Modelling landscape leakiness and sediment yields from savanna hillslopes: the critical role of vegetation configuration

J.A. Ludwig[a], **R. Bartley**[b] **and A.C. Liedloff**[c]

[a] Tropical Savannas Management CRC and CSIRO Sustainable Ecosystems, PO Box 780, Atherton, Queensland 4883, Australia, john.ludwig@csiro.au

[b] CSIRO Land and Water, PO Box 780, Atherton, Queensland 4883, Australia

[c] Tropical Savannas Management CRC and CSIRO Sustainable Ecosystems, PMB 44 Winnellie, Northern Territory 0822, Australia

Keywords: Eco-hydrology; erosion; runoff; soil surface condition; vegetation patchiness

EXTENDED ABSTRACT

The potential of a savanna hillslope to retain, not 'leak', vital soil sediments, has been modelled using a simple landscape leakiness index. This index is very sensitive to the configuration of vegetation cover on the hillslope. We asked the question: does the sensitivity of this index match reality? Runoff and sediment yield data were collected from flumes at the bottom of two sites on a savanna hillslope located near Charters Towers, Queensland, Australia. The two sites were within 200 m of each other and have the same general soils, vegetation and topography – the key difference was the spatial configuration of their vegetation cover. One site had a relatively high and uniform grass cover over the entire hillslope (34% in 2005). The other site had an even higher average grass cover (47% in 2005), but it had a patch of bare soil low on the hillslope. Over three wet-seasons, from 2003-2005, the uniformly grassy site lost almost no sediment (≤0.06 t/ha/y) whereas the site with a bare lower slope lost from 2.0 to 3.1 t/ha/y. The modelled landscape leakiness index, known as the cover-based directional leakiness index, CDLI, indicated that the potential for the uniformly grassy site to leak sediment was low (CDLI = 0.21). The index for the site with a bare patch toward the bottom of its slope was much higher (CDLI = 0.71), indicating a more leaky hillslope. This finding confirms the logic of having CDLI sensitive to the spatial configuration of cover. However, this sensitivity, and the generality, of CDLI remains to be tested for other kinds of patch configurations and vegetation types. We know that CDLI is limited to landscapes where runoff flows are by surface sheeting, not channelling. Thus, CDLI is only likely to apply to relatively gentle and uniform landscapes. We are developing a new landscape leakiness index (LI) that combines remotely sensed vegetation cover and digital elevation data. This new index should be applicable to open landscapes with rough terrain, such as those found in arid and semiarid rangelands around the globe.

1. INTRODUCTION

Hydrologists have long recognized that soil surface cover affects the amount of sediment in runoff flowing from hillslopes during rainstorms, although in modelling these stormflow events they frequently assume a uniform soil cover (Kirkby 1978). Recently, hydrologists and ecologists have collaborated to explore the specific effect of vegetation cover, and its spatial configuration (patchiness), on runoff and soil loss in semiarid landscapes (e.g., Wilcox et al. 2002, Ludwig et al. 2005b, Bartley et al. 2006). These studies build on earlier investigations of the way in which vegetation patches function to obstruct runoff and help retain water and nutrients within landscapes such as semiarid grasslands and savannas (Scanlan et al. 1996, Tongway and Ludwig 1997).

Modelling the effects of vegetation patchiness on the capacity of semiarid landscapes to retain water and soil has progressed via two complimentary approaches. In one approach mechanistic models have been used to simulate runoff and erosion processes at hillslope, watershed and catchment scales (e.g., Rose et al. 1998, Liedloff et al. 2003). These models aim to predict the actual amounts of runoff and sediment flowing off landscapes during individual storm events. To accurately predict measured runoff and soil losses from a landscape numerous interacting processes and factors need to be built into such simulation models. Thus, their generality is constrained by the specific scales in space and time that they target (e.g., Coughennour 1992, Yu et al. 1997).

A second approach is to conceptualize and mimic general landscape processes in simple models that indicate the potential for landscapes to retain (not leak) sediments. These models do not attempt to simulate complex hydrological processes, or predict actual amounts of soil loss. Rather, these simple models focus on landscape metrics, or indicators, that can be estimated from remotely sensed vegetation cover data (e.g., Bastin et al. 2002, Ludwig et al. 2002). A landscape 'leakiness' indicator has been formulated (the cover-based, directional leakiness index, CDLI) that is particularily sensitive to the spatial arrangement or patchiness of vegetation cover in semiarid landscapes (Ludwig et al. 2005a). A key question is, does this sensitivity of CDLI mimic reality?.

The aim of this paper is to evaluate whether CDLI indicates measured soil loss data for two sites located on the same hillslope in the semiarid savanna landscapes of eastern Australia. One site had a relatively high and uniform grass cover whereas the second site had an even higher average grass cover, but it's cover was patchy because an area of bare soil occurred on the site's lower slope.

2. METHODS

2.1 Modelled landscape leakiness

The cover-based, directional leakiness index, CDLI, aims to indicate the potential for sediments to flow in runoff from the top of a landscape system and out the bottom of the system (Ludwig et al. 2005a). Flows are assumed to be one-directional, that is, straight downslope because sheet flows dominate and channelized flows are minor and unimportant. The landscape system is represented by a matrix or grid of cells (pixels) of known dimension, such as those in a remotely sensed image (e.g., 30-m pixels from Landsat Thematic Mapper). The image is rotated so that flows are directly down the columns of the matrix. The amount of vegetation cover for each pixel is estimated by an appropriate cover index, such as the PD54 index developed for the reddish soils that dominate much of arid and semiarid Australia (Pickup et al. 1993). The amount of potential flow from pixel to pixel down the columns of the grid or matrix is defined by a simple linear loss term:

$$l_{i,j} = 1 - (c_{i,j}/100) \qquad (1)$$

where the percent cover of each pixel or cell in the matrix, $c_{i,j}$, is divided by 100 and subtracted from 1 so that a pixel with low percent cover will have a high loss multiplier. We used a linear decay function because our aim was to represent loss in a general way until experimental data are available to more precisely define this loss function, which is likely to be a curvilinear decay.

The loss term, $l_{i,j}$, was then built into an equation that calculates a potential landscape leakiness value, $Lcalc_j$, for each column, j, in the matrix. This computation of $Lcalc_j$ is derived by progressively calculating values for a variable $p_{i,j}$ going down the cells, i, in each column, j. The $p_{i,j}$ values are computed using the equation:

$$p_{i,j} = (p_{i-1,j} + 1.0) * l_{i,j} \qquad (2)$$

where the progressive value for a pixel in the previous cell in a column, $p_{i-1,j}$, is added to a unit value, 1.0, and this sum is multiplied by $l_{i,j}$, the potential loss term. This equation aims to conceptually mimic, in a general way, what happens during rainstorms. During such storms, sediments in runoff will flow down the landscape from upslope to downslope pixels in columns (the $p_{i-1,j}$ value in Eq. 2), adding to the rainwater falling onto the pixel (the +1.0 value in Eq. 2). Some sediment will be trapped by the pixel while the rest will be lost to the next pixel in the column (the loss term, $l_{i,j}$, in Eq. 2). The loss term depends on the amount of cover on the pixel, which indicates the potential to obstruct runoff and trap sediment. The higher the cover the greater the potential for landscapes to retain more, or leak less, water and soil sediments (Tongway and Ludwig, 1997). The progressive value, $p_{i,j}$, for the last cell in each column, j, is taken as the calculated leakiness value, $Lcalc_j$, for that column, that is, this value is taken to represents the potential flow off the bottom of the landscape. These $Lcalc_j$ are summed across all columns to obtain an Lcalc value for the site.

The calculated potential leakiness term, Lcalc, is then used to estimate the potential leakiness index, CDLI, for a landscape (Ludwig et al. 2005a), using the equation:

$$CDLI = 1 - [(Lmax - Lcalc)/(Lmax - Lmin)]^{k} \quad (3)$$

where Lmax and Lmin define maximum and minimum potential leakiness values. Conceptually, maximum leakiness is viewed as a landscape where all its pixels are totally leaky and minimum leakiness is where all pixels totally non-leaky. The term in square-brackets on the right raised to the power of *k* indicates the potential of a landscape to retain resources, hence, leakiness = 1 – retention. As an index, CDLI ranges from 1 (totally leaky) to 0 (non-leaky). When plotted against amount of vegetation cover, CDLI takes the form of a decay function (Fig. 1), with parameter *k* defining the steepness of the curve. We found that $k = 3$ is a good fit of CDLI to published soil loss data for semiarid sites (references in Ludwig et al. 2002).

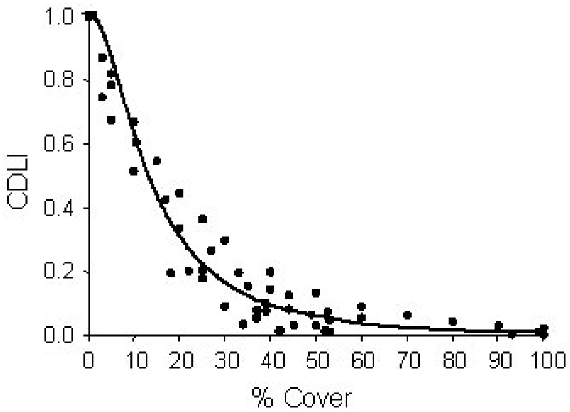

Figure 1. The curvilinear relationship between CDLI and % cover. The data points are soil loss ratios, defined as measured soil losses relative to maximum loss in each field study.

2.2 Measured landscape leakiness

Soil sediment yields were measured for two savanna hillslope landscapes in the Weany Creek sub-catchment of the Burdekin River catchment in north Queensland, Australia. The closest town to the sites is Charters Towers. The two sites were located about 200 m apart on the same hillslope. They were in a paddock that has been grazed by cattle for about 100 years. One site was relatively uniformly covered with grass (Fig. 2a). The second site was more patchily covered with grass and it had an area of bare soil (white colour) at the bottom of its slope (Fig. 2b). The uniformly covered site was 2,031 m^2 in area and had a mean slope of 3.1% extending over 130 m (Bartley et al. 2006). The patchily covered site was 2,861 m^2 and its 3.6% slope extended for 150 m.

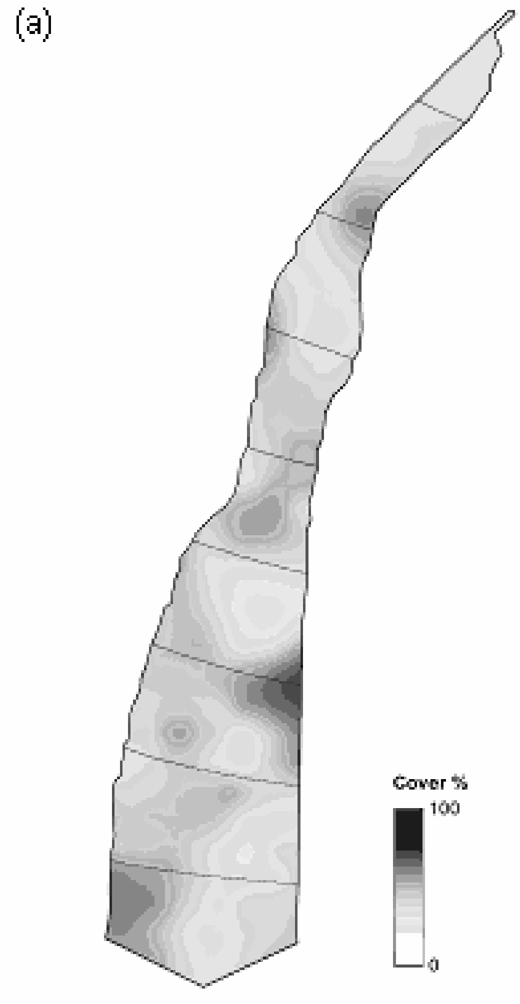

Figure 2a. Site with relatively uniform grass cover (black = high cover areas, white = low cover or bare soil areas, and grey = intermediate covers). Contours are at 1-m intervals from top to bottom. The V-shaped flume, raingauge, sediment collectors and other instruments are at the bottom.

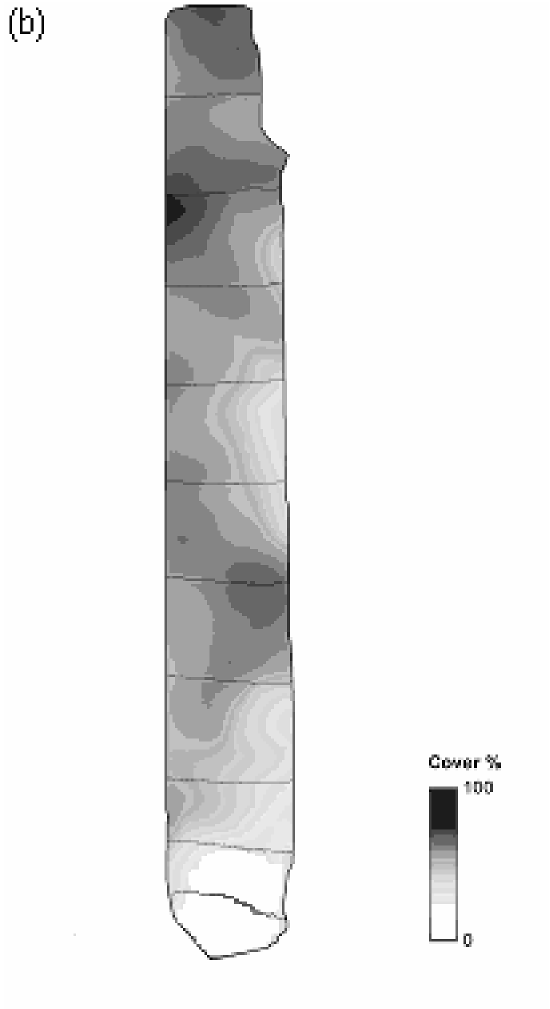

Figure 2b. Site with a more patchy grass cover and a bare soil area on its lower slope.

A raingauge was installed at each site (Bartley et al. 2006). During major rain events, runoff was directed through cut-throat flumes where runoff recorders, suspended sediment samplers, and bedload collectors were installed at the bottom of each slope. Total sediment discharge was computed from the suspended sediment samples and bedload collections. Sediment data were collected over three wet seasons (November 2002 to February 2005).

A grid of cells (4 x 4 m) was overlain on each site and oriented so that the direction of flow was down the columns of the grid (down the slope). The leakiness index, CDLI, was computed for each grid or site.

3. RESULTS

The amount of sediment lost from the patchily covered site greatly exceeded that from the uniformly grassy site in all three years of measurement (Table 1). The total rainfall was similar at the sites over the three years (250-300 mm) but the number of runoff events at the patchily covered site was almost double the number at the uniformly grassy site (11 compared with 6). This difference occurred even though the patchily covered site had higher average vegetation cover values than the uniformly grassy site in each of the three years. The key affect appeared to be the bare area immediately above the flume at the patchily covered site.

Table 1. Soil sediment loss, total number of runoff events and average vegetation cover for the two sites for three wet seasons. The landscape leakiness index, CDLI, was calculated for the year with the highest mean cover (2003).

	Patchily Covered Site	Uniformly Grassy Site
Soil loss: 2003	3.10 t/ha	0.003 t/ha
2004	2.46 t/ha	0.040 t/ha
2005	2.03 t/ha	0.060 t/ha
Total runoff events	11	6
Mean Cover: 2003	68%	58%
2004	46%	38%
2005	47%	34%
CDLI	0.71	0.21

The landscape leakiness index, CDLI, was more than 3-times greater for the patchily covered site than for the uniformily grassy site. A value of 1.0 equates to maximum leakiness so the CDLI value of 0.71 indicates a relatively leaky site.

4. DISCUSSION

Although it is generally accepted and documented that a landscape with a higher ground cover will have less runoff and erosion than one with low cover (e.g., Scanlan et al. 1996), it is not generally appreciated that the location of cover is also very important. The location of where patches of bare soil occur on a hillslope is especially important. The sediment loss patterns reported here confirm that a bare patch located low on a hillslope can have disproportionally large affects on the amounts of sediment lost during runoff events. The leakiness index, CDLI, nicely indicated this influence of ground cover configuration on soil sediment yields.

We intentionally formulated the cover-based directional leakiness index, CDLI, to be sensitive to the spatial configuration or patchiness of vegetation cover. In this study, we found that CDLI indicated that a gentle hillslope site, with a bare patch located near the bottom of the slope, was much more likely to be leaky than a nearby site on the same hillslope that had a relatively uniform grass cover. This difference in leakiness was confirmed by measured sediment yields from these two sites over three years (Bartley et al. 2006). Although our results are limited to this specific patch configuration, a general finding that landscapes with patchy covers are more 'leaky' than those with more uniform covers (other factors being equal) was confirmed in a companion paper using a spatially-explicit, mechanistic model (Liedloff et al. 2005; this volume). Thus, deriving a landscape leakiness metric to be sensitive to the spatial configuration of cover appears to be reasonable assumption for semiarid savannas, although further testing over a much wider range of landscape types is needed.

The potential leakiness of landscapes largely depends on the amount and spatial configuration of persistent or perennial vegetation cover because this cover obstructs runoff and traps sediment in the long-term (Tongway and Ludwig 1997). However, in the short-term, rains can produce ephemeral vegetation cover, which may dominate remotely sensed images. To reduce this ephemeral effect, we recommend using images acquired well into dry periods when persistent vegetation cover is likely to dominate. Remote sensing should estimate the amount, and pattern, of persistent vegetation cover on the immediate landscape surface to indicate where flows are most strongly obstructed and retained. Arid and semiarid grasslands and savannas have ground surfaces that are open and strongly reflect to satellites. This is not the case for closed woodlands and forests where ground surface cover is obscured by tree canopies. The general applicability of landscape leakiness indices, such as CDLI, needs to be investigated for a much wider range of vegetation types.

Because CDLI assumes flows down a hillslope are one-directional, this leakiness index is limited to those landscapes where it is reasonable to assume flows are by surface sheeting (Ludwig et al. 2005a) not channelling. Most arid and semiarid landscapes, such as rangelands, have undulating terrain, where local elevation differences cause flows to channelize. This greatly limits the use of CDLI to landscapes with relatively gentle and uniform terrain landscapes, such as small sections of gently sloping plains. Essentially, this constrains the use of CDLI to landscapes where fine-resolution satellite imagery is available, and affordable. When using remotely sensed images to estimate vegetation cover, and to compute CDLI, coarse-resolution imagery is likely to include large areas with rough terrain.

We are currently working with colleagues to develop a landscape leakiness index (LI) that is applicable to undulating terrain. Our approach combines remotely sensed vegetation cover and digital elevation data. With testing, we hope that this new index, LI, will prove to be more general, and hence more useful, than CDLI for indicating the potential leakiness of the many arid and semiarid landscapes with rough terrain located throughout the rangelands of Australia and the World.

5. ACKNOWLEDGEMENTS

We gratefully acknowledge the research funding and support provided by Meat and Livestock Australia and CSIRO. We thank Rob and Sue Bennetto for access to their cattle property where we conducted our field studies. We also thank Brett Abbott, Gary Bastin, Jeff Corfield, Aaron Hawdon and others for collecting field data and for assistance with calculating indices and discussing their signficance for this study.

6. REFERENCES

Bartley, R., C.H. Roth, J.A. Ludwig, D. McJannet, A.C. Liedloff, J. Corfield, A. Hawdon, and B. Abbott (2006), Runoff and erosion from Australia's tropical semi-arid rangelands: influence of ground cover for differing space and time scales. *Hydrological Processes*, (in press)

Bastin, G.N., J.A. Ludwig, R.W. Eager, V.H. Chewings, and A.C. Liedloff (2002), Indicators of landscape function: comparing patchiness metrics using remotely-sensed data from rangelands. *Ecological Indicators* 1: 247–260.

Coughenour, M.B (1992), Spatial modeling and landscape characterization of an African pastoral ecosystem: a prototype model and its potential use for monitoring drought. pp. 787–810, IN: D.H. McKenzie, D.E. Hyatt, and V.J. McDonald (eds), *Ecological Indicators, Vol. I.*, Elsevier Science, London, UK.

Kirkby, M.J. (ed). (1978), *Hillslope Hydrology*, John Wiley, 389 pp., New York, USA.

Liedloff, A.C., J.A. Ludwig, and M.B Coughenour (2003), Simulating overland flow and soil infiltration using an ecological approach. pp. 525–529. IN: D.A. Post (ed). Proceedings, MODSIM 2003, International Congress on Modelling and Simulation, Townsville. Published by Modelling and Simulation Society of Australia and New Zealand, Australian National University, Canberra, Australia.

Liedloff, A.C., J.A. Ludwig, R. Bartley and M.B Coughenour (2005), Modelling tropical landscapes for ecological management: what can we learn from preliminary Savanna.au simulations? pp. (this volume). IN: A. Zerger (ed). Proceedings, MODSIM 2005, International Congress on Modelling and Simulation, Townsville. Published by Modelling and Simulation Society of Australia and New Zealand, Australian National University, Canberra, Australia.

Ludwig, J.A., R.W. Eager, G.N. Bastin, V.H. Chewings, and A.C. Liedloff (2002), A leakiness index for assessing landscape function using remote-sensing. *Landscape Ecology*, 17, 157–171.

Ludwig, J.A., R.W. Eager, A.C. Liedloff, G.N. Bastin, and V.H. Chewings (2005a), A new landscape leakiness index based on remotely-sensed ground-cover data. *Ecological Indicators* 5: (in press).

Ludwig, J.A., B.P. Wilcox, D.D. Breshears, D.J. Tongway, and A.C. Imeson (2005b), Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes, *Ecology*, 86(2), 288–297.

Pickup, G., V.H. Chewings, and D.J. Nelson (1993), Estimating changes in vegetation cover over time in arid rangelands using Landsat MSS data. *Remote Sensing of Environment*, 43, 243–263.

Rose, C.W., and B. Yu (1998), Dynamic Process Modelling of Hydrology and Soil Erosion, pp. 269–286, IN: F.W.T. Penning de Vries, F. Agus, and J. Kerr (eds), *Soil Erosion at Multiple Scales*, CABI Publishing, Wallingford, UK.

Scanlan, J.C., A.J. Pressland, and D.J. Myles (1996), Run-off and soil movement on mid-slopes in North-east Queensland grazed woodlands. *Rangeland Journal*, 18(1), 33–46.

Tongway, D.J. and J.A. Ludwig. 1997. The conservation of water and nutrients within landscapes. Pp. 13–22. IN: J.A Ludwig, D.J. Tongway, D.A. Freudenberger, J.C. Noble and K.C. Hodgkinson (eds), *Landscape Ecology, Function and Management: Principles from Australia's Rangelands*. CSIRO Publishing, Melbourne, Australia.

Wilcox, B.P., D.B. Breshears, and C.D. Allen (2002), Ecohydrolgy of a resource-conserving semiarid woodland: effects of scaling and disturbance. *Ecological Monographs*, 73(2), 223–239.

Yu, B., C.W. Rose, K.J. Coughlan, and B. Fente (1997), Plot-scale rainfall-runoff characteristics and modeling at six sites in Australia and Southeast Asia. *Transactions of the American Society of Agricultural Engineers*, 40(5), 1295–1303.