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The effect of a wildfire on stream water quality and catchment water yield in a tropical savanna excluded from fire for 10 years (Kakadu National Park, North Australia)

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Abstract

The wet/dry tropics of the Australian savannas are particularly prone to fire due to the highly seasonal rainfall and accumulation of grassy fuels. The effect of an early dry season wildfire (May, 1998) on the water quality of a seasonally flowing stream (December–June) was examined for a lowland savanna forest in Kakadu National Park (northern Australia) which had remained unburnt for 10 years. The water quality variables assessed were: total and volatile suspended sediment, phosphorus, nitrogen, iron and manganese. Compared to three years of pre-fire water quality data and 5 years of stream flow data, there was no detectable impact of the wildfire on the volume of stream flow, mean concentrations and the total mass transported by the stream for each water quality variable, except possibly nitrogen. The limited effect on water quality is attributed primarily to the timing of the wildfire and the low intensity relative to fires later in the dry season (September). The retention of canopy cover and the accumulation of leaf litter following the wildfire, and the catchment's gently undulating terrain all contributed to the negligible impact on water quality. Early dry season fires appear to be a viable management option for reducing accumulated fuel loads and hence reducing the risk of destructive wildfires later in the dry season.

Keywords: Erosion; Vegetation cover; Riparian vegetation; Loads; Hydrology; Savanna

1. Introduction

Savanna ecosystems in wet/dry tropical climates feature a continuous layer of grasses with a discontinuous layer of trees and/or shrubs [1]. In Australia, tropical savannas cover 20% of the continent [2] and, unlike savannas elsewhere, have not experienced intensive anthropogenic use. Pastoralism is the main use, whilst other uses include mining, military training, tourism, nature conservation and traditional use by indigenous people.

Tropical savannas are characterised by a seasonal cycle of profuse vegetation growth over the wet season, followed by a period of "drought" lasting several months when grasses, herbs and other vegetation dry out and become increasingly flammable [3,4]. Consequently, fires are common throughout the world's tropical savannas [3]. Each year an extensive area of Australia's tropical savannas is burnt, mostly by human-lit fires. The extent of burning is probably best known for Kakadu National Park (KNP; Fig. 1) in the Northern Territory where, on average, 46% of the Park was burnt each year between 1980 and 1994 [5]. In this

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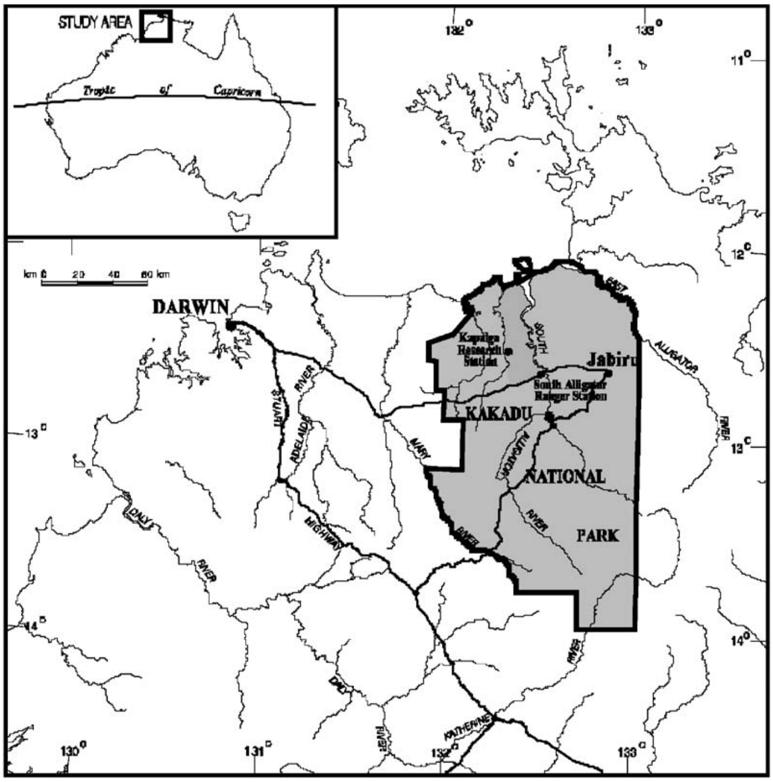

Fig. 1. Kakadu National Park, Australia. The study catchment is approximately 8 km north-west of the South Alligator Ranger Station.

region, fire intensity depends on the level of fuel accumulation, the time of year, and the prevailing weather conditions. As the dry season progresses, fuel loads increase, fuel moisture decreases, and weather conditions become conducive to more intense fires [4,6]. Consequently, fires late in the dry season are typically three times more intense than fires earlier in the dry season [6].

To examine the effect of fire regimes in Australian tropical savannas, a landscape–scale fire experiment at Kapalga in KNP was conducted between 1990 and 1994 [7,8]. Townsend and Douglas [9] used this experiment to examine the effect of annual fire regimes on stream water quality and catchment water yield. They found that a catchment burnt late in the dry season had 50% less canopy cover, 80% lower density of riparian vegetation and more bare ground than catchments burnt early in the dry season or excluded from fire. This increased the vulnerability of the catchment to erosion, resulting in a doubling of the mass of sediment exported in a wet season.

Despite the widespread occurrence of annual fires in KNP, a proportion of the lowland savanna remains unburnt every year. Between 1980 and 1994, 0.8% of the lowlands remained unburnt, whilst 13% of the lowlands were burnt only 1–5 times [5]. In the absence of fire, fuel loads increase over the first 3–7 years, reaching maxima of 10–15 t/ha [10,11]. A wildfire late in the dry season and following several years of fire exclusion and fuel accumulation can result in a very intense fire that causes tree mortality comparable to years of annual fires [6]. However, it is not known whether several years of fuel accumulation will always result in such catastrophic fires, or if the season of fire will still be important in determining the effects on catchment vegetation and stream responses. The opportunity to examine this question arose when a wildfire occurred in a Kapalga catchment in May 1998 following 10 years of fire exclusion.

The effect of this wildfire on stream sediment, nitrogen, phosphorus, iron and manganese fluvial exports, canopy cover, ground cover and riparian vegetation density were compared with pre-fire observations. Vegetation cover intercepts rainfall to reduce its erosive power, whilst the riparian zone plays an important role in regulating the inputs of water, sediments and nutrients from catchments into streams [12,13]. Sediment export is an indicator of catchment erosion, whilst fluvial exports of nitrogen and phosphorus are fundamental components of catchment nutrient budgets. Iron and manganese exports have been determined because these metals in water supply reservoirs can impair the aesthetic quality of potable water [14]. Moreover, the aquatic chemistry of iron is linked to the solubility of phosphorus [15] and hence indirectly the trophic state of lakes and reservoirs.

2. Study site

Kapalga Research Station lies in the wet/dry tropics of northern Australia (Fig. 1). Annual rainfall at Jabiru, 50 km east of the study site, averages 1473 mm, with 66% falling between January and March, and 98% falling between October and April, Rainfall exceeds evapo-transpiration between December and April [16]. Most lowland streams in the region are intermittent, typically flowing from December–January to May–June [17].

The study catchment (area 6.6 km^2) comprises the upper portion of compartment C of the Kapalga Fire Experiment [7], and is located approximately 8 km north–west of the South Alligator Ranger Station (Fig. 1). The catchment lies on the Koolpinyah Surface [18], which was formed by the erosion of older surfaces comprising mainly Late Tertiary sediments. Intense weathering has produced soils of low fertility in the region [19–21], whilst lateritisation has led to iron enrichment of the soils and formation of ferruginous nodules. The soils are well drained and feature a veneer of ferruginous gravel and siliceous sand. The study catchment terrain is gently undulating, with catchment slopes averaging 0.5%, rising from 15 to 40 m above sea level [9].

Catchment vegetation consists mainly of eucalypt open forest dominated by mixed *Eucalyptus* communities, mainly *E. miniata* and *E. tetrodonta* [22], with a range of other genera with sub-tropical affinities comprising the canopy sub–dominants [23]. This vegetation type covers nearly 52 000 km^2 of the Northern Territory, with structurally and floristically similar vegetation types covering an additional approximately 190 000 km^2 [24]. These tall open forests range in canopy cover from 60% to 80% and have canopy heights ranging from 12 to 20 m [22]. Tall C4 grasses, which may reach a height of up to 3 m during the wet season [22], dominate the understorey. These grasses include annual (*Sorghum* spp.) and perennial (e.g. *Heteropogon* spp.) species [22,23].

3. Fire description

The wildfire burnt the study catchment on May 22/23, 1998. A helicopter survey a few days later revealed the fire had burnt 95% of the catchment. Prior to this, the catchment had been burnt in 1988 by a low intensity fire [25].

The spatial intensity of the wildfire was variable. Interspersed amongst the burnt landscape were patches of unburnt grass, understorey and trees. Some trees up to 15 m high were scorched, but not all, indicating variable fire intensity [25]. Based on these observations, we estimate the average intensity of the wildfire to be 2000–5000 kW/m. This is within the range of June early dry season fire intensities for an adjacent catchment (300–5000 kW/m, [9]), though intensities of up to 10,000 kW/m have been estimated from this region for fires lit in June [25]. The May 1998 wildfire appeared to be more intense than the mean intensity of prescribed early dry season fires (2100 kW/m, $n = 15$) measured during the Kapalga Fire Experiment [25] but less intense than the mean intensity of fires lit late in the dry season (7700 kW/m, $n = 14$).

Rainfall for the 1998/1999 wet season, commencing September 1, totalled 1650 mm at Jabiru, 228 mm higher than the long-term average, and 1718 mm at the nearby South Alligator Ranger Station. Weather conditions in April and May before the 1998 wildfire were similar to long-term averages, except for the higher rainfall in April 1998 (Table 1). The last substantial storm (27 mm) before the May 22 wildfire fell on April 22, with an additional 2.4 mm on May 17, based on rainfall records for the South Alligator Ranger Station.

4. Methods

4.1. Stream flow and water quality

Stream water level was recorded at a hydrographic station between September 1992 and July 1999, excluding the 1998 wet season when equipment failure resulted in periods of missing data. Flow was calculated from an equation relating stream water level to flow. The catchment water yield is calculated by dividing the annual (commencing September 1) stream flow volume by the catchment area and represents the runoff volume as a depth over the catchment.

Water samples were collected by an automatic water sampler installed at the hydrographic station. Pre-burn water quality was assessed over the 1992/1993, 1993/1994 and 1994/1995 wet seasons, by the collection of discrete water samples during storm events in response to changes in flow to ensure samples were collected throughout the storm event. Flow between storms (baseflow), when overland runoff was absent and stream flow declined gradually, were sampled approximately every 3 days. Between 135 and 218 samples were collected each wet season for chemical analysis. Mean concentrations of water quality parameters were calculated for each storm event and baseflow period, then

Table 1
Meteorological conditions in April and May, 1998, compared to long term averages for Jabiru Airport

	Minimum air temperature (°C)	Maximum air temperature (°C)	9 am relative humidity (%)	3 pm relative humidity (%)	Rainfall (mm)	9 am wind speed (km/hr)	3 pm wind speed (km/hr)
April long term average	23.4	34.4	68	41	76.3	5.8	8.8
April 1998	25.3	35.2	[a]	[a]	125[b]	6	8
May long term average	21.7	33.4	62	37	10.8	8.2	10.3
May 1–23, 1998	24.2	34.7	62	42	2.4[b]	13	13
May 22, 1998	22	34	61	42	0[b]	15	11
May 23, 1998	24	33	64	47	0[b]	17	13

[a] No data;
[b] Rainfall at South Alligator Ranger Station. Jabiru Airport and South Alligator Ranger Station meteorological collection commenced, respectively, in 1971 and 1995.

weighted by the percentage of the total wet season flow volume represented by each sample period, and finally summed to provide a volume–weighted mean concentration. The export coefficient for each parameter is the product of the volume–weighted mean concentration and total flow volume, divided by the catchment area. Further details are provided by [9].

The water quality of the stream, after the catchment was burnt in 1998, was assessed using an automated water sampler collecting composite samples. Composite samples comprise many subsamples bulked together as a single sample for chemical analysis. A total of 14 composite samples were collected over the wet season with each one comprising 17–60 subsamples. Each subsample was collected after a nominated volume of water had passed the station to ensure sample collection throughout storm and baseflow periods. The volume-weighted mean concentrations for each parameter were then calculated as described above.

All water samples were analysed by APHA [26] standard methods for the following parameters, with APHA method numbers shown in parentheses: total phosphorus (424F), nitrate (418F), nitrite (418F), total Kjeldahl nitrogen (420A, 417G), total iron and manganese (303A) and total (TSS) and volatile (VSS) suspended sediment (209C, 209D). The latter approximates organic matter. The nitrogen analyses have been summed to give total nitrogen.

4.2. Canopy cover, ground cover and riparian vegetation

Catchment canopy and ground cover were measured in December 1998 and compared with pre-fire data collected in December 1997. In both years, canopy and ground cover were measured at six (1997) or four random points at least 50 m apart at each of four different randomly selected sites located at least 1 km apart. Percentage canopy cover was measured using a convex, hemispherical densiometer (Model-A, Forest Densiometers, Bartlesville, Oaklahoma, USA). The densiometer was held at a height of approximately 1 m, and an average was taken of four readings taken 90° apart [27]. At each point, the percentage cover of bare ground, leaf litter and grassy, herbaceous and woody vegetation were estimated from within a 1 m^2 quadrat. Canopy and ground cover variables were analysed using a two-factor analysis of variance with Year (Before and After fire; fixed) and Site (random and nested in Year) as factors. All cover variables were arcsin transformed to meet the assumption of homogeneity of variances.

In August 1999 woody riparian vegetation was sampled in the upper (within 100 m of the origin of the stream) and middle ($\sim$2 km from the origin of the stream) reaches of the stream. At each reach, four quadrats (two on each bank) were located along a randomly selected 200 m section. Each quadrat enclosed an area of 0.06 ha, running 30 m along the bank and 20 m away from the bank. All woody vegetation above 1 m high was counted in each quadrat and density compared to pre-fire data collected in October 1993 using the same methods [9]. Data were compared using a two-factor analysis of variance with Year (before or after fire) and Reach (Upper or Middle) as fixed factors and quadrats as replicates.

5. Results

5.1. Stream flow and water quality

Stream flow commenced on December 8, 1998, and ceased mid-May 1999, with no episodic runoff events occurring before the continuous wet season flow, as has been reported for a Kapalga catchment burnt late in the dry season [9]. The catchment pre-fire (1993–1997) water yield comprised between 10% and 28% of annual rainfall. The yield for the 1998/1999 wet season (22% of annual rainfall) fell almost on the pre–fire regression line of annual rainfall against catchment water yield (Fig. 2), indicating that the May 1998 wildfire had no detectable impact on the catchment's water yield.

Post-fire concentrations of the six water quality parameters tested were within the 95% confidence interval of pre- fire concentrations (Table 2), suggesting no major differences between pre- and post-fire stream water quality. Similarly, post-fire export coefficients fell within the 95% confidence interval of pre-fire values (Table 3). The effect of the fire on nitrogen, however, should be viewed with caution because small differences, within the variability of pre-fire values, could not be detected.

5.2. Canopy cover, ground cover and riparian vegetation

Mean canopy cover was about 20% lower and mean litter cover was about 50% lower in the year after the wildfire (Table 4). However, these differences were not statistically significant, probably because of the much greater variability in the data after the wildfire and lack of statistical power to detect small differences. There was no significant difference in mean grass or woody vegetation cover between years, with each accounting for a relatively small proportion (<7%) of the total ground cover in both years (Table 4). Herbaceous vegetation cover was ten times higher after the wildfire and was largely ground cover species such as *Galactica*. Bare ground was about 20 times higher in the year following the wildfire but, even after burning, less than 17% of the soil surface was exposed (Table 4). The mean density of riparian vegetation (stems/ha) was significantly lower following the wildfire with a density in 1998 less than half of that recorded in 1993 (Table 4).

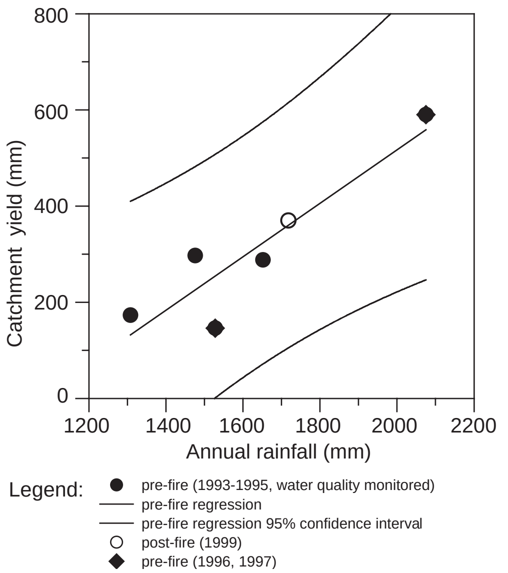

Fig. 2. Linear regression between annual rainfall (commencing September 1) and catchment water yield for pre-fire data (closed symbols) and post-fire (open circle). Pre-fire data regression: $y = 0.56x + 96$; $r^2 = 0.83$, $p = 0.031$, shown with 95% confidence interval.

6. Discussion

The wildfire in May 1998 appeared to be of lower intensity than fires that typically occur later in the dry season at Kapalga (2000–5000 kW/m vs. 7700 kW/m; [25]), which reflects the seasonal pattern of weather, fuel load and moisture content. Therefore, the low intensity of the 1998 wildfire is primarily attributed to the timing of the fire.

There were few changes of hydrological significance, with the possible exception of nitrogen concentrations and loads, following the wildfire despite the loss of half of the density of woody riparian vegetation. Canopy cover, which is important in reducing the impact of rainfall, was not significantly lower after the wildfire. Leaf litter cover was not significantly reduced but was more patchy after the wildfire. It may have been supplemented, to some extent, by the fall of scorched leaves immediately following the wildfire and by natural leaf fall from deciduous, semi–deciduous and some evergreen species throughout the dry season [28]. The significance of pre-wet season litter cover in reducing overland flow and rates of soil erosion in the region has been emphasised by Duggan [29,30]. Furthermore, the significant increase in herbaceous vegetation would also protect the soil surface from erosion. Although there was a significant increase in the amount of bare ground following the wildfire, over 80% of the soil surface was still protected from erosion.

Increased water yield, primarily due to reduced evapo-transpiration, is a commonly reported effect of fire on catchment hydrology [31–34,36]. However, as with annual early and late dry season fire regimes at Kapalga [9], the May 1998 wildfire did not significantly increase the water yield. In the current study, no reduction in canopy cover was detected following the fire, and any potential reductions in evapo-transpiration may have been partially offset by the increase in herbaceous vegetation cover. The absence of a substantial increase in water yield is consistent with the observations in other fire studies that water yield is approximately proportional to the fraction of vegetation loss [35].

The May 1998 wildfire had a negligible impact on most wet season stream water quality variables. The most responsive water quality parameter to annually lit

Table 2
Volume-weighted mean concentrations of pre-fire (1993–1995) and post-fire (1999) stream water quality variables at Kapalga, Kakadu National Park. (TSS, total suspended sediment; VSS, volatile suspended sediment; CI, confidence interval assuming a normal distribution of pre-fire values)

	TSS (mg/L)	VSS (mg/L)	Total P (μg/L)	Total N (μg/L)	Total Fe (μg/L)	Total Mn (μg/L)
Pre-fire						
1993	14	2.8	4.7	250	540	16
1994	8	2.6	3.2	210	380	6
1995	11	3.4	10	300	420	11
Average	11	2.9	6.0	250	450	11
95% CI	4.7–17	2.1–3.7	−1.1–13	170–370	280–610	1.8–20
Post-fire						
1999	7	2.1	8.2	320	330	6

Table 3
Export coefficients of pre- and post-fire stream water quality variables at Kapalga, Kakadu National Park. (TSS, total suspended sediment; VSS, volatile suspended sediment; assuming a normal distribution of pre-fire values)

	TSS (kg/ha)	VSS (kg/ha)	Total P (g/ha)	Total N (g/ha)	Total Fe (g/ha)	Total Mn (g/ha)
Pre-fire						
1993	41	8.7	15	770	1400	48
1994	13	4.9	5.3	370	660	11
1995	33	9.3	30	870	1200	33
Average	29	7.6	17	670	1090	30
95% CI	1.6–56	2.9–12	−6.5–41	150–1200	340–1800	−7.2–67
Post-fire						
1999	26	8.0	31	1200	1200	22

Table 4
Mean and standard deviation of canopy cover, ground cover and riparian vegetation in pre- and post-fire years (n.s. = not significant) at Kapalga, Kakadu National Park)

	Pre-fire (1997[a])		Post-fire (1998)		Significance
	Mean	Std. dev.	Mean	Std. dev.	
Canopy cover (%)	85	8.8	67	19	n.s.
Leaf litter cover (%)	92	5.8	43	29	n.s.
Grass cover (%)	3.3	2.9	6.3	2.3	n.s.
Woody vegetation cover (%)	2.9	4.5	3.8	5.2	n.s.
Herbaceous vegetation cover (%)	2.3	4.3	23	15	$F_{1,2} = 28.9$; $p = 0.03$
Bare ground (%)	0.8	2.9	16	12	$F_{1,2} = 86.6$; $p = 0.01$
Riparian vegetation density (stems/ha)	28400	11300	13800	310	$F_{1,2} = 23.5$; $p < 0.0001$

[a] 1993 pre-fire riparian vegetation.

fires in other Kapalga catchments is suspended sediments [9] but following the May 1998 wildfire, concentrations of suspended sediments remained similar to pre-fire values. The higher nitrogen load following the wildfire could be due to the effects of the fire, and/or the high water yield (Fig. 2). With only three years of pre-fire water quality data, that covered only a narrow range of water yields, this study was only able to detect large changes in catchment loads. Whilst generally no effect can be clearly shown for the overall wet season water quality, it is possible the first few storm runoff events of the wet season had higher concentrations of the water quality parameters tested than pre-fire conditions, as this phenomenon occurred in another Kapalga catchment burnt annually late in the dry season (Townsend, unpublished data).

The overall negligible effect of the May 1998 wildfire on stream flow and water quality is attributed primarily to the timing and inferred low intensity of the fire, even after 10 years of fire exclusion and consequent fuel accumulation. The timing of the 1998 wildfire early in the dry season allowed sufficient time for the re-accumulation of leaf litter and the growth of herbaceous ground cover prior to the wet season. Both of these protect bare ground from rainfall impact, and inhibit overland flow and soil erosion. Moreover, nutrients leached from the ash by the first rains, before stream flow commenced, could be retained by soil or taken up by growing vegetation. Wind dispersal could also remove ash from the burnt catchment, whilst some ash could be expected to be retained on the ground surface.

The results of this study, albeit unreplicated, suggest that burning early in the dry season in areas of Kakadu National Park excluded from fire for several years is likely to have little impact on wet season stream water quality, except possibly a small increase in nitrogen concentrations and loads. This contrasts with a catchment in Kakadu National Park burnt late in the dry season which had statistically significant higher storm runoff concentrations of total and volatile suspended sediment, iron and manganese [9]. Prescribed burning early in the dry season of gently sloping landscape patches, excluded from fire for several years, represents a potentially viable management option to reduce catchment fuel load and hence the risk of wildfires later in the dry season, whilst having negligible or no detectable impact on stream water quality.

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