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Ecohydrological controls on soil erosion and landscape evolution

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ABSTRACT

The ecohydrological controls on soil erosion and landscape evolution are difficult to quantify and poorly understood. In many parts of the world, cyclone-induced tree throw is a major source of disturbance. Tree throw may increase sediment transport by exposing a mound of fresh soil as well as providing a pit which may act as a knickpoint triggering gully erosion. Alternatively, while tree throw provides characteristic pit–mound topography, the amount of soil disturbed or exposed in a mound is relatively small on the hillslope and catchment scale and the effects may be minimal. The April 2006 tropical cyclone Monica that impacted the coast of northern Australia with winds' speeds >100 m s^{-1} uprooted approximately 50% of the trees in the study catchment. We use a landscape evolution model with repeated occurrence of the cyclone over a 1000-year simulated period to quantify the effect of pit–mound topography distributions on both sediment transport and landscape evolution by including the fallen trees into the digital elevation model both as a pit–mound and also as a pit–mound and tree trunk. The results show that the inclusion of pit–mound topography substantially reduced erosion for the first 10–15 years of its introduction and adding pit–mound–trunk topography reduced erosion rates even further. The pit–mound and pit–mound–trunk acted as sediment traps, capturing sediment from upslope and storing it in debris dams reducing hillslope connectivity. Model simulations predict average denudation rates for the catchment approximating field measured data. These findings suggest that any tree throw is unlikely to result in landscape instability. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS soil erosion; landscape evolution; tree throw; SIBERIA; climate change; cyclone; connectivity

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INTRODUCTION

The role of tree throw on long-term soil erosion and landscape evolution is poorly understood (Petersen, 2000). Although soil erosion is governed by many factors, including the underlying geology and soil characteristics, topography, hydrology, land use and management practices, tree throw represents a major, episodic disturbance with potential large consequences for soil erosion and landscape development. In the tropics, cyclonic events are the major cause of tree throw where high wind and high rainfall have the potential to cause major geomorphological change (Figure 1). Such events are a regular occurrence in many parts of the world (Petersen, 2000; Phillips and Marion, 2006; Phillips *et al*., 2008; Cook and Nicholls, 2009).

At present, the effect of tree throw on hillslope sediment transport and long-term geomorphology is speculative (Phillips *et al*., 2008; Samonil *et al*., 2010). Tree throw may increase sediment transport by exposing a mound of fresh soil as well as providing a pit which may act as a knickpoint triggering gully erosion, thereby enhancing overall erosion rates and increasing overall landscape lowering (Figure 2). Alternatively, while tree throw provides characteristic pit–mound topography, the amount of soil disturbed or exposed in a mound may be relatively small on the hillslope and catchment scale. In many cases, a large proportion of soil material uplifted on the root ball may fall back into the pit from which it came. To create a knickpoint for gullying the disturbance needs to concentrate flow and this requires a location on the hillslope where this can happen—which is not likely to happen for all pit–mounds. Although it is unlikely that a tree trunk will fall along a contour, the fallen tree trunk on the ground can act as a sediment trap or debris dam capturing material from upslope. Therefore tree throw has the potential to reduce erosion to below that of pre-cyclone levels.

The literature on tree throw and geomorphology is very limited (Samonil *et al*., 2010). Heimsath *et al*. (2001) investigated soil production and transport in a steep, soil-mantled landscape of the Oregon Coast Range and observed that stochastic tree-throw processes and shallow land sliding may dominate soil production and transport. They reported that 'sediment transport by tree throw is an important factor'. Norman *et al*. (1995) reported detailed findings on pit and mound volumes as a function of slope angle and found that on progressively steeper slopes tree throw became an increasingly important component of mass wasting. They found that for tree-throw mounds on slopes above 47°, nearly all the uprooted

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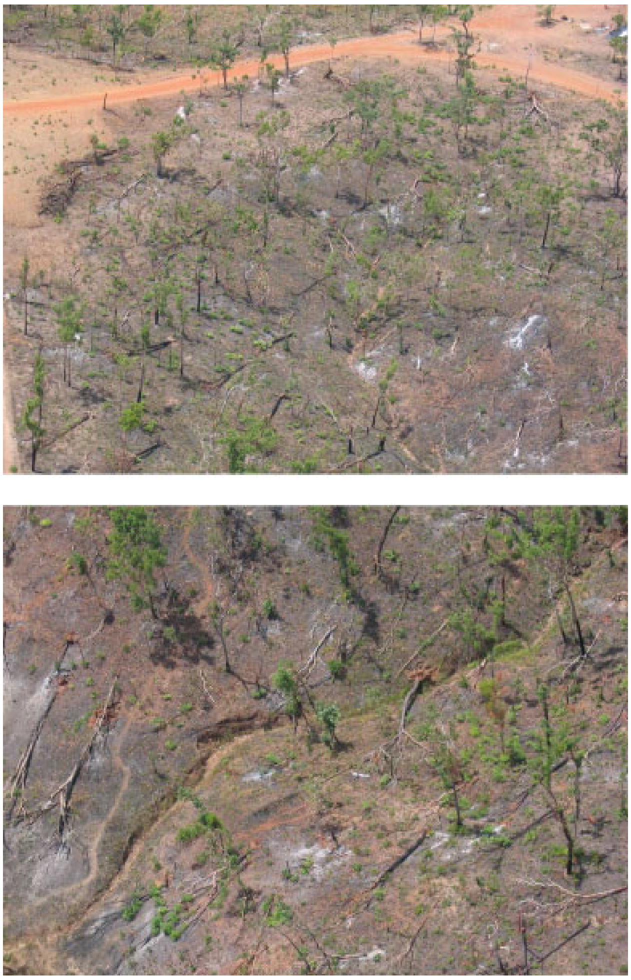
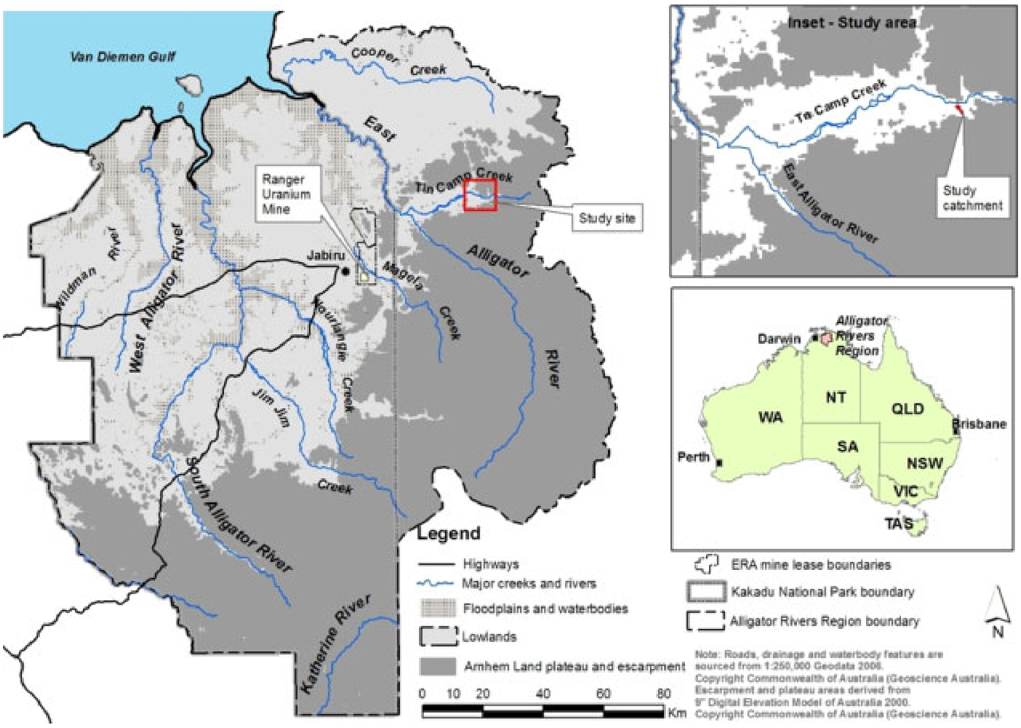


Figure 1. Aerial view of the catchment showing both standing and fallen trees in September 2006 after cyclone Monica. The top photograph is located in mid-catchment, whereas the bottom photograph location is in the upper catchment and displays an incised first-order stream running diagonally across the image.

sediment was transported downslope rather than returning to the pit. In addition, the pit resulting from tree throw created a significant change in local slope, disrupting the sediment continuity and reducing hillslope sediment connectivity and creating a sink for sediment. It would appear that there is a tendency for tree-throw pits to fill relatively rapidly with soil from surrounding slopes such that the hillslope returns to its pre-tree-throw state. Clinton and Baker (2000) examined pit and mound dimensions in detail that resulted from catastrophic wind throw events within the southern Appalachians. They suggested that pit–mound dimensions varied greatly and not all were proportional to tree size. Tree root strength and distribution together with lithology were important factors. Although some trees may be directly blown over by wind, some trees fall onto other trees pushing them over (i.e. domino principle) while others can be pushed and rotated while still remaining in place. Phillips *et al.* (2008) examined the role of tree throw on bedrock weathering and soil development and found that the process plays a role in soil formation.

Figure 2. Tree fallen by cyclone Monica with root ball removed by fire (top) and intact root ball and tree (bottom) 6 months after the cyclone.

Here we examine the impact of a cyclone on tree throw and resultant soil disturbance in a catchment largely undisturbed by Europeans in the Northern Territory, Australia. We use a soil erosion and landscape evolution model, SIBERIA (Hancock *et al.*, 2008), to quantify the effect of pit–mound topography distributions on both sediment transport and landscape evolution. It is only in recent years that such computer-based landscape evolution models have been developed to the point where features such as tree throw can be examined over decadal and geomorphic time scales. To our knowledge, this is the first attempt to explore these specific ecohydrological effects on long-term geomorphological development. These processes are of particular importance for northern Australia and other cyclone-dominated regions as climate change modelling suggests that these areas will receive an increase in the frequency of high-intensity storms and cyclonic events (CSIRO, 2007). Projections indicate an increase in cyclone activity of 0·2 days per year with an increase of 60% in Category 3–5 storms and of 140% in the intensity of the most extreme storms for the period between 2030 and 2070, respectively (Chiew and Wang, 1999; Johnston and Prendergast, 1999; Jones *et al.*, 1999; CSIRO, 2007).



Note: Roads, drainage and waterbody features are sourced from 1:250,000 Geodata 2006. Copyright Commonwealth of Australia (Geoscience Australia). Escarpment and plateau areas derived from 9" Digital Elevation Model of Australia 2000. Copyright Commonwealth of Australia (Geoscience Australia).

Figure 3. Location of study site.

Our work capitalizes on the April 2006 severe tropical cyclone Monica that impacted the coast of northern Australia. The eye of this cyclone passed almost directly over our study site where it was estimated that winds' speeds were approximately 50 m s^{-1}. The event uprooted approximately 50% of the trees in the catchment. The specific objectives of this article are to:

1. Quantify the form and distribution of tree throw in the Alligator Rivers Region and Tin Camp Creek study catchment (the focus of this study) following cyclone Monica
2. Use measured tree-throw data to insert such features into a high resolution digital elevation model (DEM) of the Tin Camp Creek study catchment
3. Use the SIBERIA soil erosion and landscape evolution model to explore the consequences of tree throw on long-term erosion rates and catchment evolution, on decadal to centennial time scales
4. Perform multiple realizations of tree-throw orientation and cyclonic frequency to explore the sensitivity of ecohydrological controls on long-term erosion rates and catchment evolution on decadal to centennial time scales.

STUDY SITE

This study examines the impact of cyclone Monica in a subcatchment of the Tin Camp Creek system, Northern Territory, Australia. Located in the catchment of Tin Camp Creek in western Arnhem Land, Northern Territory, Australia (Figure 3), this study site lies in the Myra Falls Inlier in Lower Member Cahill Formation (Needham, 1988). This metamorphosed schist formation also hosts the Energy Resources of Australia Ranger Project Area (RPA) mine and the surface properties are analogous to rehabilitated landforms at RPA in the long term (Uren, 1992). Other studies in the catchment have examined soil erosion and gully development (Hancock and Evans, 2006; Hancock *et al.*, 2008; Hancock and Evans, 2010).

The Tin Camp Creek catchment is located in the wet–dry tropics of northern Australia. The mean annual rainfall for the region is approximately 1400 mm, almost all of which falls in the wet season months from November to April. Short, high-intensity storms are common, consequently fluvial erosion is the primary erosion process (Saynor *et al.*, 2004). Generally, most of the erosion occurs during a small number of high-intensity tropical storms.

The area is presently tectonically inactive (Needham, 1988). Tin Camp Creek is part of the Ararat Land System (Story *et al.*, 1976) and developed in the late Cainozoic by the retreat of the Arnhem Land escarpment, resulting in a landscape dissected by active gully erosion (Hancock and Evans, 2006, 2010). For the purposes of this study, a smaller 50 ha catchment, representative qualitatively of many others in the area was selected (Figure 4). The catchment consists of closely dissected short, steep slopes 10–100 m long with gradients generally between 15 and 50%. The soils are red loamy earths and shallow gravely loam with some micaceous silty yellow earths and minor solodic soils on alluvial flats. Much of the surface of slopes and hill crests is covered by a gravely cobble quartz lag.

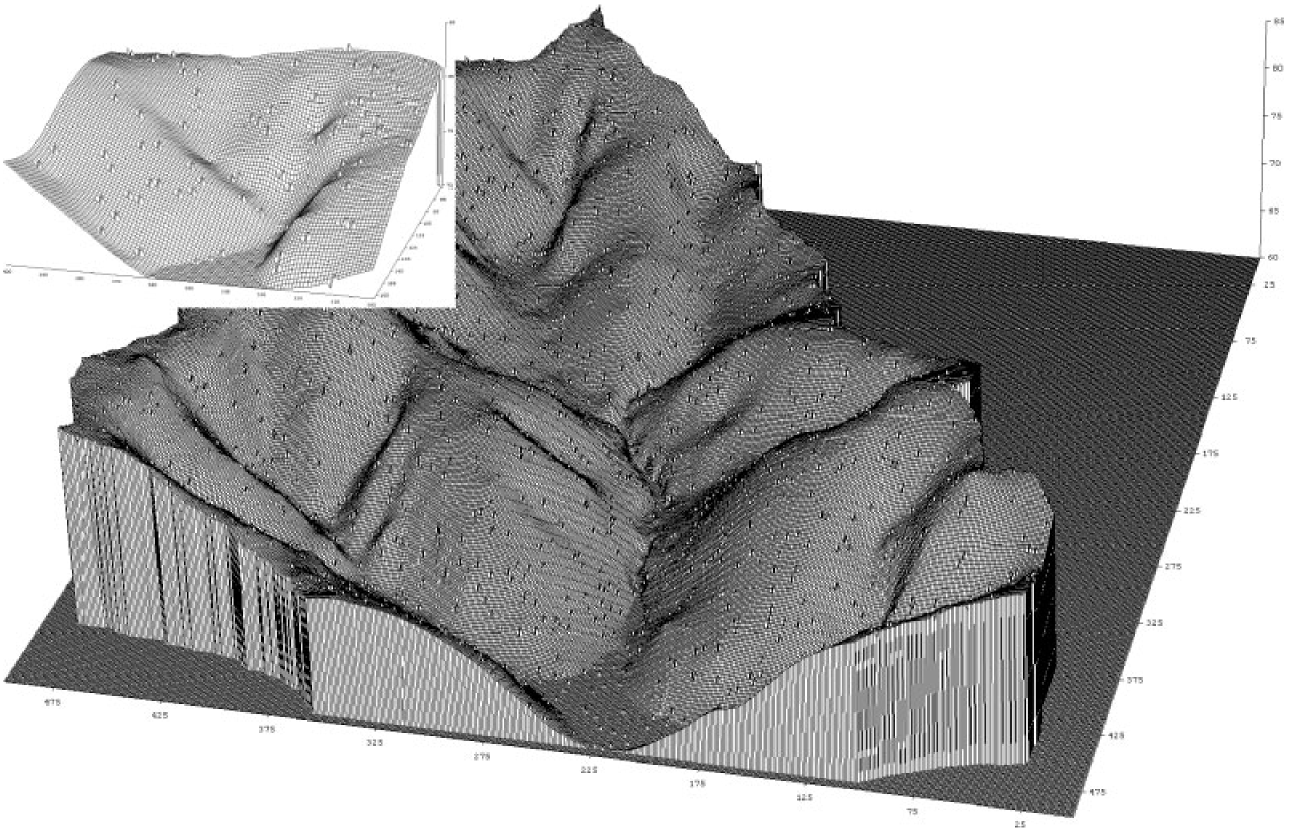


Figure 4. Digital elevation model (1 m pixels) of the Tin Camp Creek catchment with 0·5 m deep pit and 0·5 m high mounds (Pit–Mound) randomly distributed over the catchment at the beginning of the simulation. Inset displays close-up of the Pit–Mound topography.

The native vegetation is open dry-sclerophyll forests and, although composed of a mixture of species, is dominated by *Eucalyptus* and *Acacia* species (Story *et al.*, 1976). *Melaleuca* spp. and *Pandanus spiralus* are also found in the low-lying riparian areas with an understorey dominated by *Heteropogon contortus* and *Sorghum* spp. There is vigorous growth of annual grasses during the early stages of the wet season. These grasses often fall over during the wet season, providing a thick mulch which causes high reductions in erosion rates of bare soil. Cover afforded by vegetation is often reduced by fire (both naturally occurring and lit with incendiaries) during the dry season, which enhances the potential for fluvial erosion (Saynor *et al.*, 2004).

Erosion and denudation rates have been established for the catchment using a variety of different methods. An assessment using the fallout environmental radioisotope caesium-137 (^{137}Cs) as an indicator of soil erosion status for two transects in the catchment produced net soil redistribution rates between 2 and 13 t ha^{-1}year^{-1} (0·013–0·86 mm year^{-1}) (Hancock *et al.*, 2008). The measured erosion rates, using ^{137}Cs, for the upper hillslopes of this study site compare favourably with that of overall denudation rates for the area (0·01–0·04 mm year^{-1}) determined using stream sediment data from a range of catchments of different sizes in the general region (Cull *et al.*, 1992; Erskine and Saynor, 2000). Soil production rates of 0·02 mm year^{-1} have been determined for this study site using cosmogenic analysis (Heimsath *et al.*, 2009).

Cyclone Monica and significant climate events

Over the past 10 years, three Australian Category 5 cyclones (wind gusts greater than 78 m s^{-1}) have passed within 400 km of Darwin. During April 2006, severe tropical cyclone Monica impacted the coast of northern Australia. The very destructive core of Monica crossed the Northern Territory coastline and continued in a south-westerly direction, rapidly weakening in intensity as it moved across land. Maximum wind gusts have been estimated to be up to 99 m s^{-1} near the coast (Cook and Nicholls, 2009). The eye passed almost directly over the former Nabarlek mine tracking close to the Tin Camp Creek area and continuing through to Jabiru (Figure 1) where it had reduced to a Category 2 level. It is estimated that at Nabarlek winds' speeds were 50 m s^{-1}. The cyclone then continued to track westerly, and weakened to below cyclone intensity (Staben and Evans, 2008).

Return intervals (RIs) for Category 5 cyclones are currently being reassessed (Cook and Nicholls, 2009; Wang and Wang, 2009) but current estimates of an RI of winds of 50 m s^{-1} are approximately 1:100 years. Although cyclone Monica was an example of an extreme event, it did not have the accompanying prolonged heavy rainfall and subsequent runoff that is usually associated with a cyclone or associated rain depression. Although no weather station exists at Tin Camp Creek, the winds in the study catchment were so strong that infrastructure in a mining camp located near the study catchment had several portable buildings lifted off foundations, transported several metres and tipped on their side. This

Table I. Recent fire history and annual rainfall (mm).

Year	Vegetation	Annual rainfall
2002	Burnt August	1392
2003	Not burnt	1309
2004	Burnt September	1792
2005	Not burnt	1416
2006	Burnt July	2062
2007	Not burnt	2528
2008	Burnt September	1646
2009	Not burnt	1056

wind uprooted approximately 50% of the trees in the catchment (Figures 1 and 2).

Post-cyclone Monica there was significant rainfall. The 2006–2007 wet season, following cyclone Monica was the wettest season on record (Moliere *et al.*, 2008) (Table I). The total annual rainfall at Jabiru during 2006–2007 of 2528 mm was the highest annual rainfall recorded since rainfall data collection commenced at Jabiru in 1971. This can be largely attributed to rainfall which occurred during February and March 2007 (800 and 1140 mm, respectively), two of the highest monthly rainfall totals ever recorded at Jabiru airport (previous highest monthly rainfall total was 807 mm which occurred in January 1997). Conversely, January 2007 rainfall at Jabiru airport was the lowest monthly total for January ever recorded.

FIELD ASSESSMENT OF THE IMPACT OF CYCLONE MONICA

An assessment of the damage of cyclone Monica was carried out both in the local region (Staben and Evans, 2008; Saynor *et al.*, 2009) and in the study catchment. In addition, erosion pins have been used to measure sediment transport. This assessment is described as follows.

Assessment of tree throw

The occurrence of cyclone Monica provided a rare opportunity to study the effect of such an extreme event. A regional-scale assessment was conducted across three areas within the Alligator Rivers Region. This included the Gulungul Creek Catchment, rehabilitated areas on the ERA Ranger mine within the Magela Creek catchment and also rehabilitated and natural areas at the Nabarlek uranium mine adjacent to the Tin Camp Creek study site (Saynor *et al.*, 2009). The regional assessment used pre- and post-Landsat data to assess the damage produced by the cyclone. From each of the major Land and Vegetation Units, a 30 m × 30 m pixel was randomly chosen to assess the damage to vegetation. A total of fifty-five 30 m × 30 m plots were examined: 31 in Gulungul Creek Catchment, 15 at Nabarlek and 9 on the Ranger mine site (Saynor *et al.*, 2009).

Each of the 55 sites was assessed and a number of the parameters were measured for trees within each plot including the number and species of both fallen and standing trees and direction of fall. The dimension of any crater caused by tree throw and the material uplifted was also measured (Saynor *et al.*, 2009).

To quantify the effect of cyclone Monica, sites from the Saynor *et al.* (2009) study were selected that had similar vegetation and soils to that of Tin Camp Creek. From this data set average, tree-throw density was 56 trees ha^{-1} ($\sigma = 44$ tree ha^{-1}). These trees had an average diameter at breast height of 0·16 m ($\sigma = 0{\cdot}11$ m) and average height of 10 m ($\sigma = 5$ m). Average width, length and depth of the pit produced by the fallen tree was 0·64 m ($\sigma = 0{\cdot}39$), 1·16 m ($\sigma = 0{\cdot}5$ m) and 0·51 m ($\sigma = 0{\cdot}13$ m), respectively.

In addition to the above sites, fallen trees were identified within the Tin Camp Creek study catchment for examination (Figure 2). Details regarding these trees were recorded in 2006 after cyclone Monica and they have been monitored in 2007, 2008 and 2009 for (i) removal of tree superstructure by fire or termites, (ii) erosion of the soil mound and infilling of the pit and (iii) evidence for enhanced erosion at or around the site of tree throw.

Field measurement of erosion

In addition to the ^{137}Cs analysis described in Section on Cyclone Monica and Significant Climate Events, erosion pins were installed in the catchment in 2002 as part of an assessment to quantify annual erosion and deposition rates as well as gully erosion (Hancock and Evans, 2006, 2010). Erosion pins are a simple and inexpensive method to quantify soil loss and soil creep (Ireland *et al.*, 1939; Emmett, 1965; Haigh, 1977; Loughran, 1989). A pin or rod is inserted into soil leaving a known length protruding; repeated measurements can then determine both soil erosion and deposition. Net erosion or deposition at a site is calculated by determining the arithmetic mean of the measured values. Disadvantages of the method are that insertion of pins can disturb the soil and subsequently may be buried by deposition and/or disturbed by animal and human activity.

The erosion pins installed in 2002 were part of an assessment to quantify gully erosion in the catchment (Hancock and Evans, 2006, 2010). In all, 43 erosion pins were used, equivalent to approximately one pin per hectare. These erosion pins were distributed approximately evenly over the catchment so that average basin soil loss could be determined. In all cases for positional consistency, the pins were positioned near the base of the hillslope with some on the hillslope. The erosion pins consisted of galvanized steel pegs 750 mm in length. When placed in the ground the height of pegs was measured to the nearest millimetre. Long pins were used so they were visible in dense vegetation.

THE SIBERIA LANDSCAPE EVOLUTION MODEL

SIBERIA is a mathematical model that simulates the geomorphic evolution of landforms subjected to fluvial and diffusive erosion and mass transport processes (Willgoose *et al.*, 1991). The model links widely accepted hydrology and erosion models under the action of runoff and erosion over long-time scales. Hence it can be used as a tool to understand the interactions between geomorphology and erosion and hydrologic process because of its ability to explore the sensitivity of a system to changes in physical conditions, without many of the difficulties of identification and generalization associated with the heterogeneity encountered in field studies. The sediment transport equation of SIBERIA is

$$q_s = q_{sf} + q_{sd} \tag{1}$$

where q_s ($m^3\ s^{-1}\ m^{-1}$ width) is the sediment transport rate per unit width, q_{sf} is the fluvial sediment transport term and q_{sd} is the diffusive transport term (both $m^3\ s^{-1}\ m^{-1}$ width).

The fluvial sediment transport term (q_{sf}), based on the Einstein-Brown equation, models incision of the land surface and can be expressed as:

$$q_{sf} = \beta_1 q^{m_1} S^{n_1} \tag{2}$$

where q is the discharge per unit width ($m^3\ s^{-1}\ m^{-1}$ width), S ($m\ m^{-1}$) the slope in the steepest downslope direction and β_1, m_1 and n_1 are calibrated parameters.

The diffusive erosion or creep term, q_{sd}, is

$$q_{sd} = DS \tag{3}$$

where D ($m^3\ s^{-1}\ m^{-1}$ width) is diffusivity and S is slope. The diffusive term models smoothing of the land surface and combines the effects of creep and rainsplash.

SIBERIA does not directly model runoff (Q, m^3—for the area draining through a point) but uses a subgrid effective parameterization based on empirical observations and justified by theoretical analysis which conceptually relates discharge to area (A) draining through a point as

$$Q = \beta_3 A^{m_3} \tag{4}$$

where β_3 is the runoff rate constant and m_3 is the exponent of area, both of which require calibration for the particular field site.

For long-term elevation changes it is convenient to model the average effect of the above processes with time. Accordingly, individual events are not normally modelled but rather the average effects of many aggregated events over time are quantified. Consequently, SIBERIA describes how the catchment is expected to look, on average, at any given time. The sophistication of SIBERIA lies in its use of digital terrain maps for the determination of drainage areas and geomorphology and also its ability to efficiently adjust the landform with time in response to the erosion that occurs on it.

The SIBERIA erosion model has recently been tested and evaluated for erosion assessment of post-mining landforms (Hancock *et al.*, 2000, 2008, 2010). A more detailed description of SIBERIA can be found in Willgoose *et al.* (1991).

SIBERIA input parameters

Before SIBERIA can be used to simulate soil erosion the sediment transport and area–discharge relationships require calibration. The fluvial sediment transport equation is parameterized using input from field sediment transport and hydrology data. For this study, the SIBERIA model was calibrated from field data collected at Tin Camp Creek from a series of rainfall events. Two catchments of size 2032 (catchment C1) and 2947 m^2 (catchment C2) with average slopes of 19 and 22%, respectively, were instrumented during the wet season of 1990. Both sites are incised and channelized and are representative of the overall 50 ha catchment. The study sites were monitored during rainfall events in December 1992. At this time, the catchments had a good covering of spear grass, which quickly regenerates each wet season.

To calibrate the erosion and hydrology models, complete data sets of sediment loss, rainfall and runoff for discrete rainfall events in both catchments were collected allowing calibration for the two individual catchments. Using these individual data sets parameter values of $\beta_1 = 1880$, $\beta_3 = 0{\cdot}83$, $m_3 = 0{\cdot}1$, $m_1 = 1{\cdot}69$ and $n_1 = 0{\cdot}69$ were determined representing annual hydrology and sediment transport rates (Moliere *et al.*, 2002). Although no field data exist for diffusion or hillslope creep for the area, a value of 0·0025 where length units are metres and time units are years (Hancock *et al.*, 2000, 2002) has been used for previous studies in the area and is used here. A description of the parameters and this parameterization process is described in detail by Evans *et al.* (2000) and Hancock *et al.* (2000). Boundary conditions for the simulations were such that all areas within the catchment boundary were allowed to erode and a series of outlets allowed sediment to exit from the domain. The calibration of SIBERIA for the Tin Camp Creek is described in detail elsewhere (Hancock *et al.*, 2000, 2008; Moliere *et al.*, 2002).

Catchment DEMs

SIBERIA uses DEMs to capture hillslope and catchment geomorphology. A regular grid DEM of the area was created from 240 000 irregularly spaced data points using digital photogrammetry by AIRESEARCH Pty Ltd, Darwin. The DEM has been used extensively in past studies (Hancock *et al.*, 2008, 2010).

In this study, the irregularly spaced data were gridded by the commercially available and widely used Surfer 7·04 (Golden Software Inc) program using simple Kriging onto a 1 m × 1 m spacing. This 1 m × 1 m spacing was used as it allows the incorporation of features such as pit–mound topography and fallen trees into the DEM providing a reasonable approximation of any disturbance by tree throw. It also allows any simulation to be completed within a reasonable time (several days) frame. All elevation depressions (an anomalous low surrounded by highs) were removed from the DEM using the Tarboton *et al.* (1989) method as they can falsely reduce erosion rates over the short term until the depressions fill with sediment. Nevertheless, previous work

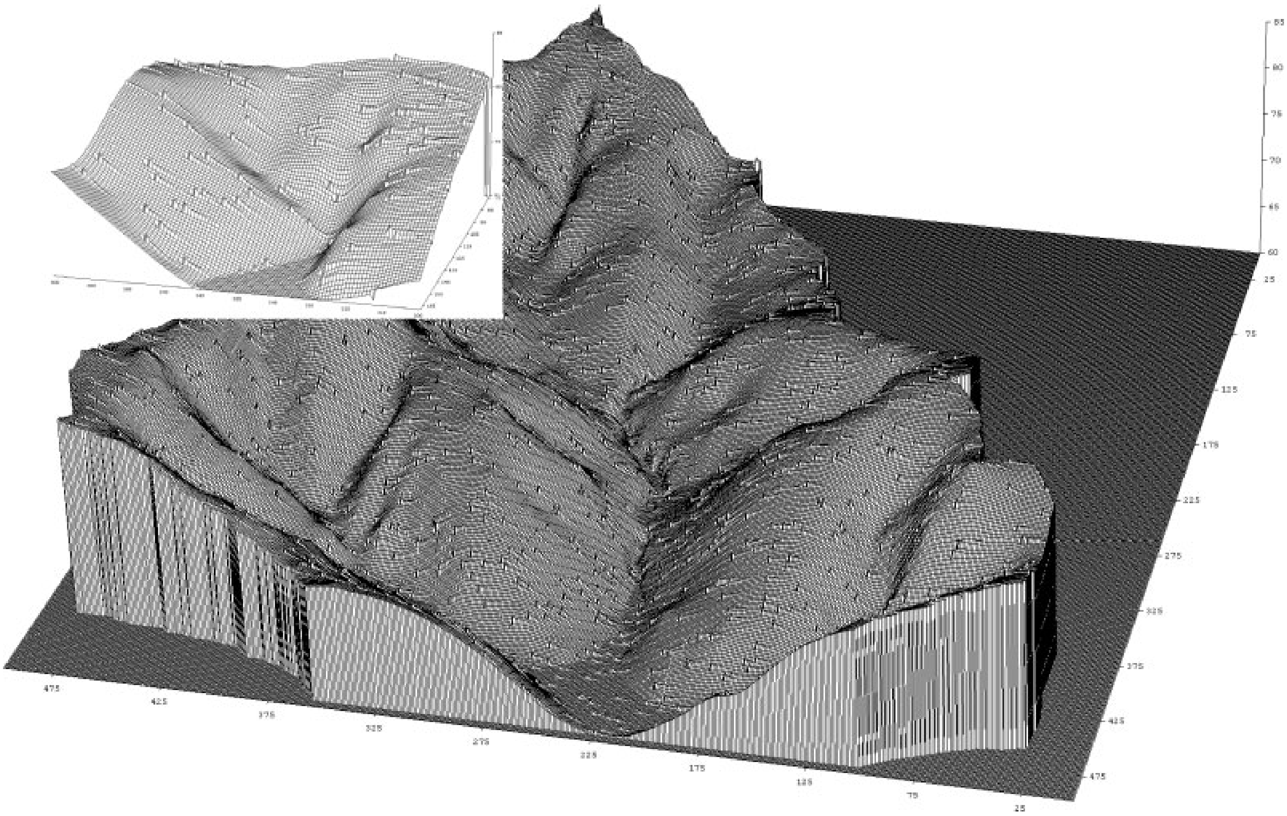


Figure 5. Digital elevation model (1 m pixels) of the Tin Camp Creek catchment with 0·5 m high pit and 0·5 m mounds and tree (Pit–Mound–Tree) trunk randomly distributed over the catchment. Inset displays close-up of the Pit–Mound–Tree topography.

has shown that the number and size of depressions in this data are small and that removing them has little effect on long-term landscape evolution (Hancock, 2008).

METHODS

To represent tree throw, pit–mound topography was randomly distributed across the landscape surface with a mound height of 0·5 m and pit of 0·5 m and lateral dimensions of 1 m × 1 m (one pixel). This approximates the average physical size of the pit–mounds caused by the tree throw as described from the field measurements above. Pit–mound density was distributed at approximately 100 pit–mounds ha^{-1} thus approximating the mean data plus one standard deviation (Figure 4).

To represent tree throw including both the pit–mound and tree trunk on the ground a trunk 10 m long with a diameter of 0·2 m tapering to a minimum diameter of 0·02 m was added to each 0·5 m tall mound in the above DEMs (Figure 5). These trees were aligned in one direction representing the single direction in which the trees were pushed over.

A series of simulations were run (using SIBERIA) examining the effect of no disturbance by tree throw and also disturbance by tree throw and pit–mound topography. These were

1. Baseline: The 1 m DEM without any disturbance by tree throw. This provided a baseline with which to compare all other simulations (termed Baseline hereafter).
2. Pit–Mound: A simulation with the pit–mound topography at the start of the simulation (i.e. Figure 4) (termed Pit–Mound hereafter).
3. Pit–Mound with a cyclone RI: A simulation with repeated cyclonic events and resultant repeated tree throw with an RI of 1:100 years (as this is reasonable given the speculated RI; Cook and Nicholls, 2009; Wang and Wang, 2009). To do this, the simulation was run using a random RI of 1:100 years with the simulation stopped at the randomly determined intervals and tree throw added. This cycle was repeated for a total of 1000 years (termed Pit–Mound–RI hereafter). In addition to these, additional simulations were run with a tree-throw event at regular 100-year intervals.

To test the effect of larger Pit–Mounds and the sensitivity of the system additional simulations were run with a mound height of 1 m and pit of 1 m and lateral dimensions of 2 m × 2 m (termed Pit–Mound–Big hereafter).

Lastly, a second series of simulations were run as described above but with both the Pit–Mound topography and tree trunk included (Figure 5) (termed Pit–Mound–Tree hereafter).

RESULTS

Field observations and erosion pins

Field measurements of the 30 fallen trees at Tin Camp Creek collected since 2006 showed little change in sediment production. During this 3-year period, the catchment was been burnt twice as well as record rainfall in 2007 (Table I). In general, over this period there was little change in the size and shape of the pit or significant loss of sediment from the raised root ball for 28 of the 30 monitored trees. Only two trees had significant fire damage (Figure 2). There was no evidence of any movement of sediment downslope or indication of rilling or gullying produced from the pits. There was no evidence of any debris build up at/or around the pit–mound or along any of the tree trunk length on the ground. Therefore observation suggests that the tree-throw event had little large-scale impact on the catchment over the monitoring period.

Although erosion pins were installed in the catchment since 2002, complete annual data did not exist as some pins were not measured every year. On average since 2004, the entire catchment lowered at a rate of 0·052 mm year^{-1}. While slightly higher, this approximated the overall denudation rate for the region of 0·01–0·04 mm year^{-1} (Cull *et al.*, 1992; Erskine and Saynor, 2000).

Nevertheless from year to year there was considerable variation. From 2005 to 2007, the variation in erosion and deposition was relatively subdued. From 2007 to 2008, there was a large peak in deposition followed by a substantial decline (erosion) from 2008 to 2009 (Figure 6). The spike in deposition in 2007–2008 coincided with the occurrence of cyclone Monica in 2006 and the large wet season in early 2007. From 2008 to 2009, there was an increase in erosion which likely represented the accumulated sediment (deposition) in 2008 leaving the catchment system. This suggested that the system is a dynamic system responding to both climate and fire regime (Table I). Nevertheless, separating the two influences is difficult.

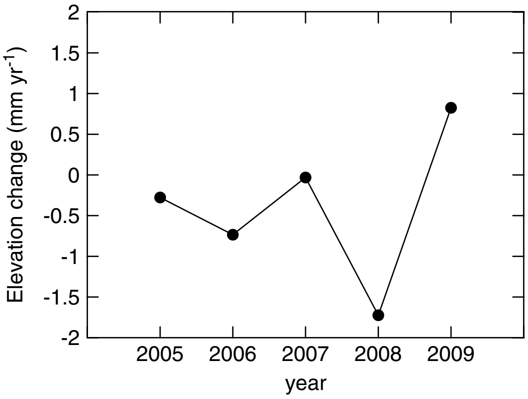


Figure 6. Erosion and deposition rates for the catchment using erosion pins. Negative values represent deposition, whereas positive values represent erosion.

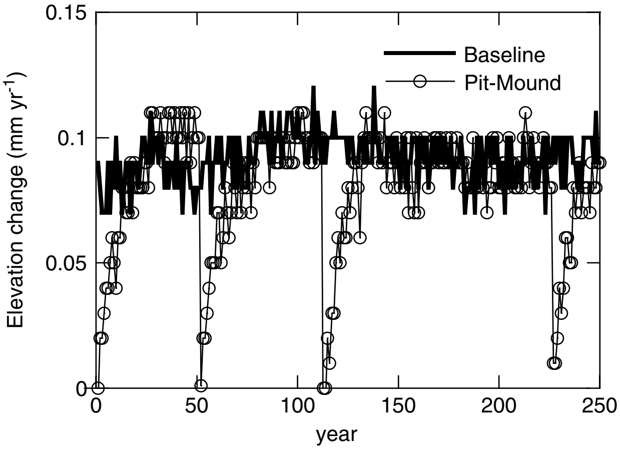


Figure 7. Annual elevation change (denudation rate) for the SIBERIA simulations for the Baseline simulation (no tree throw) and repeated tree throw (Pit–Mound) at random 1:100 year intervals. Only the first 250 years of the simulation shown for clarity.

SIBERIA simulations

The Baseline simulation without any tree throw produced a relatively constant denudation rate of approximately 0·085 mm year^{-1} (Figure 7). This was higher than the erosion pin derived rates and approximately double the long-term denudation rate for the region but within the range of values found for the catchment using ^{137}Cs (see Section on Cyclone Monica and Significant Climate Events). We hypothesize that the reasons for the higher than background erosion rates predicted by SIBERIA is that the calibrated parameters are determined from a limited series of storms in the middle of the wet season. These storms may firstly not have incorporated the full range of storm duration and intensity and secondly the vegetation may not have fully grown when the storms occur. Nevertheless, the denudation rate is a regional value only and the SIBERIA predicted results are at the bottom end of the range found using the ^{137}Cs method for the catchment therefore providing confidence in the results.

Overall, there is little difference in erosion rates between the Baseline simulations and the single tree-throw event (Pit–Mound) and repeated cycling of the tree throw (Pit–Mound–RI) at the end of the 1000-year simulation period (Table II). After the introduction of the Pit–Mound topography, erosion rates reduce for approximately 10–15 years then climb back to the average long-term rate (Figure 7). The addition of the Pit–Mound–Tree topography reduces erosion considerably both after the introduction of the Pit–Mound and Pit–Mound–Tree trunk and also over the long term to less than half that of the Pit–Mound topography only.

The addition of Pit–Mound and Pit–Mound–Tree trunk topography substantially altered the drainage network of the catchment from a hydrologically linked network to a series of incoherent links (Figure 8). These features introduced both pits (depressions in the DEM), which ultimately must be filled before sediment can pass downslope, raised points which are eroded or smoothed as well as provided a point of deposition upslope of the raised point and break hillslope connectivity. The

Table II. Erosion rates from the SIBERIA simulations.

Year interval	Baseline	Pit–Mound	Pit–Mound–Big	Pit–Mound 1:100	Pit–Mound–Tree 1:100
		One tree-throw event		Repeated events	
0–10	0.081	0.035	0.039	0.0004	0.045
0–1000	0.086	0.086	0.085	0.0809	0.028

The baseline data are for simulations without any disturbance by tree throw. The Pit–Mound and Pit–Mound–Big data are for a single tree-throw event with a 1 m × 1 m Pit–Mound and a 2 m × 2 m Pit–Mound, respectively. The Pit–Mound 1:100 and Pit–Mound–Tree 1:100 data represent a random 1:100 return interval for simulations with the Pit–Mound and Pit–Mound–Tree trunk simulations, respectively. The data are expressed in terms of average lowering across the catchment in mm year^{-1}.

inclusion of the tree trunk greatly enhances the points of deposition on the hillslopes and interruption of the drainage network. Figure 7 suggests that it takes approximately 10–20 years for these features to be removed and the drainage network to recover its integrity and connectivity.

Here we have assumed that the trunks have the same erodibility as that of soil. While this is not strictly correct, we have no data for the decay of fallen timber in this environment. This is a complex issue as fire has been recorded every second year which we have observed to completely remove fallen trees, leaving the pit–mound only. Termites also quickly remove both living and dead timber. Furthermore, all fallen timber is not always in full contact with the ground for the length of the trunk. However, the SIBERIA model has the ability to include such erodibility differences if data were available.

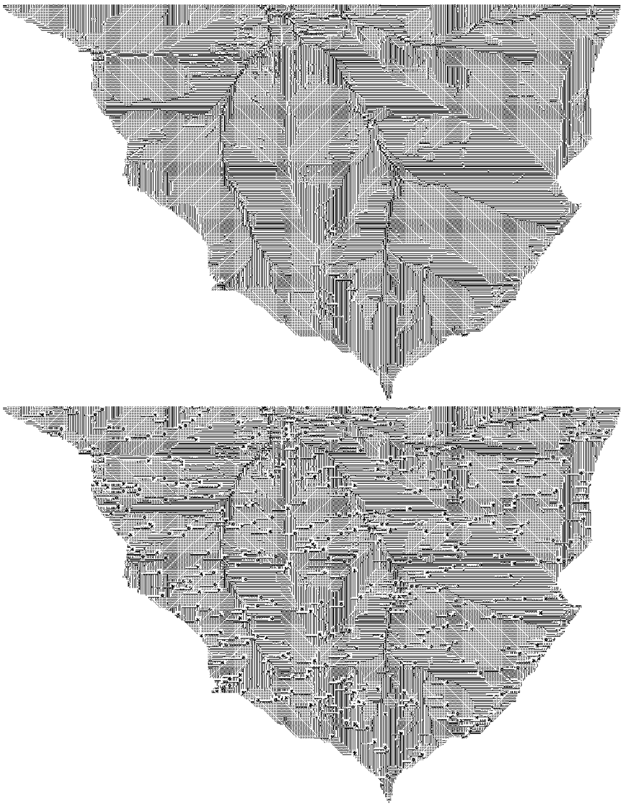


Figure 8. Drainage network with all depressions removed from the DEM (1 m × 1 m) without any tree throw (Baseline) (top) and after a tree-throw event with pits, mounds and tree trunk (Pit–Mound–Tree) randomly distributed. Only the top one third of the catchment is shown for clarity. Catchment outlet at the top of each image.

To test the effect of regular tree-throw events as opposed to a random RI, additional simulations were run with a tree-throw event at regular 100-year intervals. Interestingly, this produced very similar erosion rates to that of using a random RI over the 1000-year period.

There was no evidence in any of the simulations for the Pit–Mound or Pit–Mound–Tree trunk topography initiating any gullying. Nevertheless, gullying was produced by the SIBERIA model in the main drainage lines similar to what is observed in the catchment (Figure 9) (Hancock and Evans, 2006, 2010). This provides confidence in the model itself and its parameterization.

Running the simulation for 50 000 years, geomorphologically, the simulated catchments were little different from each other with measures such as the area–slope relationship (Hack, 1957; Flint, 1974), hypsometric curve and integral (Strahler, 1952), cumulative area distribution (Rodriguez-Iturbe *et al.*, 1992), width function (Surkan, 1968), optimal channel network (OCN) energy and network convergence (Rodriguez-Iturbe and Rinaldo, 1997) showing little difference between simulations. Other measures such as mean elevation show a slight reduction but are all very similar at completion of the simulation. This suggests an equifinality of final form and disturbance events such as tree throw have little impact on landscape evolution in this environment.

DISCUSSION

To our knowledge, this is the first examination of the effect of tree throw of soil erosion and long-term catchment evolution using a landscape evolution model. Our expectation going into the work (based on previous process work by Norman *et al.*, 1995; Clinton and Baker, 2000; Heimsath *et al.*, 2001 and others) was that tree throw would result in quantifiable increases in soil erosion and gullying over decadal and centennial time scales. Our expectation was that these sites of downed wood and their related exposed soil pits (as observed by Clinton and Baker, 2000) and subsequent bioturbation of the uprooted area (as observed by Paton *et al.*, 1995) would be nick points for erosional development. In terms of the post-tree throw, fire effects observed at the site, we expected some enhanced level of erosion based on previous field studies by Dragovich and Morris (2002)

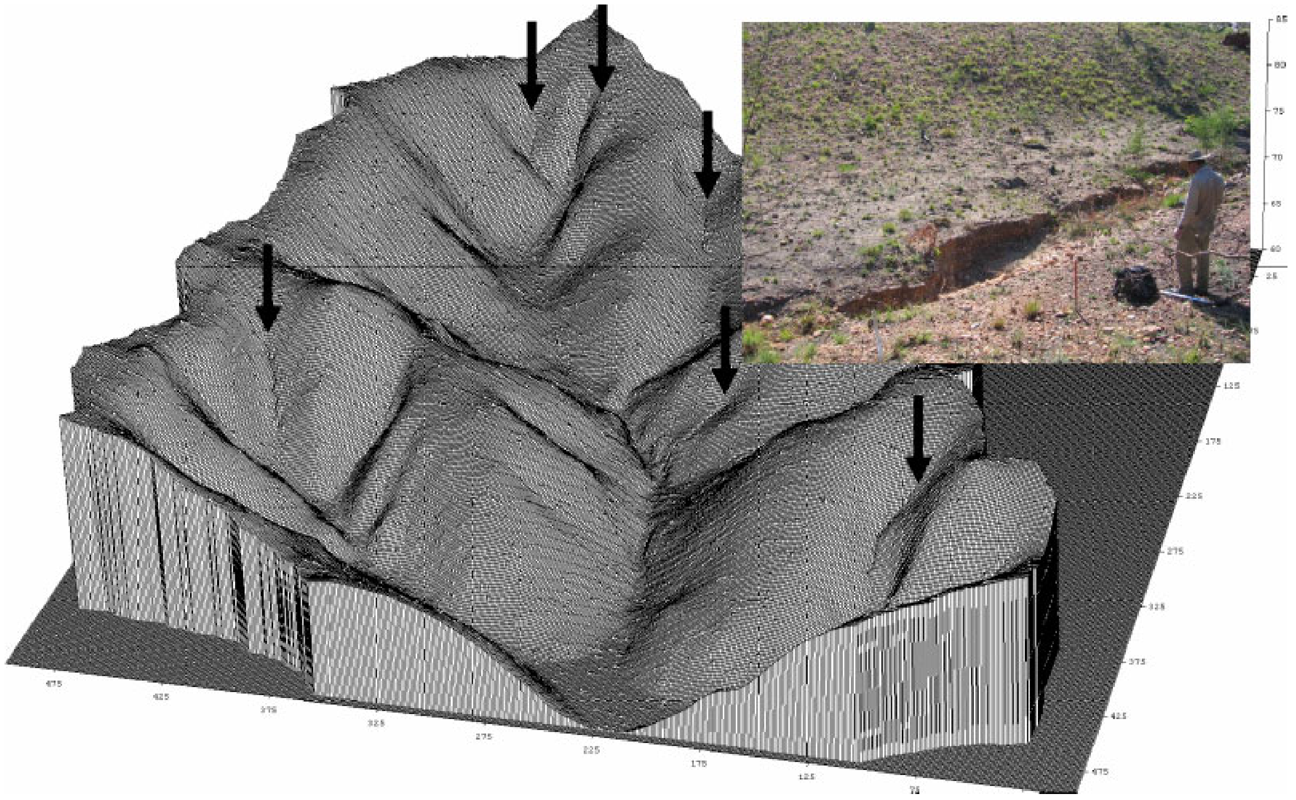


Figure 9. Digital elevation model of the Tin Camp Creek catchment with 0·5 m high pit and 0·5 m mounds and tree (Pit–Mound–Tree) trunk randomly distributed over the catchment after 25 years of erosion using the SIBERIA model. Incision within the first-order streams indicated by arrows with photograph of a typical incised stream (top right).

who examined sediment movement in a eucalypt forest after fire. Phillips and Marion (2006) suggest that not just tree throw but also displacement of soil by root and trunk growth have significant effects on soil development and surface evolution.

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To our surprise, the inclusion of Pit–Mound topography substantially reduced erosion for the first 10–15 years of its introduction (Figure 7). Adding Pit–Mound–Trunk topography reduced erosion rates even further. The Pit–Mound and Pit–Mound–Tree trunk acted as sediment traps, capturing sediment from upslope and storing it in place. Examination of the drainage network after disturbance by tree throw demonstrated a large incoherent network structure that must be wholly reintegrated across the entire catchment before sediment output can reach its pre-disturbance levels (Figure 8). Only after approximately 25 years, the majority of the Pit–Mound and Pit–Mound–Tree trunk topography had been removed from the surface (Figure 9).

The inclusion of the Pit–Mound–Tree trunk reduced erosion rates to approximately 0·03 mm year^{-1} (Table II) which is well within the range of regional denudation rates and soil production rates for the region. If it is assumed that soil production rates are equivalent to erosion rates then the model is predicting rates slightly greater than the long-term lowering of 0·02 mm year^{-1} when Pit–Mound–Tree trunk topography is included.

The SIBERIA model simulations predict average denudation rates for the catchment of approximately 0·08 mm year^{-1}. The erosion pins produce an average lowering of 0·052 mm year^{-1}. Both are within the range found using the ^{137}Cs method for the catchment and provide confidence in the model calibration and model results. While slightly elevated compared to regional denudation rates, the calibration of SIBERIA was done over a single wet season and therefore may not have been representative of the long-term rates. Nevertheless, the ^{137}Cs results provide an approximately 50-year average rate and therefore the SIBERIA predictions are reasonable.

Although the SIBERIA simulations predict slightly higher denudation rates, it is believed that the erosion processes and parameterization are reasonable. Examination of the stream lines in the simulated landscape demonstrates that small gully placement is consistent with the same scale of these features in the field (Hancock and Evans, 2006, 2010) (Figure 9). The ability to correctly capture gullies at a grid scale of 1 m suggests that the fluvial and diffusive erosion parameters used here are meaningful. For example, in our sensitivity analysis, adjusting diffusivity up slightly removed the gullying and ultimately results in a more smooth landscape while adjusting diffusivity down resulted in a more incised landscape.

Nevertheless, while the 3-year monitoring programme at the Tin Camp Creek catchment has not shown any influence of tree throw by cyclone Monica on erosion or deposition patterns or process, fallen trees are likely to play a role in retaining sediment in the catchment. A response may only be detected in later years or with pins directly positioned to detect differences pre- and post-cyclone. Unfortunately, we have no pins positioned for this. For trees fallen pre-cyclone, we have observed them acting as a sediment dam in the catchment (see Figure 10 where the tree pictured has captured a considerable amount of sediment). Therefore the finding that the SIBERIA model predicts a reduction in sediment when Pit–Mound–Tree trunk is included in the DEM is supported by field evidence.

It is unlikely that a large cyclone had caused damage in the catchment in the period 50–60 years prior to cyclone Monica as the vegetation assemblage in the catchment and region is believed to be mature. It is speculated that large cyclones have not occurred at a frequency higher than 1:50 years as the eucalypt vegetation is believed to have a life of 50–60 years when the tree succumbs to the cumulative effects of termite damage and fire. The size of the trees and the Pit–Mound topography is not therefore likely to be larger than that measured and distributed across the landscape here.

Interestingly, introducing Pit–Mound topography with a 2 m × 2 m pit and corresponding mound produced little difference over simulations using a 1 m × 1 m disturbance. A further simulation was run to examine the effects of increased cyclone RIs of 1:50 years. This produced results little different to that of the previously described data. This suggests that in this environment, disturbance at unrealistic time and space scales has little long-term effect on soil erosion and landscape evolution.

While temporally constant erosion parameters have been used here, the erosion pin data (Figure 6) suggest that the system is sensitive to climate forcing and that the erosion response is dynamic. Although there was an increase in erosion from 2008 to 2009, there was no visual evidence to support the development of significant erosion features such as gullying. The monitoring of the erosion pins and gullying in the catchment will continue (Hancock and Evans, 2010).

Figure 10. Fallen tree trunk in the base of a first-order stream showing damming of sediment upslope.

The simulations including the tree trunks all assumed that the trunk was flush with the ground surface. Field observation showed that only a few had trunks contacting the ground for their entire length with majority having points of contact with the ground at the base and also on a tree limb near the crown. The nonlinearity of the ground surface and bowing of the tree trunk all prevented a continuous contact along the trunk. Hence the simulations employing a tree trunk completely flush with the ground are likely to provide an overestimation of the reduction in erosion rates.

Nevertheless, there is field evidence to support the finding that tree throw acts as a sediment trap (Figure 10). The reality is likely to be somewhere in between that of just Pit–Mound and Pit–Mound–Tree trunk topography. The continued field monitoring of fallen trees and erosion in the Tin Camp Creek catchment will provide information on this over the longer term (Hancock and Evans, 2010).

Management implications

In the Alligator Rivers Region, there are several former and one operating uranium mine. There is also the potential for several others, all of which will need to be rehabilitated for long-term environmental sustainability. Our findings are useful for sites such as mines where vegetation is part of the post-mine rehabilitation.

This work here suggests that any tree throw is unlikely to result in landscape instability over decadal to centennial time scales. It should be recognized though that the natural catchment examined here is very different to that of post-mining landscapes where there in no bedrock impeding the movement of tree roots, therefore allowing roots to penetrate deeper. Geochemically, the mine waste and resultant soil is likely to be different to that of the natural environment so different tree species and densities may evolve (Phillips and Marion, 2006). It is possible that large trees unimpeded by bedrock may have deeper roots and grow to a larger size therefore producing a different erosional environment when subject to wind throw by resulting in larger pits and mounds. Caution should be used in the direct transfer of these findings from that of a natural setting to that of a post-mining catchment. Phillips *et al.* (2008) have suggested a close coupling of the co-evolution of geomorphological systems therefore different findings may results in different soil environments.

CONCLUSION

Our findings are the first that we are aware of to use a landscape evolution model to investigate the ecohydrological controls on soil erosion and landscape evolution. While catastrophic on human time scales and for human environmental management, the cyclonic events studied are part of the natural cycle of events in Australia. The present landscape has been shaped by such events over time and has evolved according to the frequency of such events. Therefore the finding that Pit–Mound topography has little effect on sediment transport rates and overall landscape evolution is not surprising. The findings also demonstrate how loss of hillslope connectivity can affect sediment transport.

Therefore in this environment, tree throw is postulated to have little if any substantial effect on sediment transport and landscape evolution. The model results suggest that in this environment tree throw may actually reduce erosion rates. Caution should be used here though as the site is located in the monsoonal tropics conditions with unique soils, vegetation and landscape management encompassing a regular fire regime. Furthermore, the trees are not large in size by temperate climate mid-latitude standards, therefore the transferability of these findings should be viewed with caution.

The methods and approach used here demonstrate how a DEM-based model can be used to examine ecohydrological processes. The results also show that such an approach can be used to assess nonlinear systems influenced by both auto and exogenic forcings. The methods here also demonstrate how different climate scenarios as expressed as cyclone RIs can be examined on the catchment scale to better understand geomorphic systems.

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