bare ground, litter, grass, shrub and weed) was estimated by walking the plot and estimating and generalising a cover category for each class (Kercher *et al.* 2003). Percentage cover was estimated using categorical breaks of 0, 1–5, 6–15, 16–25, 26–35, 36–50, 51–75, 76–95 and 96–100% .

Forage wet biomass was measured four times within each sample plot ($n = 1668$). All green and senescent herbaceous biomass was clipped and weighed in an ordinary paper bag using a Pesola scale (Kapuskasing, ON, Canada, ±1 g) tared to the weight of the bag. All grass species were considered forage and these measurements were used to estimate forage availability, expressed as kilograms per hectare. Dry biomass would have been preferable. However, there have been accumulated up to 10 years of data in the study area; all the previous field surveys collected wet biomass. The dry biomass data between 2004 and 2006 are not available for this study. Wet biomass could represent vegetation productivity as well, though dry biomass might be better in this study.

Table 2. Natural Resources Conservation Service (NRCS) and AgriMet survey site list and monthly precipitation and mean temperature data for this study

Site name	Latitude	Longitude	Year	Precipitation (mm)				Mean temperature (°C)			
				March	April	May	June	March	April	May	June
Garfield	43°36′	−113°55′	2004	10	36	74	33	1	5	7	12
			2005	53	58	198	74	0	3	7	9
			2006	76	130	43	15	−3	4	9	13
Swede Peak	43°37′	−113°58′	2004	15	46	94	25	1	4	6	11
			2005	81	61	188	86	−1	2	6	8
			2006	117	160	51	15	−4	2	7	13
Smiley Mountain	43°43′	−113°50′	2004	20	46	102	30	0	1	4	8
			2005	76	112	226	119	−3	0	4	6
			2006	130	208	51	25	−6	0	6	10
Howell Canyon	42°19′	−113°36′	2004	66	79	112	15	2	3	5	11
			2005	114	127	208	94	−1	2	6	9
			2006	168	145	74	38	−3	3	7	13
Wildhorse Divide	42°45′	−112°28′	2004	66	36	76	48	2	5	8	12
			2005	76	86	117	71	1	4	8	10
			2006	132	155	25	28	−1	4	9	13
Fort Hall	43°04′	−112°25′	2004	7	19	30	26	5	9	12	17
			2005	18	46	86	29	3	7	12	15
			2006	36	67	9	21	2	8	13	18
Rupert	42°35′	−113°52′	2004	8	15	20	2	6	9	12	17
			2005	19	71	124	22	5	7	12	14
			2006	26	54	37	8	2	8	14	19
Picabo	43°18′	−114°09′	2004	5	17	46	16	3	9	11	17
			2005	51	21	86	28	2	6	11	13
			2006	40	89	22	6	−1	7	12	18
Aberdeen	42°57′	−112°49′	2004	5	23	33	7	4	9	12	16
			2005	16	50	67	12	4	7	12	15
			2006	37	33	18	39	1	8	13	18

In this study, monthly precipitation and monthly mean temperature data were provided by the USDA Natural Resources Conservation Service (NRCS) (http://www.id.nrcs.usda.gov/snow/data/historic.html, accessed June 2011) and the United States Bureau of Reclamation (USBR) AgriMet Program (http://www.usbr.gov/pn/agrimet/, accessed June 2011). Although no weather station survey sites were available within the Big Desert study area, nine sites bounding the study area (<70 km from the Big Desert study area) were located and used (Fig. 1). Though some sites are in the mountains, the weather there has identical change trends compared with the Snake River Plain (Table 2).

Landsat-5 TM NDVI and fPAR calculation

Because Terra satellite was launched in December 1999, there are no MODIS data available between 1998 and 1999. Therefore, four cloud-free TM scenes (path/row: 039/030) captured on 10 August 1998, 25 May 1999, 29 August 1999 and 27 May 2000 were used to derive NDVI and fPAR before the Millennial Fire of August 2000. Digital Number (DN) values were converted into planetary reflectance using gain and offset coefficients, solar zenith angle, solar irradiances and the sun–earth distance factors from the metadata of the imagery (Chander and Markham 2003). The imagery was then processed to reflectance by performing an atmospheric correction using the dark object subtraction (DOS) method (Chavez 1996; Song *et al*. 2001). All imagery was projected into Idaho Transverse Mercator NAD 83 and was georectified against 2004 National Agriculture Imagery Program (NAIP) natural colour aerial imagery (1 × 1-m pixels) (root-mean-square error (RMSE) = 8.126).

TM NDVI values were calculated using Eqn 1. Because there were no ground-measured fPAR data available for this study, TM fPAR estimations were accomplished using the simple ratio (SR)-fPAR algorithm, built on the remote sensing of vegetation and plant physiology described by Sellers *et al*. (1992). The SR is the ratio of reflectance in the red band to that of the near-infrared band (Eqn 2) and NDVI and SR are related functionally ($NDVI = (SR - 1)/(SR + 1)$), as both represent slope-based spectral vegetation index band ratios designed to characterise photosythetically active vegetation (Chen and Cihlar 1996; Stenberg *et al*. 2004). The SR-fPAR algorithm is a straightforward fPAR retrieval approach and is considered applicable within a variety of biome types (e.g. broadleaf evergreen trees, needle-leaf deciduous trees and grasslands) (Paruelo *et al*. 1997; Los *et al*. 2000; Hassan *et al*. 2006). A near-linear relationship between fPAR and SR (Eqn 3) was assumed and followed Sellers *et al*. (1996): ‘The value of the 98% NDVI for tall vegetation and agriculture is assumed to represent vegetation at full cover and maximum activity with fPAR values close to 1. The 98% NDVI value of agriculture was used to represent all short vegetation types, whereas the 5% desert value is assumed to represent no vegetation activity with an fPAR of 0.001

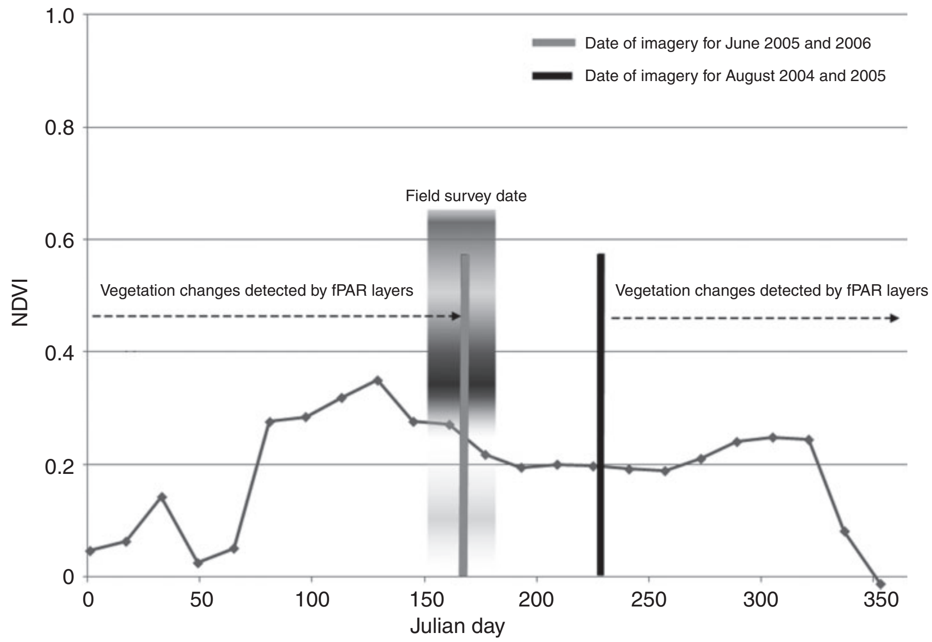

Fig. 2. Annual phenology as described using NDVI (normalised difference vegetation index) in relation to the dates of imagery selected for the study.

(Sellers *et al*. 1996, p. 722)'. Once these two values are determined, the relationship between fPAR and SR can be described as shown in Eqn 3:

$$\mathrm{NDVI} = \frac{NIR - RED}{NIR + RED} \tag{1}$$

$$SR = \frac{NIR}{RED} \tag{2}$$

$$\mathrm{fPAR} = \frac{(SR - SR_{i,\min})(\mathrm{fPAR}_{\max} - \mathrm{fPAR}_{\min})}{(SR_{i,\max} - SR_{i,\min})} + \mathrm{fPAR}_{\min} \tag{3}$$

where *RED* and *NIR* stand for the spectral reflectance measurements acquired in the red and near-infrared regions respectively. $SR_{i,\max}$ and $SR_{i,\min}$ correspond to the maximal and minimal NDVI data population for type *i* vegetation, and the maximum ($\mathrm{fPAR}_{\max} = 0.950$) and minimum ($\mathrm{fPAR}_{\min} = 0.001$) values of fPAR are independent of vegetation type (Sellers *et al*. 1996).

MODIS NDVI and fPAR Product

Collection 5 MODIS NDVI (MOD13A2) and fPAR (MOD15A2) products (1-km spatial resolution) were used in this study. The MODIS NDVI algorithm operates on a per-pixel basis and relies on multiple observations over a 16-day period to generate a composite NDVI (Huete *et al*. 2002; Tarnavsky *et al*. 2008). The MOD15A2 fPAR product represents a time interval of 8 days and in the case of fPAR, the values represent 8-day maxima. The theoretical basis of the MODIS fPAR algorithm is the three-dimensional radiative transfer theory, and the inversion of the three-dimensional radiative transfer problem is solved using a look-up table method (Knyazikhin *et al*. 1998; Myneni *et al*. 1999). In the present study, four MODIS NDVI and four MODIS fPAR scenes were used. MODIS fPAR imagery for the entire study area was captured between 12 and 19 August 2004, 10 and 17 June 2005, 13 and 20 August 2005 and 10 and 17 June 2006 before the Crystal fire. In addition NDVI imagery was also acquired on the basis of temporal coincidence with existing MODIS fPAR imagery.

Based on MODIS NDVI and fPAR quality control (QC) layers, NDVI and fPAR data were screened to reject all data of insufficient quality. Only pixels with the best possible quality (i.e. values on all bit fields are equal to zero) under the fPAR QC definition and pixels with 'use with confidence' under the vegetation indices QC definition were retained. The QC filter includes pixels with good quality and removes pixels that were not produced owing to cloud or other reasons.

Data analysis

Field work began in June, as this was considered optimal to characterise the phenological changes over the growing season through to late fall (autumn). There were no field surveys conducted before 2000 and field data were only used in conjunction with MODIS image analysis. For these analyses, field data were collected between June and early July at the same time as the remotely sensed data were acquired. Imagery for the August 2004 and 2005 time periods were also used to capture late-summer senescence and thereby better assess changes in fPAR over each growing season.

In the semiarid sagebrush-steppe rangelands of Idaho, plant growth rates dramatically decrease following the active growth period, which typically ends in June (Fig. 2). However, plant growth does continue and in some years exhibits a spike of activity when sufficient autumn precipitation is present. Therefore, the fPAR change layers, calculated by finding the

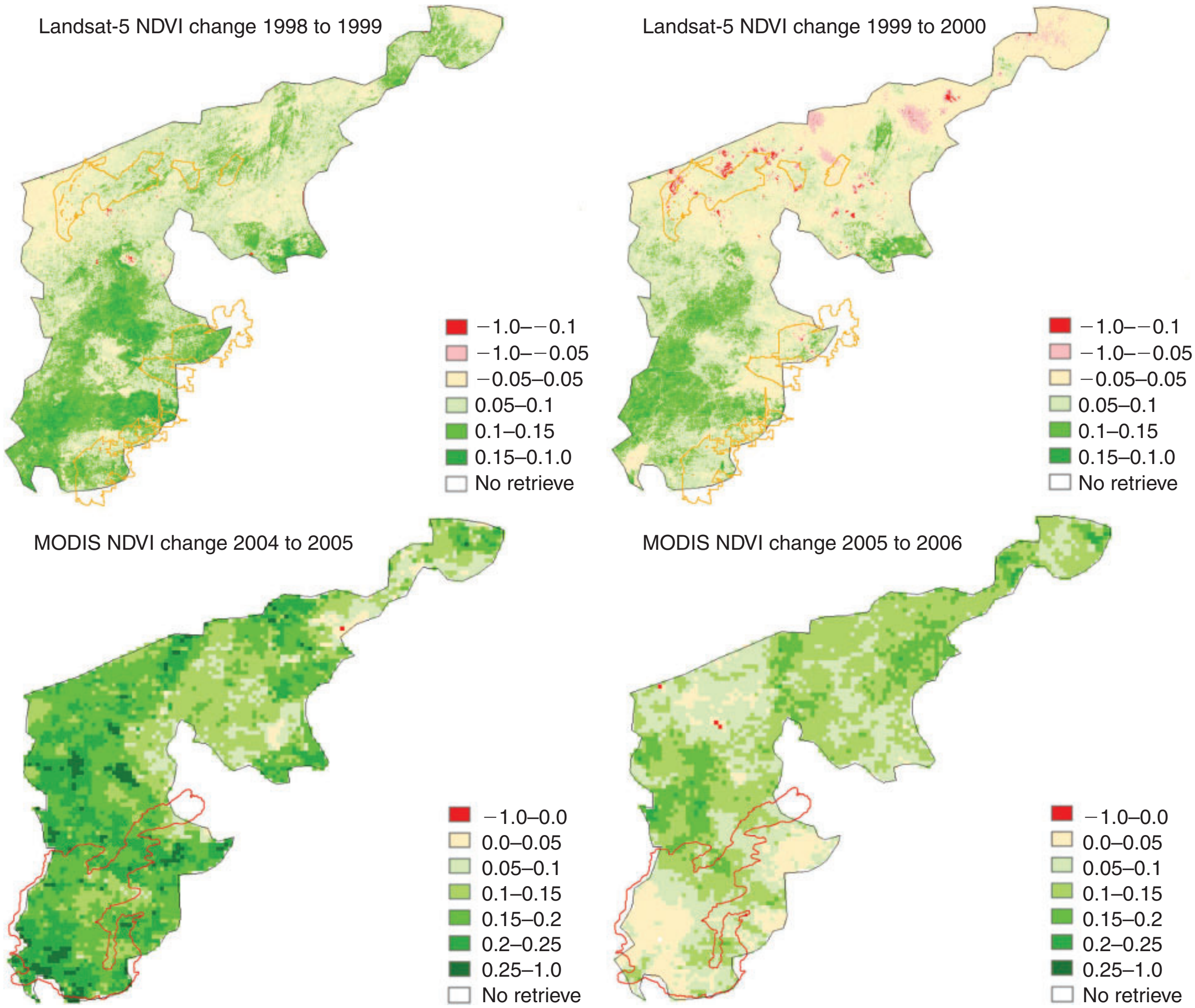

Fig. 3. Prefire Landsat-5TM NDVI and MODIS NDVI (Moderate Resolution Imaging Spectroradiometer normalised difference vegetation index) change layers.

difference in fPAR between August 2004 and June 2005 (i.e. dotted line marked in Fig. 2), do not include vegetation changes that occurred between June and early August of 2005. Following this approach, the resultant change layers represent the amount of new green biomass available (e.g. actively growing grasses) as the difference between the total biomass during the fall active growth period (i.e. actively growing grasses, accumulated litter and residual plant matter) and the total biomass at the end of the spring growing season (i.e. accumulated litter and residual plant matter).

Using 4 years of field survey data, we note that grass, shrub and dominant weeds tend to be green and actively growing, resulting in high fPAR values, during spring and early summer (i.e. June). In the late-summer senescence period, high temperatures hasten the desiccation of plants and in contrast to the active growing period, fPAR values are reduced and substantially different at this time. Therefore, we selected TM and MODIS imagery during these periods to optimally detect fPAR change and thereby better understand seasonal productivity within semiarid rangelands.

Two notable wildfires occurred in the Big Desert study area: one in August 2000 (Millennial Fire) and another in August 2006 (Crystal Fire). The Millennial Fire burned ~62 018 ha within the Big Desert study area. The Crystal fire burned ~90 528 ha of grasslands and sagebrush between 15 and 31 August 2006, and more than 16 100 ha of grassland were burned in a single day.

Prefire vegetation change distribution monitoring

Image differencing is a widely used change detection technique for remotely sensed data and change data are often threshold processed (Singh 1989; Ridd and Liu 1998) or classified (Lyon *et al*. 1998). In the current study, image differencing was used to calculate prefire NDVI and fPAR changes in different years; however, image differencing was not used for setting thresholds to determine whether fPAR changed or not. TM NDVI and fPAR change layers were calculated by subtracting NDVI and fPAR values for 10 August 1998 from NDVI and fPAR values for 25 May 1999. Similarly, NDVI and fPAR values for 29 August 1999 were subtracted from NDVI and fPAR values

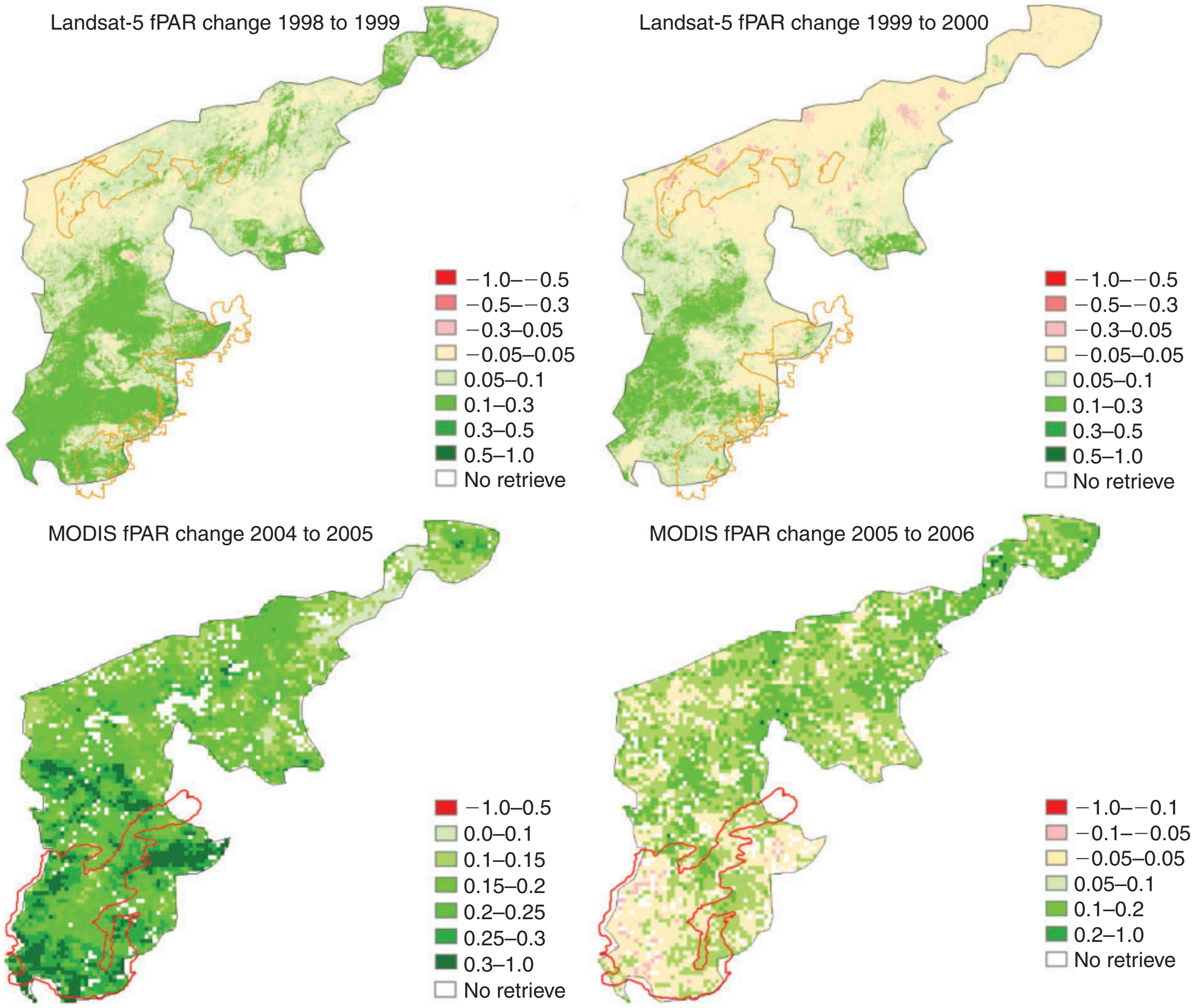

Fig. 4. Prefire Landsat-5 TM (Thematic Mapper) fPAR (fraction of photosynthetically active radiation) and MODIS (Moderate Resolution Imaging Spectroradiometer) fPAR change layers.

for 27 May 2000. MODIS NDVI and fPAR change layers were calculated by subtracting August 2004 values from June 2005 values and subtracting August 2005 values from June 2006 values. The historic fire perimeter database of Idaho maintained by USDI BLM (BLM, Idaho State Office, http://inside.uidaho.edu/geodata/BLM/index.htm, accessed June 2011) was used to overlay wildfire perimeter layers on Landsat-5 NDVI and fPAR change layers and MODIS NDVI and fPAR change layers for inspection. NDVI and fPAR change layers were compared with monthly precipitation, monthly mean temperature and field-based measurements of forage biomass and percentage ground cover within the Crystal Fire area. This was not done for the Millennial Fire area as detailed field data were not available within its fire perimeter. Last, a total of 500 independent randomly distributed test points were selected from NDVI and fPAR change layers. Of these, 207 points were retained for analysis within the Millennial Fire area and 238 points were retained within the Crystal fire area after removing all points falling in 'no-data' areas of the imagery. Pixel values were extracted, and mean values of NDVI change and fPAR change at different years were summarised to assess the susceptibility of semiarid rangelands to wildfires.

Results and discussion

Prefire TM NDVI and fPAR change layers illustrate an overall increase in NDVI and fPAR values ($0.1 < \text{NDVI}$ and fPAR change < 0.5) within the Millennial Fire area between 1998 and 1999 (i.e. 2 years before the fire; Figs 3, 4). Similarly, NDVI values increased 0.15–0.25 and fPAR values increased >0.20 within the Crystal Fire area from 2004 to 2005 (i.e. 2 years before the fire). Compared with the '2 years prior to the fire' period, where NDVI and fPAR change values showed an overall increase, there was a substantial difference with the '1 year prior to fire' period (NDVI and fPAR change < 0.1). In general, NDVI and fPAR values for both the Millennial and Crystal Fire areas experienced large increases 2 years before the fire period, with much lower increases in NDVI and fPAR values just 1 year before the fire. These changes likely correspond to a change in vegetation conditions (e.g. vegetation cover and biomass)

Table 3. Forage biomass and percentage ground cover for fPAR (fraction of photosynthetically active radiation) change analysis

	Forage biomass (kg ha^{-1})	Average ground percentage cover (%)					Number of sample plots
		Shrub	Grass	Litter	Bare ground	Weed	
Fire areas 2004	334	5–12	5–12	6–15	53–78	1–5	47
Fire areas 2005	583	6–14	5–13	1–7	48–71	1–6	57
Fire areas 2006	283	17–26	6–16	18–29	15–23	5–11	24
Changes in fire areas 2004–05	249	1–2	0–1	−(5–8)	−(5–6)	0–1	N/A
Changes in fire areas 2005–06	−300	11–12	1–3	17–22	−(33–48)	−(1–5)	N/A

Table 4. Analysis of precipitation and temperature in 2004, 2005 and 2006

Year	Average precipitation (mm)				Average temperature (°C)				Average of 4 months precipitation (mm)	Standard deviations
	March	April	May	June	March	April	May	June		
2004	22	35	65	22	3	6	9	13	145	57[A], 73[B]
2005	56	70	144	59	1	4	9	11	330	
2006	85	116	37	22	−1	5	10	15	259	

[A]Standard deviation of precipitation for 2004 and 2005.
[B]Standard deviation of precipitation for 2005 and 2006.

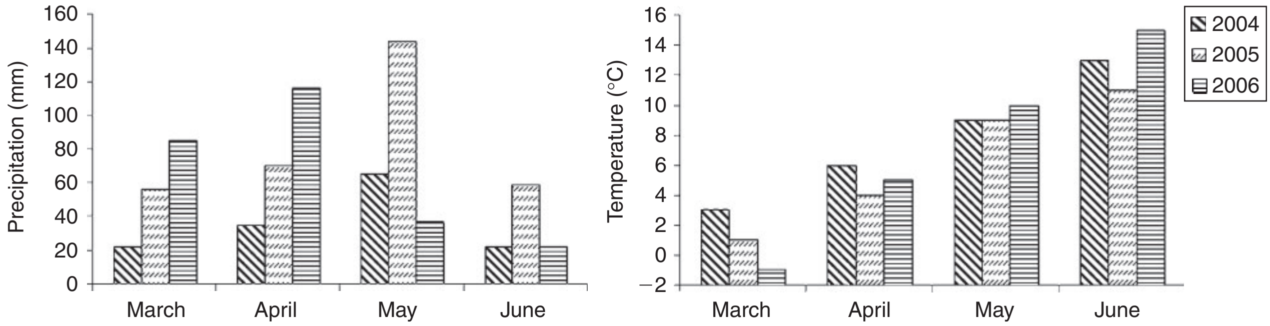

Fig. 5. Monthly precipitation and temperature for the study.

within the fire areas as the same overall trend of change was depicted in both the fPAR and NDVI change maps.

Grass is a common component of the fuel load in south-east Idaho, and accumulated fuel loads can burn intensely and severely. The development of fuel stockpiles and the prevalence of cheatgrass (*Bromus tectorum*), an invasive annual grass, have made the fuels on Idaho's rangelands increasingly problematic (Weber *et al*. 2008*b*). Historically, rangelands in south-east Idaho experienced wildfire throughout a 2–3-week period in late summer (F. Judd, pers. comm.). However, with the introduction of cheatgrass, the wildfire 'season' has been inadvertently extended to ~2–3 months as this non-native annual grass senesces early in the growing season and produces large contiguous areas of highly flammable fine fuels. Therefore, in rangeland ecosystems like these, ground vegetation conditions closely correlate with fuel load, which in turn can function as an early warning for rangeland wildfire.

The observed NDVI and fPAR changes are a function of changes in grasses as these are more ephemeral in nature than shrubs. In order to validate this observation, field-based measurements of forage biomass and percentage cover of grasses in the Crystal Fire area were examined. Average grass cover in 2004 and 2005 was similar; however, forage biomass in 2004 (334 kg ha^{-1}) was less than in 2005 (583 kg ha^{-1}) (Table 3). Although more grass was produced in 2005 than in 2004, this is most probably the result of increased precipitation during that same year (Le Houérou and Hoste 1977; Fisher *et al*. 1988). Average precipitation between March and June of 2005 (a crucial part of the growing season in south-east Idaho rangelands) was 330 mm, with 40% of the total falling in May whereas in 2004, there was only 145 mm of rainfall (s.d. 57 mm) (Tables 2, 4). From 2005 to 2006, average grass cover increased only 1–3%, and forage biomass decreased by 300 kg ha^{-1}. Similarly, average precipitation between March and June of 2006 was reduced as well (259 mm) (s.d. 73 mm), with most of this precipitation falling between March (85 mm) and April (116 mm).

The majority of grass growth activity occurs within a specific range of temperatures (Went 1953). Comparing average temperatures in May 2005 (9°C), which was the major precipitation period for 2005, with average temperatures in March (−1°C) and April (5°C) of 2006, the effect on grass growth becomes apparent (Table 4) (Fig. 5). Because temperature and precipitation act together to affect the biophysical and ecological status of grasses, we conclude that monthly precipitation and mean temperature in the spring of 2005 were much better suited for grass growth than that seen in 2006; hence, more grass was produced between 2004 and 2005 than between 2005 and 2006 (Fig. 6). These differences in grass growth activity suggest a concomitant change in NDVI and fPAR should exist. Analysis of monthly precipitation, mean temperature, field-based measurements of ground cover and measures of biomass suggest that the Crystal Fire area should have a greater NDVI and fPAR change between 2004 and 2005 than between 2005 and 2006.

In order to validate this supposition, fPAR and NDVI annual changes are shown in Fig. 7. It is noted that for either NDVI or fPAR, the value changes 2 years before the fire (e.g. 2004 to 2005) were greater than those 1 year before fire (e.g. 2005 to 2006). This suggested that there was a prevalence of grasses 2 years before the fire period for each wildfire. Thus, it is concluded that the information represented by field-based measurements follows the same trend as indicated in the NDVI and fPAR change maps. NDVI and fPAR provide means for assessing prefire vegetation changes, and the susceptibility to wildfire can be estimated using an NDVI and fPAR change analysis.

Another important component of fine fuels in semiarid ecosystems is litter. Litter is senescent (dead or dry) plant material, and in general, an abundance of grasses ultimately leads to an increase in litter (Nagler *et al*. 2000) unless herbivory, trampling by livestock (leading to accelerated rates of organic decomposition) or wildlife remove the litter. Although rangeland fuels are relatively simple compared with forest fuels, different species of rangeland plants generate different fire-behaviour characteristics depending on factors like moisture content and blade height (Sandberg *et al*. 2001; Agee *et al*. 2002). In comparison with green grass, litter and dry grass flash much more quickly and burn easily. Therefore, an area covered by a continuous surface of litter and dry grass is more flammable than areas with less litter cover.

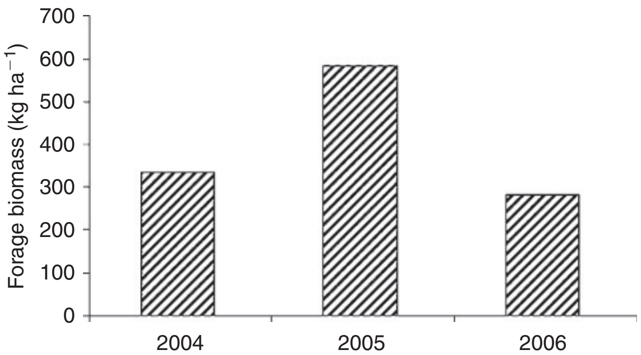

Fig. 6. Yearly forage biomass for the study.

Average percentage litter cover increased 17–22% (whereas forage biomass decreased by 300 kg ha^{-1}) in the Crystal Fire area from 2005 to 2006 (Table 3). The mean litter cover class in 2005 was only 1–7%; however, mean litter cover increased to 18–29% in the following year. In light of these data, the following interpretation is offered: the prevalence of grasses reported from 2004 to 2005 was followed by a reduction in photosynthetically active grass productivity between 2005 and 2006 in the Crystal Fire area. Following 2 years of highly productive growth, many grasses died back (owing to drier conditions) and contributed to an increase in litter (i.e. fine fuels).

The observed changes in grass productivity reported in this study were found to closely correlate (albeit with a lag interval) to a change in litter cover. As a result, the prevalence of litter in 2006 most likely had an effect on the size and severity of the Crystal Fire. These observations and trends were observed in both the NDVI and fPAR change layers, which suggests the potential for these data to be used for future fire-risk modelling. The absence of field data between 1998 and 1999 limited the susceptibility analysis to the Millennial Fire. However, interpretation of 2004–06 field data offers insights into the patterns TM data represented.

A survey of current literature indicates that multisensor NDVI (thus, fPAR) derived from AVHRR, MODIS, TM, ETM+, SPOT-4 and QuickBird exhibit offsets (Goetz 1997; Steven *et al*. 2003). Sensor spatial resolution, atmospheric calibration and the fPAR retrieval algorithm will have an effect on the accuracy of the NDVI and fPAR comparison. There is no comparison between TM and MODIS in this study; however, we would anticipate that the error caused by spatial resolution, reflectance calibration and the fPAR calculation method would have an effect on the sensitivity of the change algorithm to actual changes on the ground. In addition, NDVI may not exhibit an immediate and direct response to changes in vegetation moisture

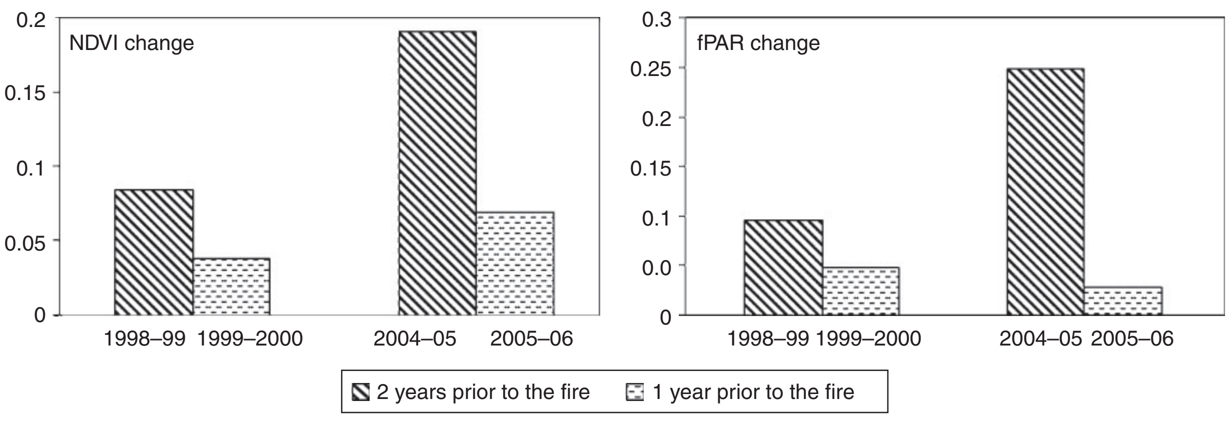

Fig. 7. Summary for NDVI (normalised difference vegetation index) and fPAR (fraction of photosynthetically active radiation) change in different years.

and water content, as high temperatures hasten the desiccation of grass during the late-summer senescence period (Ceccato *et al*. 2001). As a result, dry grasses and litter constitute part of any NDVI value and can range from 0.09 to 0.20 in areas entirely covered by litter in late summer (Nagler *et al*. 2000). In contrast, fPAR values of dry grass and litter decrease to 0.00, and are substantially different from those seen during the active-growth period. For these reasons, fPAR change layers were considered sensitive to litter within semiarid rangeland ecosystems. Therefore, fPAR could be an input source for fire early warning models, and increase the efficiency of fire management in semiarid rangeland.

Conclusion

Using MODIS NDVI and fPAR products and TM NDVI and fPAR algorithms, this study focussed on assessing prefire vegetation characteristics and fuel load change. TM and MODIS NDVI and fPAR data were compared between active growth periods and late-summer senescence periods and interpreted using monthly precipitation, mean temperature and field-based measurements of forage biomass and percentage ground cover from 2004, 2005 and 2006. In general, fPAR exhibited a similar trend of change relative to NDVI, and the results of this study indicate that both NDVI and fPAR can be used to assess susceptibility of rangelands to wildfire. Used over long time periods, these data may also be applied to the determination of areas suitable for fuel-load reduction, which may eliminate or reduce wildfire danger in many areas. In an ideal situation, both MODIS and Landsat imagery would have been available for all parts of this study. In addition, it would have been useful to have had extensive prefire vegetation data for all fire areas. These needs were very difficult to anticipate and future field campaigns are planned to address this issue. Furthermore, wildfire susceptibility predictions are very complicated and this study represents an incremental step towards improved wildfire susceptibility modelling research. We are considering additional ecological and environmental parameters to improve future models and the incorporation of pixel-based parameters (e.g. precipitation and temperature), which might produce better results in the future.

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