Chapter 7. General discussion and conclusions

7.1. INTRODUCTION

The theme of this research was the investigation of runoff and erosion in areas of woody encroachment and related vegetation states occurring in semi-arid New South Wales. Woody encroachment has been a management issue on the Cobar pediplain for more than 100 years. It has been associated with increased runoff and erosion, and reduced site productivity. Understanding relationships between runoff, soil erosion, ground cover and vegetation states is important for managing these semi-arid landscapes to enhance their resource retention and productivity. However, detailed understanding of runoff and erosion in woody encroachment, in pasture following management of woody encroachment, and in open woodland has been lacking. This research investigated runoff and erosion in the four vegetation states of woody encroachment, recently established pasture (established in the last 23 years following control of woody encroachment), long-established pasture (50–100 years old) and open woodland on the Cobar pediplain in semi-arid New South Wales. The study elucidated the factors influencing hydrological and erosional responses in these vegetation states.

This chapter summarises the research findings presented in this thesis. The objectives of this chapter are to: (1) outline the main findings of the research; (2) highlight the main theoretical advances and management contributions of the work, and (3) discuss future research needs.
7.2. SUMMARY OF MAIN FINDINGS

Chapter 2 reported on erosional and hydrological responses of patches and inter-patches in the four vegetation states examined, using small-scale rainfall simulations. All four vegetation states contained well vegetated patches, medium vegetated patches, and inter-patches with low levels of ground cover. Hydrological and erosional responses differed consistently between patch types and inter-patches within each vegetation state. Inter-patches (mean ground cover = 23.5% ± 2.7% SE) had the least desirable hydrological and erosional responses, and produced the highest amounts of runoff and sediment followed in decreasing order by medium vegetated patches (mean ground cover = 54.8% ± 3.1% SE) and well vegetated patches (mean ground cover = 77.3% ± 3.1% SE). When hydrological and erosional responses from the same patch/inter-patch type were compared between vegetation states, only two differences were found: well vegetated patches in woody encroachment produced higher runoff than other well vegetated patches, and inter-patches in recent pasture had higher sediment concentration and production than inter-patches in other vegetation states.

Total ground cover was negatively correlated with runoff and sediment production within the two patch types and the inter-patch type identified in all vegetation states. Cryptogam cover in well vegetated patches was associated with higher runoff and sediment production, but cryptogam cover in inter-patches was associated with lower sediment concentration and production. The results indicated that patches and inter-patches are functional units from an eco-hydrological perspective in this semi-arid region and they influence soil hydrological and erosional characteristics, largely irrespective of vegetation state.
Chapter 3 compared the hydrological and erosional responses of the four vegetation states in the study area, using the same small-scale rainfall simulations as in Chapter 2. Runoff and sediment production did not differ significantly between vegetation states when data from all sites were analysed. Runoff and sediment production in woody encroachment were generally similar to those in the recent pastures established after woody vegetation removal. One pasture site in which rotational grazing and minimum tillage had been implemented had significantly lower runoff and sediment production than woody encroachment. This example of a pasture that had been managed to increase ground cover illustrated the effect that pasture management can have on reducing runoff and sediment production. Average runoff rate and total sediment production across all vegetation states were negatively related to total ground cover. Small-scale runoff and sediment production were minimal or zero where total ground cover (herbaceous, litter and cryptogam cover) was 73% or higher, across all vegetation states.

In Chapters 4 and 5, ground cover, comprised of herbaceous and litter cover, formed patches which were shown to be capable of obstructing runoff and sediment. An innovative method to map ground cover at hillslope scale in woody encroachment and pasture using high resolution Quickbird imagery was reported in Chapter 4. The chapter: (1) investigated several techniques of image fusion to increase the spatial detail of multispectral Quickbird data, namely principal component analysis (PCA), Brovey transformation, modified intensity–hue–saturation (MIHS) and wavelet transformation; (2) evaluated the performance of the red and near-infra-red bands and the difference vegetation index (DVI) and normalised difference vegetation index (NDVI) in estimating ground cover (herbaceous and litter cover), and (3) mapped and assessed spatial and temporal changes in ground cover at hillslope scale using the most appropriate combination of methods. The MIHS algorithm produced images that best preserved spectral and spatial integrity, while
the fused red band produced the most accurate ground cover maps. Estimation of ground cover under the canopy of woody plants presented difficulties, but patch size of ground cover beneath canopies was similar to canopy size, and percent ground cover (mainly litter) increased with canopy size. Ground cover (herbaceous and litter cover) was mapped with accuracies of 84% in the woody encroachment and 86% in the pasture. From 2008 to 2009, ground cover increased 10% on the woody hillslope and 5% in the pasture hillslope. Higher rainfall and livestock exclusion in the second year were potentially the causes of these ground cover increases, as well as the effect of establishing a water spreading system designed to slow down and retain water and sediment higher in the pasture hillslope. The ground cover maps were used to explore the spatial eco-hydrological interactions between areas of different ground cover in Chapter 5.

In Chapter 5, relationships between ground cover and hydrological and erosional responses of patches and inter-patches identified in Chapters 2 and 3 were up-scaled (with extra rainfall simulations at the hillslopes), using the ground cover maps developed in Chapter 4. Runoff and sediment transfer on the two adjacent hillslopes (woody encroachment and recent pasture) were estimated and described in this chapter. Spatial modelling was undertaken to integrate data on runoff and erosion from small-scale rainfall simulation, slope direction and the spatial distribution of ground cover on the hillslopes from high-resolution satellite data, to estimate runoff and sediment production at hillslope scale.

The estimates of runoff and sediment in the woody hillslope were lower than in the pasture hillslope in both 2008 and 2009. Estimates of runoff and sediment production in the woody hillslope were similar in both years, while the estimates of runoff and sediment production in the pasture hillslope were lower in the second year as a result of the establishment of a water spreading system. The physical effect of the contour banks disrupted the
connectivity of runoff source areas in the pasture hillslope and resulted in lower runoff and sediment production than before their construction. The results showed the importance of measuring ground cover, patch areal proportion and density and connectivity of runoff source areas for describing spatially distributed runoff and sediment production. This case study improved understanding of eco-hydrological function in the study landscapes. It demonstrated that high areal proportion of high ground cover areas in woody encroachment and the management of pasture through water spreading banks decreases runoff and erosion, and increases resource retention ability.

Relationships between gully erosion and site characteristics such as topography, vegetation cover and road infrastructure in a part of the study region with woody encroachment were investigated in Chapter 6. Gully erosion occurs when thresholds of flow hydraulics, rainfall, topography, soil, land use and land cover are exceeded, and it has been associated with woody encroachment in the region. Relationships between gully volume and topography, vegetation cover and road infrastructure were explored, and site characteristics of 32 sub-catchments with and without gullies were compared in this Chapter. The relationships between slope and drainage area were estimated for unstable and stable sub-catchments with and without gullies, respectively. The topographic threshold for gullying was estimated using the slope – drainage area relationship ($S = aA^b$). All gullies were active.

High gully volume was related to large sub-catchments, long gullies and short distances to unsealed tracks. Stable sub-catchments (without gullies) had gentler slopes and higher foliage projective cover and ground cover than unstable sub-catchments (with gullies). Drainage area at the gully or stream head and local slope as well as ground cover were the main factors related to gully volume when data for sub-catchments with and without
gullies were combined. The mean topographic threshold for gully development provided estimates of the drainage area and slope conditions needed for gully development. Gully erosion in the study area is most likely the result of interactions among topography, vegetation, land use and human-made structures (unsealed tracks) in space and time.

7.3. MAIN CONTRIBUTIONS OF THIS STUDY

7.3.1. Contribution to scientific theory and practice

This study contributed to theory and practice by (1) greatly increasing the knowledge of hydrological and erosional responses in patches and inter-patches in vegetation states in semi-arid ecosystems, including hydrological and erosional responses in woody encroachment and pastures that have been established after woody vegetation removal; (2) providing new knowledge about contrasting relationships between runoff and sediment production and cryptogam cover in patches compared with inter-patches (which has explained apparently contradictory, past results); (3) outlining the importance of pasture management in controlling runoff and erosion; (4) developing an innovative and accurate technique for mapping ground cover combined with modelling of runoff and sediment production at hillslope scale; (5) producing new information to identify areas susceptible to gullying, monitoring gully volume and for managing gully erosion in woody encroachment; and (6) greatly advancing the overall understanding of runoff and erosion responses at the small and hillslope scales in vegetation states in these semi-arid landscapes.

This study contributed to the knowledge of eco-hydrological function of vegetated patches and inter-patches in patterned semi-arid vegetation states. The rainfall simulation studies
that had been undertaken in the region to date (Eldridge and Rothon, 1992; Eldridge and Koen, 1993; Greene et al., 1994; Eldridge and Robson, 1997) had not targeted the eco-hydrological functioning of patches and inter-patches in different vegetation states in the study region or compared eco-hydrological function among vegetation states. This study confirmed the functional role of patches and their capacity to capture runoff and sediment from inter-patches.

The results of extensive small-scale rainfall simulations provided considerable insight into the factors associated with hydrological and erosional responses in patches and inter-patches, and in the different vegetation states. Patches and inter-patches in the patterned landscapes in the region had consistently different hydrological and erosional responses and thus can be considered functional hydrologic units that control the redistribution of runoff and sediments. This finding is in agreement with Ludwig et al. (2005) and Reid et al. (1999). The basic functional units of patches and inter-patches generally occur across the four vegetation states. However, well vegetated patches and inter-patches have distinct hydrological and erosional responses in different vegetation states: under-shrub patches in woody encroachment have higher runoff than other well vegetated patches, and higher sediment production is generated from inter-patches in recent pasture compared with other inter-patches.

The rainfall simulation results clarified the uncertainty surrounding the influence of cryptogam cover on runoff and sediment production (West, 1990; Eldridge and Greene, 1994b; Belnap, 2006). The study found that higher cryptogam cover was associated with lower sediment concentration and production when other ground cover components were at low percentages. Conversely, as other ground cover components increased in proportion,
higher cryptogam cover was associated with higher runoff and sediment production, as cryptogam cover is not as effective as herbaceous or litter cover in intercepting raindrops.

Runoff and sediment production in inter-patches are mainly controlled by micro-topography, surface texture and cryptogam cover. In contrast, runoff and sediment production in patches with high ground cover are largely controlled by herbaceous cover and micro-topography, and higher cryptogam cover in patches is associated with higher runoff and sediment production. Inter-patches are more prone to runoff and sediment production than patches and are the main driver of runoff and erosion processes in the vegetation states studied here. Most importantly, the amount and type of ground cover appeared to control small-scale runoff and sediment generation under a range of conditions in the Cobar pediplain.

The spatial modelling approach used to model runoff and sediment production at hillslope scale demonstrated the: (1) capability of satellite image fusion techniques to map ground cover (herbaceous and litter cover), and, (2) likely spatial eco-hydrological interactions between ground cover (herbaceous and litter cover), runoff and sediment production. Quickbird imagery has been used to map ground cover previously at the sub-catchment scale using the original spatial resolution of the multi-spectral data (4 m) (Bastin et al., 2007b). However, higher spatial resolution, as used in this study, captures more detailed ground cover patterns at the hillslope scale. The modified intensity–hue–saturation (MIHS) image fusion technique used in this study increased the spatial detail of the multi-spectral Quickbird data to 1 m, while preserving the original radiometric information. Image fusion at this scale for mapping ground cover has not been reported in the literature. The approach permits ground cover mapping using standard quantitative digital image analysis with a high degree of confidence and detail.
The modelling approach to up-scaling runoff and sediment production by integrating small-scale hydrological and erosional responses, slope and ground cover to estimate runoff and sediment production at hillslope scale constitutes a valuable exploratory tool for describing the spatial distribution of runoff and sediment production, and has not been used in similar, previous approaches describing how landscapes retain resources (Ludwig et al., 1999; Ludwig et al., 2002). The modelling approach incorporates most of the major controls of hydrological and erosional responses at the hillslope scale (ground cover, slope and connectivity of runoff source areas) and contributes to understanding of surface eco-hydrological relationships in woody encroachment and pasture hillslopes in the study region.

Thresholds of gully formation in woody encroachment have not been studied previously. Relationships between slope and drainage area were estimated for both stable (non-gully) and unstable (gully) sub-catchments with woody encroachment, and the topographic threshold for gullying was determined. The mean topographic threshold for gully development provided an estimate of the drainage area and slope conditions needed for gully development. The results of the study advance understanding of gully erosion dynamics in woody encroachment, and can be used to monitor gully volume and to identify areas susceptible to gullying.

The reduced herbage production resulting from high densities and cover of unpalatable shrubs is viewed as degradation from a socioeconomic perspective because encroachment reduces the potential of the land for livestock production (Archer and Stokes, 2000). However, the present study found that runoff and sediment production are not entirely dependent on vegetation state, including the presence or absence of woody encroachment.
The amount, type and spatial distribution of ground cover appear to be the major factors controlling hydrological and erosional responses in the vegetation states. Runoff and sediment production did not differ between woody encroachment and pasture when all sites were included in the analysis. One pasture that had been managed to increase ground cover had significantly lower runoff and sediment production than woody encroachment. Average runoff rate and total sediment production across all sites and vegetation states were negatively related to total ground cover.

### 7.3.2. Management recommendations

Management strategies for controlling erosion in the study region should focus on the two phases that characterise soil erosion. Management should aim to reduce soil detachment and minimise sediment transport. Hydrological and erosional responses to simulated rainfall in woody encroachment at the site scale were generally similar to the responses in other, structurally and compositionally quite different, vegetation states, and those responses were highly dependent on the amount and type of ground cover. Ground cover intercepts and reduces the energy of raindrops, diminishing the detachment of soil particles (Eldridge and Koen, 1993; Renard et al., 1996). Therefore, ground cover, such as perennial herbaceous vegetation and litter (e.g. leaf litter, crop residue in pasture, coarse woody debris in woody vegetation) is desirable to reduce erosion and runoff. Together, the combination of ground cover components in different vegetation states is capable of eliminating runoff and sediment production once the sum of all ground cover components is \( \geq 73\% \).

Herbaceous and litter cover are the most desirable ground cover components of patches for reducing runoff and sediment production. However, surface roughness and cryptogam cover can help retain and reduce runoff and sediment in inter-patches, compared with
smooth, bare surfaces. The stability of ground cover (i.e. how well it stays in place under the impacts of raindrop splash and surface flow of water) is important when managing ground cover for increased resource retention, as perennial plants and large, heavy items of litter are likely to remain in place once runoff starts (Goodrich and Reid, 1999). Therefore, management encouraging perennial grasses and/or deposition of coarse woody debris will increase surface roughness and thus intercept rainfall and obstruct runoff and sediment.

Runoff and sediment production at the hillslope scale also depend on the spatial distribution of ground cover. The amount of ground cover, the areal proportion, density and size of patches and inter-patches, their spatial distribution and the connectivity of runoff sources all appear to be related to the susceptibility of a site to runoff and erosion.

Effective pasture and grazing management should focus on reducing runoff and erosion to increase site productivity, for instance, minimum tillage for crop establishment followed by rotational grazing, as opposed to disc ploughing and set stocking (Chapter 4). Water spreading is also a valuable tool (Chapter 5) that can initiate desirable ground cover changes in pasture. Effective management should aim to obstruct or capture runoff and sediment and reduce the connectivity of runoff source areas in pastures, either by increasing patch density or size or through the construction of contour banks.

The removal of woody encroachment and replacement with pasture may not result in lower runoff and sediment production in the medium term (up to 23 years), unless the pasture is effectively managed to improve and retain ground cover. Improving ground cover of currently established pastures is essential to reduce runoff and sediment production (unless the ground cover is already very high).
If desired and funds are available, management of woody encroachment can be conducted to increase and maintain resources within the systems. The inter-canopy zone is important in retaining runoff and sediments in other semi-arid woodlands (Reid et al., 1999). Forage productivity in areas of woody encroachment perhaps can be increased by managing the resource retention capacity in the inter-canopy zone by restoring and creating new patches (Ludwig and Tongway, 1996). Examples of practices that graziers might employ in the inter-canopy zone include the construction of piles of branches and litter to trap resources and increase infiltration and promote positive responses of grasses and forbs, which has been demonstrated elsewhere under similar conditions (Tongway and Ludwig, 1996).

Gully erosion occurs in unstable sub-catchments with woody encroachment in a small part of the study region. The topographic threshold indicated that gully erosion is likely where slope exceeds 4% and drainage area exceeds 0.2 ha in steeper areas, and where slope exceeds 1% and drainage area exceeds 7.0 ha in more gently sloping areas. In such locations, managers should be wary of developing vehicular tracks, permitting livestock to form pads or creating any other disturbance that will incise the surface crust and channel overland flow downslope.

### 7.4. Further Research

Small-scale (1 m²) rainfall simulation allowed the intensity and duration of natural storms that occur frequently in the region to be experimentally replicated in this research. Further experiments could be undertaken to assess runoff and sediment production responses under a range of rainfall intensities. Higher intensity rainfall is likely to produce higher rates of soil erosion. Small-scale rainfall simulation provided results relevant to splash and sheet
erosion, but other forms of water erosion such as rill erosion cannot be assessed in plots <4 m in length (Foster et al., 1981). Therefore, the rainfall simulation results in Chapters 2 and 3 represent the hydrological and erosional responses of treatments (i.e. patches and inter-patches, or different vegetation states) relative to each other, rather than hydrological and erosional processes at hillslope or broader scales. One of the strengths of small-scale rainfall simulation is its ability to compare the eco-hydrological responses of different treatments (Mutchler et al., 1994).

This research evaluated hydrological and erosional responses under a range of conditions (i.e. patches and inter-patches, different land management practices) to compare the surface eco-hydrology of different vegetation states. Well managed pasture was not replicated due to the time and cost of using the rainfall simulator. However, different pasture management styles including different cultivation and grazing approaches should be investigated from a hydrological and erosional perspective in future work, with replicated sites comparing rotational grazing vs set stocking in pastures. Rainfall simulations could also be undertaken across a stratified range of areas of woody encroachment with varying vegetation composition, structure and density.

The canopies of shrubs and trees obstructed the spectral response of the ground surface in woody encroachment and impeded the mapping of ground cover with high accuracy under woody canopies. Although the size of canopies was generally similar to the patch size under shrubs and trees, the amount of ground cover was unknown. More research is needed to estimate accurately the amount of ground cover under the canopies of shrubs and trees through field monitoring. Relationships among ground cover, woody species, the degree of spatial aggregation of woody plants and the amount of litter movement under the canopies
and near shrubs and trees should be investigated, as these are related to ground cover under canopies.

More data would be useful to validate the spatial modelling of runoff and sediment production at the hillslope scale. Long term measurements of runoff, sediment and ground cover data would be useful to calibrate model outputs and satellite imagery and for validation purposes. The main controls on runoff and sediment production at scales broader than the 1 m$^2$ scale should be confirmed. The water spreading system, with its gaps at intervals along the banks, provides an ideal opportunity to install flumes and automated runoff and sediment measuring instrumentation to test and calibrate the spatial modelling reported here. Movement of small litter particles and their potential export from the system, which can decrease the resource retention capacity of woody encroachment, need further investigation. Additionally, runoff and sediment production at different initial soil moisture and rainfall intensities should be modelled to extend the results of the study reported in Chapter 5 over a wider range of conditions.

It would be useful to undertake before–after rainfall simulations in woody encroachment and subsequently in open woodland and pasture following experimental treatment of the woody encroachment. The experiment would comprise replicated treatments of woody encroachment to generate open woodland and pasture, along with replicated woody encroachment controls and, if possible, reference areas of pasture and open woodland. Control sites should be paired with the experimental sites where possible. Replicated grazing management trials could be incorporated into the experimental design, if sufficient sites, area and funds were available to do this, however, the time scale required to implement such experiments and trials may be prohibitive.
The land management history and detailed historical aerial photography of the part of the study region affected by gully erosion were not available. Investigation of historical variations in rainfall, changes in land use and in areas of woody encroachment, and gully erosion rates would provide understanding of the relationships among and the respective roles of these factors. As the temporal and spatial scales of the available historical aerial photography were insufficient to estimate erosion rates and the initiation dates of gullies, other methods might be employed to overcome these issues, such as techniques involving radionuclides (i.e. Caesium-137) (Li et al., 2003) or dendrochronology (Vandekerckhove et al., 2001).

7.5. CONCLUSIONS

- Hydrological and erosional responses generally differed consistently between patch types and inter-patches within each vegetation state—woody encroachment, recent pasture, long-established pasture and open woodland.

- With some exceptions, small-scale runoff and sediment production were similar in woody encroachment, recently established pasture (developed from woody encroachment in the past 23 years), long-established pasture (50–100 years old) and open woodland, and were related to surface condition, particularly the amount and type of ground cover.

- Hydrological and erosional responses were generally site-specific. In the woody encroachment and pasture hillslopes studied in Chapters 4 and 5, these responses were related to the amount and spatial distribution of ground cover and the degree
of connectivity of runoff source areas, which in turn were related to management practices. Sites in all vegetation states with high proportions of vegetated patches with high ground cover retained considerable amounts of runoff and sediment.

- Pasture management to increase ground cover and increase the density of vegetated patches (e.g. water spreading, rotational grazing, preceded by direct drilling of forage crops) is recommended where appropriate to improve hydrological and erosional responses (reduce runoff and sediment production) in existing pastures.

- The presence of gullies in woody encroachment was related to topographic thresholds, slope and drainage area as well as ground cover amount. Steep slopes and large drainage areas were associated with the occurrence of gullies. Current gully volume was a function of sub-catchment area, distance to unsealed tracks and gully morphology.
References


REFERENCES


REFERENCES


Horton, R.E., 1933. The role of infiltration in the hydrologic cycle. Transactions of American Geophysical Union, 14: 446-460.


REFERENCES


Leica Geosystems, 2008. ERDAS IMAGINE. Leica Geosystems Geospatial Imaging, LLC, Heerbrugg, Switzerland.


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