Hydrological and erosional responses in woody plant encroachment areas of semi-arid south–eastern Australia

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Abstract

Resource retention is an important component of landscape function in semi-arid environments, with patches in the landscape serving as sink zones that capture runoff, sediments and nutrients sourced from inter-patch areas. The purpose of this rainfall simulation study was to compare hydrological and erosional responses in patches and inter-patches in woody encroachment areas (trees and shrubs >700 stems ha^{-1}) in semi-arid south-eastern Australia. Ground cover, hydrological and erosional responses differed consistently between patches and inter-patches. Inter-patches had low ground cover and produced more runoff and sediment than patches with medium to high ground cover. Patches displayed delayed initiation of runoff and a deeper soil wetting front. Litter, cryptogam cover and surface sand content were the main variables controlling average runoff rate, sediment concentration and total sediment production. The results indicated that patches and inter-patches are different functional units from an eco-hydrological perspective and influence the hydrologic and erosional characteristics of woody encroached areas.

Key Words

Soil erosion, shrub encroachment, invasive native scrub, patches, landscape function, semi-arid

Introduction

Semi-arid environments are often spatially organised in a two-phase mosaic, consisting of bands or patches of individual or aggregated plants interspersed in a low-cover matrix. Runoff and erosion dynamics are different in each phase and are controlled mainly by soil surface condition, particularly the nature of the surface crust and the amount and type of vegetative cover (Greene *et al.,* 1994). The low-cover matrix or inter-patch area is dominated by bare ground, although annual herbs, perennial grasses, woody plants or biological crusts are often present. Inter-patches generally have low infiltration rates and act as source zones of runoff, sediments and nutrients, whilst vegetated patches have higher infiltration rates and serve as sink zones for these resources (Ludwig and Tongway 1995). The type and spatial configuration of patches and inter-patches regulate the redistribution of resources and determine how effectively a landscape can retain resources, and therefore influence the hydrological and erosional processes in patchy semi-arid landscapes (Bergkamp 1998).

Shrub encroachment is a widespread phenomenon which has been reported in a range of arid and semi-arid environments. Encroachment generally refers to the increase in density, cover and biomass of woody plants, particularly shrubs, into former grassland or open woodland (Van Auken 2009), and is associated with declines in herbaceous forage production and livestock carrying capacity, reductions in biodiversity and socio-economic values (Graz 2008) and with increased runoff and erosion (Parizek *et al.,* 2002). Since the early 1900s, shrub and tree encroachment has increased in semi-arid New South Wales in south-eastern Australia (Gardiner *et al.,* 1998). Relationships between woody encroachment and runoff and erosion are not well understood in this region. In this study, we investigated hydrological and erosional responses using rainfall simulation in patches and inter-patches in six woody encroached sites. The objectives of this study were to: 1) investigate hydrological and erosional responses in two types of patches (e.g. under-shrub and medium vegetated) and in inter-patches; and 2) determine the effects of ground cover on runoff, sediment concentration and sediment production.

Methods

Study region

The study was conducted across three properties within the Cobar pediplain, New South Wales, Australia (Figure 1). Rainfall is highly variable, with a slight summer dominance and an annual mean of 400 mm (Bureau of Meteorology 2008). Average maximum and minimum temperatures are 26°C in January and

12°C in July, respectively. Soils are predominantly non-sodic Kandosols to Dermosols (Isbell 1996). Vegetation communities are mostly derived from *Eucalyptus populnea–Callitris glaucophylla* grassy woodlands (Noble 1997). Sites with a known history of encroachment were selected based on soil type and topography, and comprised areas of dense *C. glaucophylla* and *Eremophila sp.* (>700 stems ha^{-1}) with a scattered overstorey of *Eucalyptus populnea, Eucalytpus intertexta* or *C. glaucophylla.*

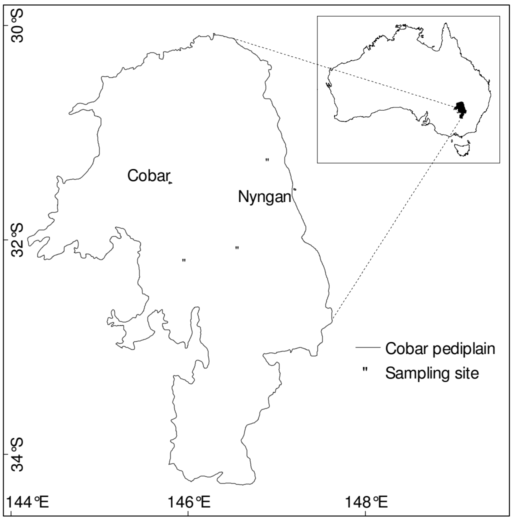

Figure 1. Location of the study area.

Identification of patches and inter-patches

Landscape function analysis (LFA) transects (Tongway and Hindley 2004) were used to define patches and inter-patches based on different amounts and components of ground cover. Patches and inter-patches were classified according to three levels of ground cover: ‘Inter-patch’ (<30% groundcover), 'Patches' comprising ‘Medium vegetated’ patches (30-65% groundcover) and ‘Under-shrub’ patches (>65% groundcover).

Surface characterisation and rainfall simulations

At each site, duplicate 1 m x 1 m plots were selected in each patch and inter-patch. Prior to rainfall simulations, percent herbaceous, litter and cryptogam cover were estimated visually in each plot, with their sum defining total ground cover. Duplicate soil samples (0–2 cm depth) were collected adjacent to the simulation plot using a hand-held soil corer (diameter 5 cm). Moisture content, oven dry bulk density and particle size distribution were determined for each sample. A Morin-type rotating-disc rainfall simulator (Morin and Cluff 1980) mounted on a trailer was used to apply rainwater to the plots for 30 min at 35 mm h^{-1}. Runoff and sediment samples were taken at regular intervals during each simulation, and time to runoff (min), average runoff rate (mm h^{-1}), average sediment concentration (g L^{-1}), total sediment production (g m^{-2}) and the depth of wetting front (cm) were also measured.

Data analysis

Mixed linear modelling with site as a random factor was used for analysis. Ground cover in patches and inter-patches and their hydrological and erosional responses were compared using pair-wise contrasts. Significance levels were set to $P < 0.05$, although P values < 0.10 were also noted. Forward stepwise multiple regression was used to explore the combined effect of rainfall simulation plot characteristics (ground cover components, bulk density and sand content as a proxy for texture values due to strong correlation between particle size components) on three hydrological and erosional responses (average runoff rate, average sediment concentration and total sediment production). Analyses were undertaken in R version 2.9.0 and SYSTAT version 12.

Results and discussion

Total ground cover was lowest in inter-patches followed in increasing order by medium vegetated patches and under-shrub patches (Table 1). Herbaceous cover was consistently low in both patches and inter-patches. Medium vegetated patches had the highest herbaceous cover, under-shrub patches had the highest litter cover, and cryptogam cover in inter-patches was higher than in patches.

Table 1. Mean ground cover (%) in patches and inter-patches. Values followed by different letters are significantly different ($P < 0.05$, or $P < 0.10$ if letters followed by *). n = 12 for each patch type and inter-patch.

Patch/Inter-patch	Herbaceous	Litter	Cryptogam	Bare soil	Total ground cover
Patch - Under-shrub	6.0b	52.6c	7.7a*	33.7a	66.3c
Patch - Medium vegetated	14.2c	22.5b	13.8b*	49.5b	50.5b
Inter-patch	0.7a	2.3a	28.2c	68.8c	31.2a

Bulk density and sand content were not statistically different between patches and inter-patches (data not shown). Hydrological and erosional responses varied consistently between patches and inter-patches (Table 2). Under-shrub patches had lower average runoff rates, total sediment production and greater depth of wetting front compared with medium vegetated patches and inter-patches, consistent with the effects of high ground cover on rainfall interception, microtopography and surface sealing (Renard *et al.,* 1996; Whitford 2002). Patches also exhibited delayed runoff initiation (Figure 2). In contrast, with their lower ground cover inter-patches had low infiltration and a rapid increase in runoff during the first 15 min of rainfall application (Figure 2). Patches and inter-patches had similar sediment concentration, indicating a similar susceptibility to soil particle detachment by rain drops, irrespective of differences in ground cover. Thus, the total sediment production of each patch and inter-patch was more closely related to the amount of runoff rather than any differences in sediment concentration. Total sediment production was markedly lower from under-shrub patches than inter-patches (Table 2), and once runoff began, the cumulative rate of sediment production was constant for each patch and inter-patch (Figure 2).

Table 2. Hydrological and erosional responses in patches and inter-patches. Values followed by different letters are significantly different ($P < 0.05$). n = 12 for each patch type and inter-patch.

Patch/Inter-patch	Time to runoff	Average runoff rate	Wetting front	Average sediment concentration	Total sediment production
	(min)	(mm h^{-1})	(cm)	(g L^{-1})	(g m^{-2})
Patch - Under-shrub	20.8b	3.3a	5.4c	2.04a	3.3a
Patch - Medium vegetated	12.7a	8.3b	3.8b	1.89a	7.5a
Inter-patch	9.6a	13.3c	2.8a	1.99a	13.0b

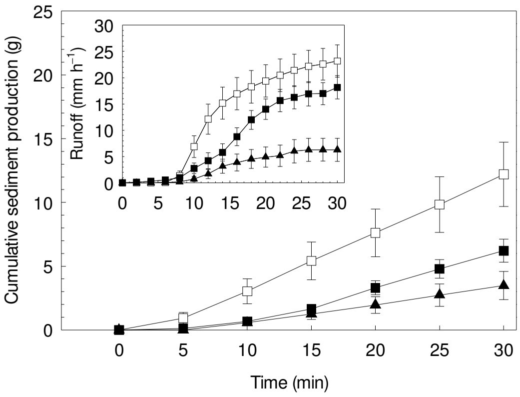

Figure 2. Mean cumulative sediment production and runoff rate (inset) in patches and inter-patches ▲= under-shrub, ■ = Medium vegetated, □ = Inter-patch. Bars represent ±1 SE.

Litter cover was the only significant predictor of runoff (Table 3). High cryptogam cover and sand content were associated with lower sediment concentration in runoff, but this relationship was weak, and the differences in cryptogam cover between patches and inter-patches did not translate into differences in sediment concentration. Total sediment production was best predicted by a combination of litter cover and sand content. These results indicated that the presence of ground cover components such as litter may partly compensate for the low herbage cover in woody encroached areas and provide soil stability and protection against raindrop impact, and in these areas of low herbaceous cover, litter plays a role in reducing total sediment production by reducing runoff.

Table 3. Stepwise multiple regression equations for average runoff (AR), average sediment concentration (ASC) and total sediment production (TSP).

Regression equation	Adjusted R^2	Model F	Significance P
$\sqrt{AR} = 3.41 - 0.03$ litter	0.44	$F_{1,34} = 28.54$	0.0001
$\sqrt{ASC} = 4.64 - 0.01$ cryptogam $- 0.04$ sand	0.35	$F_{2,33} = 10.21$	0.0001
$\sqrt{TSP} = 8.91 - 0.03$ litter $- 0.08$ sand	0.40	$F_{2,33} = 12.45$	0.0001

Conclusion

Due to consistent differences in hydrological and erosional responses, we consider that the patches and inter-patches in this patterned landscape are different functional hydrologic units that control the redistribution of runoff and sediments, in agreement with Ludwig *et al.* (2005). Inter-patches are more prone to runoff and sediment production than patches, and are probably the main drivers of runoff and erosion processes in woody encroached areas. The hydrological and erosional responses of patches and inter-patches are related to the occurrence of different ground cover components. Inter-patches have higher runoff and sediment production due to low ground cover, including low litter cover. Patches have high litter cover which appears to reduce total sediment production by reducing runoff. This effect of litter may be greater when more stable forms such as dead vegetation and large debris (i.e. logs) are considered.

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