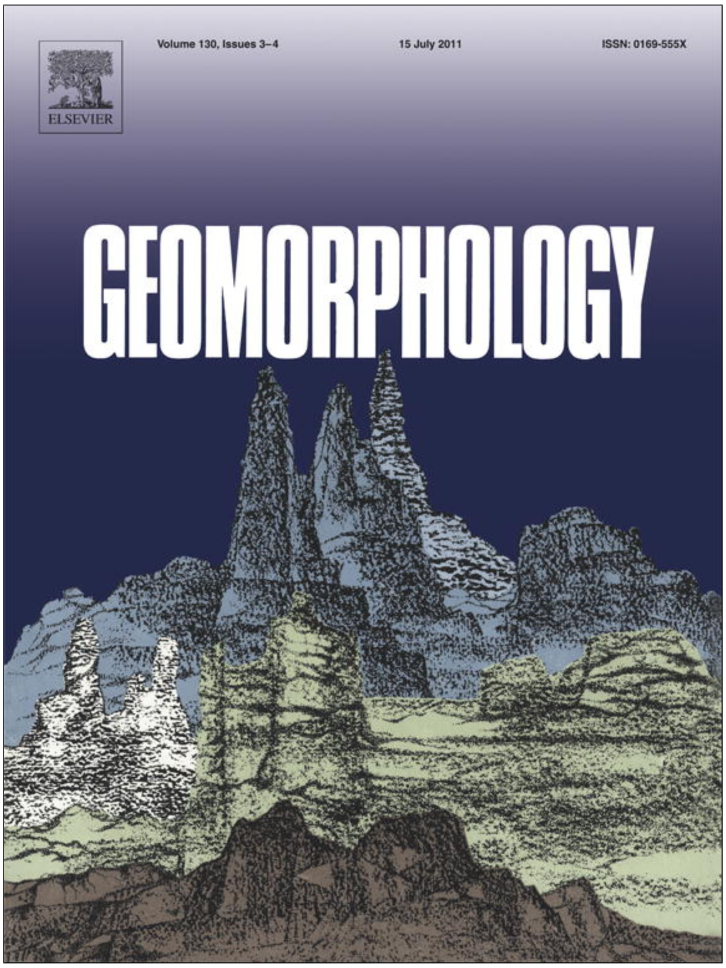
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The geomorphic signature of bare-nosed wombats (*Vombatus ursinus*) and cattle (*Bos taurus*) in an agricultural riparian ecosystem

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ABSTRACT

Riparian agricultural environments in eastern Australia are widely used for cattle grazing, but are also preferred habitat for native, soil-disturbing mammals such as the bare-nosed wombat (*Vombatus ursinus*). We examined the effects of mound construction by wombats, and track development by cattle and wombats, on soil displacement in a riparian landscape at high and low levels of cattle usage. Splash erosion was measured on mounds and inter-mounds with splashboards, and changes in the profiles of cattle-wombat tracks were assessed using a profilemeter. Twice as much soil was detached by splash erosion from mounds than inter-mounds, irrespective of cattle usage, and about three-times more coarse sand and 40% more fine sand was detached from mounds and inter-mounds at the high cattle sites. Increasing amount of rainfall corresponded with increasing splash erosion, but only on the mounds. The volume of soil displaced from wombat and cattle tracks ranged from 7.9 to 88.8 m^3 ha^{-1} (4.7 to 118.7 t ha^{-1}), but there were no differences in relation to cattle usage. Our results indicate that track development by cattle and wombats and mound construction by wombats may be substantial geomorphic processes given the large mass of soil displaced. Our results suggest that mounding by wombats may be an important process in riparian environments by providing a range of microsites that favour different plant cover densities.

1. Introduction

Soil movement and sedimentation are important processes in the development of floodplains and riparian systems (Naiman et al., 2010). Much has been written about the abiotic effects of natural riparian processes on riparian systems, particularly the roles of stream flow and river bank erosion (e.g. Hooke, 1979; Poff et al., 1997). Similarly the effects of exotic herbivores on riparian systems are well known. For example, livestock grazing and trampling influence riparian plant species through either direct removal of biomass through herbivory or by the destruction of photosynthetic and reproductive tissues through trampling (Kauffman and Krueger, 1984; Belsky et al., 1999). Less well studied, however, is the role that native herbivores play in riparian systems, with the notable exception being that of the North American beaver (*Castor canadensis*; Naiman et al., 1988; Wright et al., 2002). Because of the wide range of activities associated with browsing, burrowing and trampling, animals can have dramatic, and often contradictory, effects on ecosystem functions (Naiman, 1988; Naiman and Rodgers, 1997). Despite the paucity of information on the effects of native animals in riparian systems, an emerging body of evidence suggests that they may play important roles by dislodging and moving sediment (Moore, 2006; Byers et al., 2006; Bartel et al., 2010). These processes could be as important, or more important, in modifying riparian landscapes than abiotic processes (Butler, 1995).

An example of a native herbivore that occurs in riparian environments is the bare-nosed wombat (*Vombatus ursinus*). Wombats are widely distributed mammalian herbivores that occur within riparian, temperate forest landscapes in south-eastern Australia (McIlroy, thesis). They typically prefer stream bank habitats that provide a readily available source of burrow sites (McIlroy, thesis; Skerratt et al., 2004; Borchard et al., 2008). Wombats create large mounds of ejected soil when constructing their underground tunnels, particularly in the banks of higher order streams (Borchard et al., 2008). In riparian systems, wombats prefer to burrow under short stature vegetation, though burrowing can occur on stream bank areas devoid of any canopy cover (Borchard et al., 2008).

The effects of wombats are not limited to mounds and burrows. They create tracks (i.e. pathways that link their burrows with areas in which they graze), or reinforce existing tracks created by cattle in heavily used riparian habitats. Wombats can therefore have potentially significant effects on terrestrial ecosystems by displacing large volumes of soil and making it available for movement by processes of wind and water erosion. Estimates of soil movement for the closely-related southern hairy-nosed wombat (*Lasiorhinus latifrons*) are up to 88 t ha^{-1} (Steele and Temple-Smith, 1998). Soil trampled along tracks

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and pathways used by wombats and cattle may also be subject to the formation of rills and gullies. The potential geomorphic influence of wombats on the riparian landscape, however, is dependent on the *per capita* production of burrows, mounds and tracks, which is highly related to the size of the resident population. Given their effects on soils in riparian systems, wombats can be considered to be important biogenic agents in pedogenesis (Heimsath et al., 2000).

The distribution of bare-nosed wombats has contracted considerably since the early 20th century when large areas of forested land in south-eastern Australia were cleared for agricultural use (Triggs, 2009). In these agricultural landscapes wombats are currently restricted to patches of riparian vegetation, though their population densities can be as high as 1.9 animals ha^{-1} (Skerratt et al., 2004). The same riparian environments are also highly favoured by domestic livestock, particularly dairy cattle, for forage, water and shelter (Borchard and Wright, 2010a). This situation typically brings wombats into direct conflict with landowners because of the assumption that they destroy fences and foul water supplies, and that their extensive burrows pose a threat to livestock by increasing the chances that cattle will sustain injury by stumbling over the burrows (Borchard and Collins, 2001; Borchard and Wright, 2010b; Borchard et al., 2010). Whilst the deleterious effects of cattle grazing, trampling and wallowing are increasingly well understood (Trimble, 1994; Trimble and Mendel, 1995; Jansen and Robertson, 2001), little is known about the geomorphic consequence of wombat activities such as digging and trampling. No research has been conducted that quantifies the amount of sediment transported into streams by the degradational and excavational activities of wombats either individually, or in combination with cattle.

In this paper we present field observations and empirical measurements of the effects of wombats, with and without cattle, on soil movement in a riparian environment in eastern Australia. Our focus is on a peri-rural, agricultural environment where cattle grazing has been a predominant land use for more than 150 years, but where the surrounding relict vegetation still provides suitable habitat for wombats. In this area, wombats and cattle frequently come into close contact, and both contribute to soil displacement through burrow excavation and soil deposition (wombats) and the trampling and dislodgement of soil along tracks (wombats and cattle).

2. The study area

The study was conducted along sections of the Kangaroo River, Barrengarry Creek and Brogers Creek in Kangaroo Valley about 150 km south of Sydney, New South Wales (NSW), Australia (34°43′S, 150°31′E; Figs. 1 and 2). Kangaroo Valley was cleared extensively for dairy farming in the mid- to late-1800s (Griffith, 1986) and is characterised by undulating floodplains and terraces with minor depressions and drainage lines (Hazelton, 1992). Deep alluvial soils occur on the floodplains, and gleyed podzolic soils and soloths occur on the lower terraces and depressions (Hazelton, 1992). Average annual rainfall, measured 24 km south of the study area (Nowra), is 1110 mm. The average minimum and maximum daily temperatures are 16.3 °C and 25.8 °C in February and 6.2 °C and 15.8 °C in July, respectively (Bureau of Meteorology, 2006).

The study area was chosen because it supports a high density of wombats (Giles and Lonnon, 1999) and has a long history of grazing by dairy cattle (Griffith, 1986). Sixteen sites were chosen, each comprising a 100 m section of stream bank. The study sites included the area from the edge of the stream to the top of the bank where the slope levelled out. Distances from the water's edge to the top of the bank ranged from 7 m for steeper banks to 17 m for more gently sloping banks. The streams ranged from deeply-incised and relatively straight with steep banks up to 31°, to meandering and sinuous, with more gently sloping banks of 12°.

All of our measurements were collected from three microsites (wombat mounds, cattle-wombat tracks, non-track/non-mound control sites) at each of the 16 stream bank study sites. The study sites were categorised as having either 'low' or 'high' wombat use, based on the abundance of burrows (entry holes surrounded by mounds). Low use sites had ≤6 burrows per 100 m length of stream, whilst high use sites had ≥9 burrows per 100 m. However, not all burrows had mounds associated with them, possibly due to trampling by cattle or rain splash erosion caused by high rainfall events. Eight

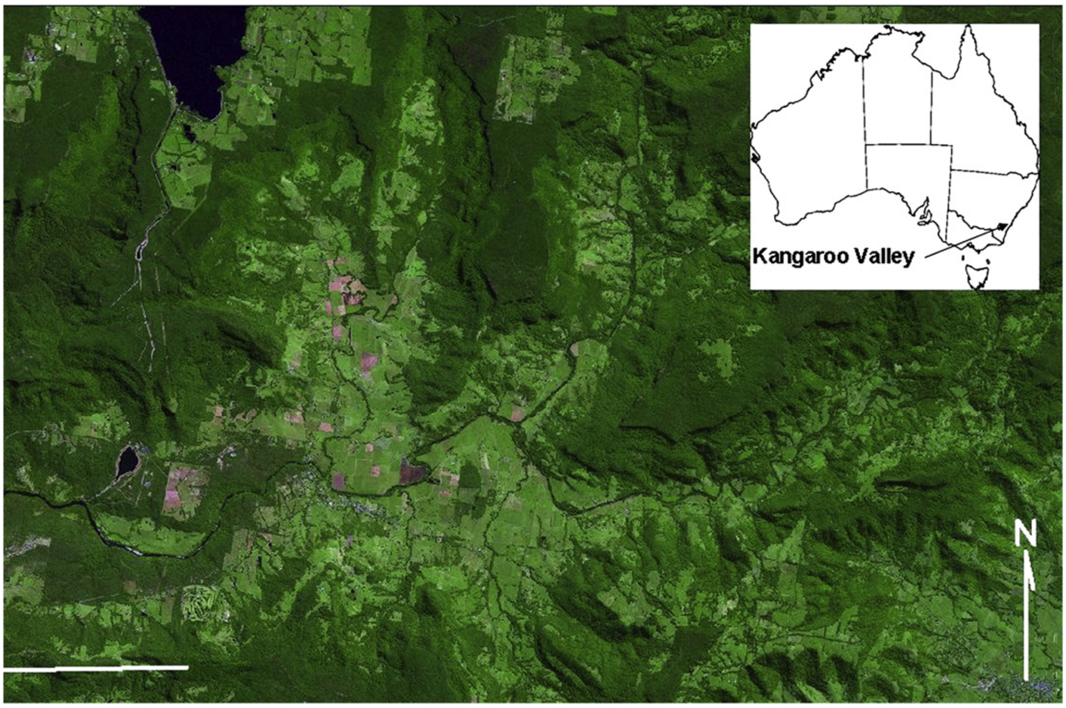

Fig. 1. An aerial photograph of the study area within Kangaroo Valley, New South Wales, Australia. The bar is equivalent to 5 km. Source: Mapinfo Co, 2007.

Fig. 2. View of the Kangaroo Valley showing agricultural land in the foreground and forested escarpments to the north.

sites had low levels of cattle use and the other eight had high levels, defined in an earlier study (Borchard et al., 2008). The assignment of low and high wombat use was confirmed in a pilot study undertaken over 6 days at all 16 sites, which showed significant greater accumulation of wombat scats in the high (32.0 ± 6.53; mean ± SE number of scats) than low (14.4 ± 6.53) wombat site categories ($F_{1,14}$ = 3.64, P = 0.039). This finding was consistent with a further study, which demonstrated the strong relationship between burrow number and wombat density (Rishworth et al., 1995). Overall, there were more than twice as many mounds (70.0 ± 21.4 mounds ha^{-1}) at the high wombat (high cattle) sites than the low wombat (high cattle) sites (23.8 ± 10.0 mounds ha^{-1}; Table 1). Independent data from landholders on cattle use over the past 15 years support our allocation of sites to different cattle use classes (Fig. 3). Based on stocking rates provided by landholders, sites of low cattle usage supported an average of 5.4 ± 4.1 cattle day^{-1} over the past 15 years compared with 79.3 ± 4.1 cattle day^{-1} in the high-use sites. Thus there were four categories of sites designated as high wombat-high cattle (HWHC), low wombat-high cattle (LWHC), high wombat-low cattle (HWLC) and low wombat-low cattle (LWLC). There were few differences in plant cover amongst cow and wombat treatments or

Table 1
Mean, SE, minimum and maximum mound density (mounds **ha**$^{-1}$) in relation to cattle and wombat usage.

Attribute	Wombat use	Cattle use	Mean	SE	Min	Max
Density (mounds ha^{-1})	High	High	70.0	21.4	4.0	16.9
	Low	High	44.1	19.0	1.0	8.0
	High	Low	23.8	10.0	1.0	5.0
	Low	Low	43.7	5.9	3.0	6.0
Volume (m^3 mound^{-1})	High	High	1.15	0.3	0.8	1.9
	Low	High	1.4	0.5	0.4	2.8
	High	Low	1.6	0.1	1.5	1.7
	Low	Low	1.3	0.4	0.7	2.0
Volume (m^3 ha^{-1})	High	High	79.0	24.5	32.3	124.1
	Low	High	85.4	48.8	4.3	209.4
	High	Low	33.6	14.0	10.0	70.7
	Low	Low	66.5	21.7	26.6	123.5

Fig. 3. Example of a high wombat-high cattle site showing wombat burrow in the foreground. The pasture grass kikuyu (*Pennisetum clandestinum*) has become established in the wombat mound and forms a continuous sward to the water's edge.

Table 2
Mean (±SE) plant and litter cover (%) at mound, track and control microsites in relation to cattle and wombat usage.

		Mound		Track		Control	
Attribute	Treatment	Mean	SE	Mean	SE	Mean	SE
Plant	HH	30.1	1.8	31.8	4.0	34.2	5.2
	LH	23.5	7.7	28.8	4.8	34.4	8.1
	HL	35.5	12.5	20.6	2.9	29.5	4.5
	LL	27.9	8.8	24.5	1.7	31.5	4.5
Litter	HH	23.0	6.5	37.8	8.2	15.9	1.8
	LH	30.6	3.6	49.6	5.9	26.0	5.0
	HL	15.0	6.8	40.1	10.8	21.5	3.6
	LL	21.6	8.4	46.2	5.4	18.0	3.4

amongst microsites. Litter cover however tended to be greater on the tracks irrespective of treatment (Table 2).

3. Field measurements

Here we consider the effects of wombats on soil displacement from the mounds, and the effects of both cattle and wombats on displacement of soil through the tracks.

3.1. Morphology of wombat mounds

The profile and plan view of a typical wombat mound located on sloping ground is shown in Fig. 4. Mound volume was calculated by measuring mound height and radius, and adjusting for relative ground slope. Full details of the algebraic procedure used to calculate mound volume can be obtained by consulting the corresponding author.

3.2. Displacement of soil from wombat mounds

We used splashboards (see Ellison, 1944; Imeson and Kwaad, 1976) to determine the amount of splashed soil and litter originating from mounds and non-mound surfaces (Fig. 5). Forty-two plywood splashboards (0.60 m high by 0.35 m wide), were established at the

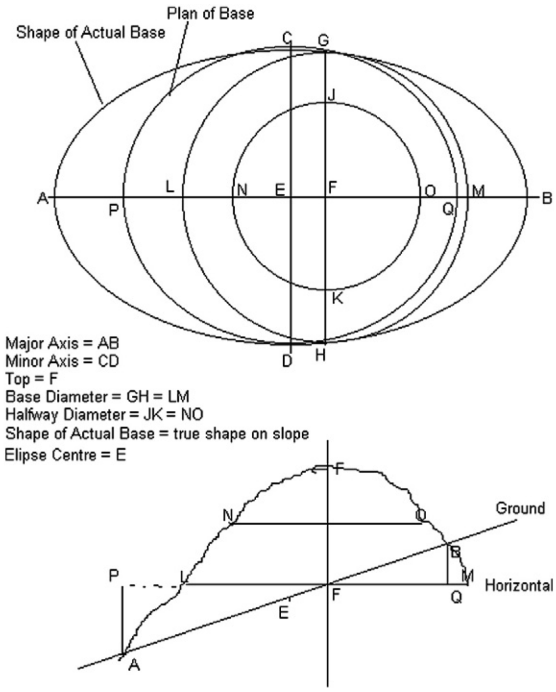

Fig. 4. Plan, elevation and the principal axes involved in assessing the volume of wombat mounds on stream bank slopes.

Fig. 5. Photograph of splashboard positioned at the side of a typical wombat mound. Note the accumulation of soil on the vertical face of the board following displacement during rainfall.

16 study sites, but we report data from only 10 sites because of continual damage to several splashboards by cattle. The splashboards were positioned in pairs, on- and off-mound. Three pairs were positioned in areas with no tree (upperstorey) or shrub (midstorey) cover, three pairs at sites under trees and shrubs with a combined canopy cover, estimated visually, of about 30%, three pairs at sites with 50% cover, and four pairs at sites with 70% cover. The on-mound splashboards were placed at the base of the mounds to avoid being directly filled by the burrowing activity of the wombat and the off-mound traps placed 2–3 m from the mound in an area of bare soil. Upperstorey and midstorey cover were visually estimated according to methods in Walker and Hopkins (1984). Material was collected from each splashboard after every rainfall event over a 12 month period by brushing material stuck to the board into the collector tray (Fig. 5). The material was later air dried and sieved to separate the collected litter (<2 mm) and four different soil fraction sizes; coarse sand (<0.600 mm), fine sand (<0.150 mm), silt (<0.045 mm) and clay. All litter and soil fractions were then weighed.

3.3. Size and erosion of cattle and wombat tracks

Soil displacement from tracks was estimated by measuring the depth and width of tracks every 2 m along vertical tracks (tracks leading downslope) and every 10 m for lateral tracks (running parallel to the slope) (Fig. 6A). The total volume was then calculated based on the total length of each track type and the mass of displaced soil calculated based on bulk density. Six cores (47.5 mm in diameter and 40 mm deep) were collected randomly from each of the 16 sites to measure bulk density, three each from worn track surfaces and non-track areas.

3.4. Statistical analyses

Differences in mound density and soil mass, length of tracks, and volume and mass of track soil were analysed using two-way ANOVA (Minitab Inc., 2007). Differences in rainsplash erosion between high and low cattle use sites and between on- and off-mound locations were analysed using General Linear Models (GLM). For some analyses, cover was used as a covariate in the analyses. Different soil displacement events were considered statistically independent, hence the large number of degrees of freedom for the residual term in the GLM models. Data were transformed, where necessary to satisfy assumptions of homogeneity of residuals. Tukey's Least Significant

Fig. 6. Photographs of A) the profile of a track at a high wombat-high cattle site, B) and old wombat mound showing the dense cover of wandering jew (*Tradescantia fluminensis*) surrounding the mound and C) a newly deposited mound. Bars are equivalent to 0.5 m.

Difference (LSD) testing was used to separate mean values after a significant *F*-statistic was reported. We used permutational multivariate analysis of variance (PERMANOVA, Anderson et al., 2008) with the Bray–Curtis similarity coefficients to test whether the particle size distribution of the eroded sediment varied between high and low cattle, on- and off-mound (or their interaction).

4. Results

4.1. Spatial distribution and morphology of wombat mounds

Across all sites wombat mounds occurred closer together at the high (7.05 m apart) than the low (31.22 m apart) wombat-use sites ($F_{1,12}=17.7$, $P=0.001$ on $\log_{10}$-transformed data). Across all sites the mounds averaged about 9.82 ± 0.06 m from the stream edge, though there were no obvious patterns in the location of mounds across stream banks. The morphology of wombat mounds and burrows varied markedly amongst sites. In general, however, mounds were ellipsoid-shaped with a short, steep upslope facing surface and a longer, more gently sloping surface facing downslope (Fig. 6B,C). The relative length of mounds increased with increasing slope, whilst the width and height decreased. The average basal diameter of mounds was 2.73 m and the average height 0.29 m. Mounds varied from being completely devoid of vegetation shortly after burrow construction to densely vegetated, often with weedy ephemeral plants. Burrows were circular shaped and ranged in size from 0.23 to 0.43 m in diameter, which reflected the average body size of wombats. Mounds generally had only one burrow, but sometimes up to three. We recorded a total of 79 mounds along a distance of 1600 m of riverbank up to the top of the bank (42.9 mounds ha^{-1}). Overall, wombat mound volume varied ranged from 4.3 to 209.4 $m^3\,ha^{-1}$. With an average bulk density of 1.23 $Mg\,m^{-3}$ for mounds across all sites, this equates to 5.3 to 258 t ha^{-1} of soil.

4.2. Soil displacement from wombat mounds

Approximately 1.8 times more soil was detached by splash erosion from wombat mounds (4.06 ± 0.78 g soil day^{-1}) than the inter-mound control locations (2.24 ± 0.77 g soil day^{-1}; $F_{1,284}=13.70$, $P<0.001$, on $\log_{x+1}$-transformed data). These trends were similar at high and low cattle sites ($P=0.53$), and using the cover of upperstorey or midstorey vegetation at each site as a covariate in the analysis did not improve the predictive power of the relationships ($P=0.18$).

Overall, the particle size distribution of sediment splashing off the mounds was similar to that of the inter-mound locations (P (perm) $=$ 0.18) and there were no differences between high and low cattle use sites (P (perm) $=0.12$). Position (on- or off-mound) had no effect on the capture of individual particle sizes i.e., there was no effect on the daily mass of trapped coarse sand ($P=0.93$), fine sand ($P=0.37$), clay ($P=0.11$) or silt ($P=0.49$; on $\log10_{x+1}$-transformed data). There were, however, significant effects of cattle use on most soil fractions. The daily rate of removal of coarse sand was 2.8-times greater on the high cattle (2.59 ± 2.52 g day^{-1}) than the low cattle (0.93 ± 0.49 g day^{-1}) use sites ($F_{1,285}=15.11$, $P<0.001$). Similarly, 37% more fine sand was eroded from the high (0.97 ± 0.21 g day^{-1}) than the low (0.70 ± 0.20 g day^{-1}) cattle use sites ($F_{1,284}=9.67$, $P=0.002$), and canopy cover at the site was a significant covariate in explaining some of the variation in fine sand capture ($F_{1,284}=4.21$, $P=0.041$). Averaged over all sand categories about 8% more sand was captured from the high cattle (0.50 ± 0.14 g day^{-1}) than the low cattle (0.46 ± 0.13 g day^{-1}) use sites ($F_{1,284}=5.20$, $P=0.023$ on $\log_{x+1}$-transformed data).

There was no difference in the mass of litter collected in the splashboards between low and high cattle use sites ($P=0.26$). However, sites with a greater canopy cover of plants (50% and 70% cover) trapped 1.5-times more litter (0.28 ± 0.04 g litter day^{-1}) than those at the low canopy cover (0 and 30% cover) sites (0.19 ± 0.10 g litter day^{-1}; $F_{3,285}=3.95$, $P=0.009$; on $\log_{10}$-transformed data).

Predictably, the amount of soil trapped on the mounds increased significantly with increases in the volume of rainfall during the intervening collection period ($F_{1,141}=4.46$, $P=0.036$; log–log data) but the explanatory power of rainfall was exceptionally low ($R^2=0.024$). Adding canopy cover or bulk density of soil to the model did not improve the predictive power. For intermound locations, there was no relationship between rainfall and soil loss ($P=0.60$), but there was a weak relationship between canopy cover and soil loss ($F_{1,144}=5.10$, $P=0.025$; log–log data), though again the explanatory power was very low.

4.3. Morphology of, and soil displacement from, cattle and wombat tracks

As tracks at the low cattle sites are used only intermittently, impacts were restricted to the tracks themselves, with little obvious disturbances off the tracks. Tracks in the high-use cattle sites showed obvious signs of cattle use. The intervening soils and vegetation were heavily modified by cattle, ranging from faecal spoilage to trampling and overgrazing.

We recorded an average of 1680 ± 178 m of wombat/cattle tracks ha^{-1} across all sites. Vertical tracks averaged 371 ± 60 m and lateral tracks 1310 ± 159 m of track ha^{-1}. The width and depth of vertical tracks averaged 39.3 ± 0.13 cm and 8.5 ± 0.02 cm, whilst lateral tracks averaged 42.0 ± 0.11 cm and 3.5 ± 0.01 cm respectively. There were no significant differences in any track dimensions between different cattle or wombat usage, and differences in track dimensions between low and high cattle usage were consistent between high and low wombat usage, i.e. there were no significant wombat by cattle interactions.

The volume of soil displaced from wombat and cattle tracks ranged from 7.9 to 88.8 $m^3\,ha^{-1}$. Adjusting volume by soil bulk density, which ranged from 0.90 to 1.59 Mg m^{-3}, the mass of displaced soil ranged from 4.69 to 118.65 t ha^{-1}. Despite the large variation in soil volume and soil mass from vertical or lateral tracks, there were no significant differences in relation to wombat or cattle use, and no cattle by wombat use interaction ($P>0.43$). The mean profile, however, of tracks was significantly greater (deeper) on vertical (10.5 ± 0.89 cm) than lateral (4.5 ± 0.30 cm) tracks across all sites ($t=-6.42$, df $=18$, $P<0.001$). Over the 18 month period there were no temporal changes in volume or mass of soil displaced from vertical or lateral tracks in relation to wombat or cattle use, and no cattle by wombat interactions ($P>0.43$).

The volume of soil displaced from wombat/cattle tracks over time varied from 9.28 to 102.7 t ha^{-1}, but it was not significant ($P=0.32$). The greatest increase in track profile was at the high wombat-low cattle sites, with an increase of 1.6 cm in the mean depth of tracks, though differences were not significant ($P=0.63$; Fig. 7).

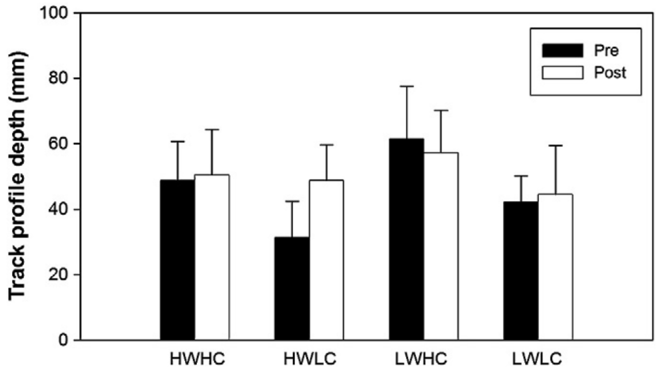

Fig. 7. Mean (±SEM) depth of trails (mm) over an 18-month period at eight of the 16 study sites across each of the four site categories (HWHC: high wombat-high cattle, LWLC: low wombat-low cattle, LWHC: low wombat-high cattle, HWLC: high wombat-low cattle) before and after assessment. Each treatment is an average of two site categories.

5. Discussion

There were three major results of our study. First, substantially more soil was detached by rainsplash from mounds than inter-mounds, irrespective of cattle usage, even though the particle size distribution of mound-derived sediment was similar to that from the inter-mounds. Second, soil removal from mounds at high cattle use sites was more than double that from low cattle use sites. Third, a substantial volume of soil was displaced from the tracks (~100 $m^3\,ha^{-1}$). Taken together, our results indicate that both cattle and wombats, by constructing tracks and mounds respectively, are important geomorphic agents in riparian landscapes in eastern Australia.

5.1. Soil excavation by wombats

Wombats excavated a relatively large amount of soil across the riparian landscape, up to 209 $m^3\,ha^{-1}$ (or 258 t ha^{-1} of soil). Anecdotal evidence suggests that burrow abandonment by wombats, re-activation of abandoned burrows, and reworking of older mounds is episodic. However, we have no data on the extent to which old structures are reworked and therefore we cannot convert these one-off values to a yearly *per capita* basis as some mounds were recently created (new mounds) whilst others were well established. The extent to which wombat-created structures contribute to landscape-level changes in sediment will therefore depend not only upon the extent to which they reactivate old burrow systems, but longevity of their mounds. Empirical evidence for a range of fossorial mammals relating the area of the disturbance to its longevity (Whitford and Kay, 1999) suggests that wombat mounds varying in size from 2 to 8 m across (Triggs, 2009) are likely to persist for periods ranging from 16 to 43 years, respectively, accelerating greatly after abandonment by wombats.

The magnitude of soil disturbance by wombats is comparable to that of similar-sized vertebrates such as the American badger (*Taxidea taxus*) from the western United States (26.7 t ha^{-1}; Eldridge, 2004) or relatively smaller vertebrates such as the long-tailed marmot (*Marmota caudata*) from mountainous grasslands in Russia (2.5 to 242 $m^3\,ha^{-1}$; Zimina and Zlotin, 1980). Our data are also within the range of sediment removal reported for mounds and foraging complexes of the European rabbit (*Oryctolagus cuniculus*; 29 to 88 t ha^{-1}, Eldridge and James, 2009), mounds of hairy-nosed wombat (88 t ha^{-1}, Steele and Temple-Smith, 1998) from arid and semi-arid Australian grassland and shrubland, and mounds of the Northern pocket gopher (*Thomomys talpoides*) from arid shrubland in the United States (88 t ha^{-1}, Richens, 1966). Our data are by no means at the upper end of sediment removal rates reported for a range of mammals (Butler, 1995). Substantially greater estimates have been reported for Botta's pocket gopher (*Thomomys bottae*) from coastal shrubland (802 t ha^{-1}) and alpine grassland (1046 t ha^{-1}; Cox and Gakahu, 1986) and the tuco tuco (*Ctenomys azarae*; 1390 $m^3\,ha^{-1}$ from Argentina; Roig et al., 1988). The substantially greater density of wombat mounds at the high wombat-high cattle sites could be due to the dense cover of exotic shrubs such as broad-leaved privet (*Ligustrum lucidum*), which is known to be an important factor in the selection of riparian burrow sites by wombats (Borchard et al., 2008).

5.2. Splash erosion from wombat mounds

Our measurements of splash erosion from mounds indicate that they are a significant source of displaced material, even under conditions of extensive vegetation cover. We collected displaced soil immediately following rainstorms, and because dense groundcover vegetation minimised the downslope movement of soil at our sites, we were confident that rainsplash, rather than overland flow (sensu Wu et al., 2010), was the predominant soil transport mechanism. Wombat-induced soil displacement is not short-lived, as indicated by the consistent quantities of soil collected over the course of a year. Lower mound volumes at the high cattle usage sites suggest to us that trampling by cattle may be reducing the size of mounds, thereby dispersing soil to annular zones around the mounds. Displacement of soil from wombat mounds likely has its greatest effect on plants and other biota in the immediate area surrounding the mound. Effects may not be detectable at larger scales such as across the landscape until mounds reach a relatively high density. For example, whilst low densities of mounds constructed by the American badger (*Taxidea taxus*) in the western United States influence mainly local-scale plant diversity and the infiltration of water (Eldridge, 2009; Eldridge and Whitford, 2009), at high densities (800 ha^{-1}) they may become significant emitters of dust during summer droughts.

In our study, the mass of splash-eroded soil from wombat mounds increased with the volume of rainfall, but not on the inter-mound locations. One explanation for the greater mass of splash-eroded material was that the plant cover on wombat mounds was greatly reduced when compared to off-mound (control) microsites (unpublished data). There was also a weak relationship between canopy cover and soil displacement. We did not record rainfall intensity at our study sites, though intensity and therefore raindrop energy (erosivity) is known to be strongly related to soil detachment (Imeson and Kwaad, 1976; Quansah, 1981; van Dijk et al., 2003). The particle size distribution of displaced mound material was similar to that of the inter-mound soil. One reason for similarity of particle sizes between mound and inter-mound locations could be the uniform nature of the surface soils down to 1.5 m in podzolic and soloth soils in the lower terraces of the riparian system (Hazelton, 1992). Equally plausible is that rainsplash is only capable of moving particles within a certain size range, generally less than 10 mm in diameter (Kwaad, 1977).

Our study presents data on splash erosion from the mounds created when wombats construct their burrows. We acknowledge, however, that much of this splash eroded material is probably captured by the vegetation surrounding the mounds and therefore does not make its way directly into the stream. Animal-created mounds are susceptible to rainsplash erosion, particularly on sloping soils (Jonca 1972; Imeson and Kwaad 1976; Butler 1995). There are few published data on splash erosion rates from animal-generated mounds. Voslamber and Veen (1985) reported mass transport rates of 15.1 g soil m^{-1} yr^{-1} on mounds of the European badger (*Meles meles*) in an agricultural landscape surrounded by forest in Belgium, whilst Sherrod and Seastedt (2001) reported rates ranging from 42 g m^{-1} yr^{-1} on the mounds of the Northern pocket gopher in an alpine meadow landscape in the USA to 11.2 g m^{-1} yr^{-1} close to the mounds, declining to about 4 g m^{-1} yr^{-1} at distances of more than 2 m from the mounds. Similarly, in a study of mole activity in a wooded forest in Luxembourg, Imeson and Kwaad (1976) reported movement of soil ranging from 0.41 g soil from the mounds of burrowing animals to 0.26 g soil on surfaces with up to 60% plant cover. In our study, splash erosion rates from wombat mounds were about 4 g of soil day^{-1}, averaged across 26 mounds with a total area of 152 m^2. Comparison with other studies reported above, however, is difficult given the different ways in which the authors have reported their results. Nonetheless, it seems that splash erosion is not insubstantial, probably because burrowing inverts the soil profile, exposing more erodible soil aggregates, and creates a sloping surface which is not only more erodible, but is likely to induce surface movement of material that has been detached by raindrop activity.

5.3. Tracks as a source of local sediment

On average, there were four-times more lateral tracks than vertical tracks, and 50% more soil was displaced from vertical than lateral tracks. This is consistent with our data on the cross-sectional area of vertical tracks, which were three-times greater (0.06 m^2) than horizontal tracks (0.02 m^2). Generally, there were more vertical tracks at sites of high wombat use, probably due to the fact that wombats need to move out of the riparian area to graze on adjacent paddocks (Skerratt et al., 2004). Fewer vertical tracks at sites of high cattle use may reflect the greater physical expenditure required by cattle to negotiate riverbanks vertically rather than on the contour (Reichman and Aitchison, 1981). In areas of dense vegetation, it also would be advantageous for cattle to use existing tracks created by wombats if the energetic cost is less than moving through undergrowth to generate a new track at a more appropriate angle. Soil displacement from tracks in low wombat-low cattle sites averaged about 0.81 m^3 per 100 m of stream bank over 18 months, similar with reports from tracks (or slides) leading to American beaver burrows in stream banks (0.49 m^3 per 100 m of stream bank per year) in the eastern United States (Meentemeyer et al., 1998).

The effects of tracks on erosion can result from two distinct, but related, geomorphic processes; 1) the removal of soil by cattle and wombats though physical dislodgement when moving along the track, and 2) trampling-induced compaction, which has substantial effects on soil hydrology, particularly runoff generation.

The tracks we measured in our study were clearly used by both wombats and cattle. We suspect however that cattle are responsible for most of the track establishment, but the extent to which wombats contribute to their formation is uncertain. The establishment of tracks by cattle whilst moving between pastures and into riparian areas is well documented. For example, several cattle tracks are common in the steep terrain foothill rangelands, resulting in many track crossings of stream channels and damage to stream banks (Trimble and Mendel 1995; George et al., 2004). We are unaware of any studies that have documented track creation by native vertebrates, including wombats, in Australia. Our observations of sites with wombats but without cattle indicate that wombat tracks are not characterised by displaced soil like cattle tracks, but there is clear evidence of flattening of the vegetation by continual movement of the animals.

It is difficult to separate the effects of direct mechanical dislodgment of materials by cattle and wombats from subsequent erosion, given that material would have been lost during the early stages of track formation before the study commenced. Studies from an arid shrubland in South Australia showed that sheep tracks formed rapidly within two weeks of the installation of a new stock watering point, and tracks were 6–18 mm deep after only two years (Andrew and Lange, 1986). In our study we found no significant effects of high or low use by either cattle or wombats on the volume of soil displaced from tracks. We monitored animal numbers over an 18-month period at 8-week intervals using motion detecting cameras and during that period recorded cattle only 29 times and wombats 162 times (Borchard and Wright, 2010a). It is our belief, therefore that most physical dislodgement of soil particles would have occurred when cattle were first introduced into Kangaroo Valley in the mid- to late-1800s (Griffith, 1986).

Animal trampling is known to increase soil bulk density (Tollner et al., 1990; Pietola et al., 2005), particularly when soils are wet and high in fine particle sizes. In our study, bulk density was significantly greater on the tracks than on the inter-track areas suggesting compaction of tracks. Most of the track compaction likely results from cattle rather than wombats, given their greater mass and therefore greater foot-ground pressure. The foot-ground pressure of wombats is about 16 kPa standing and 96 kPa walking and running (Mike Bennett, personal communication, 2006), which is substantially less than 132 and 250 kPa, respectively, for cattle (Scholefield and Hall, 1986). This suggests that the effect of wombats on compaction is likely to be substantially less than that of cattle, which is consistent with a large body of literature suggesting a more benign effect of soft-footed animals than hard-hoofed animals such as cattle (Butler, 1995; Trimble and Mendel, 1995, Bennett, 1999; Strauch et al., 2009).

Reductions in soil macroporosity from trampling on existing tracks likely reduce infiltration of water. Once formed, the deeply-incised and compacted tracks in our study area (Fig. 6A) would have concentrated overland flow and led to deep scouring and further loss of soil. We suspect that these hydrological effects would have had a greater influence on total soil displacement than any direct dislodgement of particles by the animals themselves (George et al. 2004).

6. Conclusions

Trampling by cattle resulted in generally greater levels of soil displacement through both the direct formation of tracks and subsequent loss of material by splash erosion, and this was most apparent at the high cattle sites. Conversely, although mound and burrow construction by wombats resulted in the mobilisation of substantial volumes of sediment; the effects of wombat mounds on splash erosion were relatively minimal. Mounds displaced 1.8-times more soil by rainsplash than the inter-mound areas, but much of this would have been captured by the extensive vegetation cover surrounding the mounds and incorporated into the topsoil. Our study suggests that burrowing and mounding by wombats may be an important process in providing patches of bare soil and hence a greater array of niches favouring a wider range of vascular plants. Mixing of subsoil disturbed by wombats with surface horizons may also be an important mechanism for enhancing the decomposition of surface litter.

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