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Catchment-wide soil loss from pre-agricultural times to the present: transport- and supply-limitation of erosion

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Abstract

A high-resolution record of catchment-wide soil loss for the period c. 1806–1990 has been obtained from Little Llangothlin Lagoon on the New England Tablelands of northeast New South Wales, Australia. The mean annual rate of mineral erosion since the time of European contact in the late 1830s was 269 t km^{-2}. The mean rate of mineral denudation immediately prior to this was 25 t $\mathrm{km}^{-2}\mathrm{a}^{-1}$. In the 25 years after the arrival of the first sheep in the catchment, erosion rates increased by a factor of over 50 to 1360 t $\mathrm{km}^{-2}\mathrm{a}^{-1}$. After c. 1861, however, there was an apparently sharp transition to a new, low and very constant rate of denudation, 52 t $\mathrm{km}^{-2}\mathrm{a}^{-1}$. Eighty-five percent of post-contact erosion thus occurred in the first quarter of a century of European land use.

The low and constant erosion rates of the last century or more cannot be attributed to stable environmental conditions, to a decrease in land use intensity or to the introduction of soil conservation measures. Instead, it is possible that early colonial erosion almost entirely depleted the catchment of erodible material with the result that erosion moved from a transport-controlled regime to one that was limited by the rate at which catchment material was made available for transport by weathering. Alternatively, the high, early colonial rates of erosion may have been associated with the extension and deepening of the drainage net during the initial phase of European contact. The subsequent establishment of a new drainage net equilibrium may have reduced soil loss to a low and stable level.

Much of the evidence available to test these competing hypotheses is equivocal. Nevertheless, the gullying model must be rejected, first because there is no evidence of past or present dissection of the catchment surface, second because gullying would seem incapable of providing the highly constant rate of sedimentation that has prevailed in the basin over the past century or more and third because the gullying model cannot explain the step change from high to low rates of sedimentation in the basin. Further support for the supply-limitation hypothesis comes from the concordance between likely rates of soil formation in the catchment and rates of sedimentation in the lagoon.

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These conclusions have implications for our cognisance of the role of supply-limitation in geomorphological processes, for soil conservation practice and for our understanding of the long-term impacts of agriculture on soil erosional systems.

Keywords: Australia; Soil erosion; Agriculture; Supply-limitation of erosion; Pre-European; Post-contact

1. Introduction

An understanding of the causes of soil erosion and a knowledge of those land use practices that allow the maintenance and survival of particular soils are essential for the sustainability of agricultural systems worldwide. Most attempts to obtain the information necessary to tackle these issues have involved the investigation of soil loss over limited areas, such as small test plots, and over short time spans. This work has four main drawbacks. First, it is difficult to judge the long-term effects of land use practices (and changes in land use practices) on soil loss. Second, it is hard to evaluate the impacts of secular environmental variation, to establish the antecedents of modern problems, to calculate trends and rates of change, and to establish the lag times between catchment modification and catchment response. Third, short-term measurements tend to miss the impact of rare, high-magnitude events such as major floods and droughts or, if they are fortunate enough to monitor such events, are not able to place their impact in the context of the long timescale. This means that it is difficult to obtain information on long-term responses and recoveries. Fourth, by making studies at the local or microscale, it is not always easy to extrapolate soil losses across entire catchments, particularly as such studies are often made of sites that are experiencing rapid rates of erosion or that are otherwise special for some reason. As a result of all this, it is difficult to establish relationships between erosion and productivity, to test erosion models and to suggest what restrictions to land use are necessary to minimise soil losses.

An approach that potentially overcomes one of these problems is to measure stream sediment loads and thus to determine catchment-wide rates of fluvial erosion in the upstream basin. Unfortunately, only a proportion of the material eroded in a drainage basin will find its way to the basin outlet, and the estimation of the size of that proportion is beset with difficulties (Walling, 1983). In addition, the amount of sediment transported out of a basin may reflect past erosion and sediment delivery processes rather than current activities; in other words, there may be a lag between erosional cause and sediment-yield effect.

An alternative approach involves investigating soil loss from catchments that drain into enclosed basins. These basins act as sediment traps in which the products of denudation throughout the entire catchment may accumulate over long time spans. Examination of the resultant sediments enables the investigation of the behaviour of systems over timescales longer than that allowed by direct observation. The deposits may reveal the amount of material lost from the surrounding catchment over time, may provide a comparison between agricultural and pre-agricultural rates of denudation, may show the effects of natural events of given magnitude on overall rates of denudation and may reveal the impact of changes in land use on rates of soil loss.

Although this approach has been used relatively widely in the last decade, several practical problems have limited its usefulness. First, it is essential that the results of sediment-based environmental reconstruction are placed in a high-resolution dating framework. The most appropriate technique given the timescales involved is ^{210}Pb analysis. But, because the dating range of this technique is limited to 150–200 years, in most situations this fails to cover the full span of agricultural impact on the environment. Yet the initial impacts of agriculture may have had a critical effect on the landscape and may have dictated the nature of subsequent soil loss and land degradation. Second, the restricted dating range of ^{210}Pb methods means that information on pre-agricultural conditions is often unobtainable. It may thus be impossible to establish a pre-agricultural control against which to judge the impacts of agricultural activity.

One location where these difficulties may be overcome is Australia. In most parts of the continent, the earliest agricultural impact took place well within the range of ^{210}Pb dating. In such circumstances, it is possible to obtain not only a continuous record of soil erosion from the time the first sod was turned or the first stock were grazed, but also a record of conditions prior to farming. Moreover, because early agriculture in Australia took place within the context of a fully literate society, written records of land use histories and environmental events may be used to calibrate and interpret the depositional record.

We report here a high-resolution record of soil erosion from eastern Australia extending back several decades beyond the earliest agricultural impact on the land. This study has implications for our understanding of the mechanisms of soil erosion, for efforts to minimise soil erosion and, more broadly, for research on the behaviour of geomorphic systems.

The aim of the study is to provide answers to the following questions:

(i) What has been the impact of European land use on soil loss?
(ii) How have rates of soil loss under conditions of European land use varied over time?
(iii) What factors control rates of soil erosion? Specifically, what effect have different land uses and changes in land use had on long-term rates of soil erosion, and how have high-magnitude natural events, such as floods and droughts, affected denudation?

2. The study area

This work has been undertaken on the New England Tablelands of northeast New South Wales (Fig. 1). New England is one of Australia's major agricultural areas. Fifteen percent of New South Wales' sheep and 26% of its cattle are grazed in the area, and the region contains 20% of the state's cropped area (Burnett and Raskov, 1997). Yet it is a region that has suffered gravely from soil erosion. Over 80% of the region's rural land requires treatment for degradation, and the area is one of the worst affected by sheet erosion in Australia (Woods, 1984). The region is therefore one in which soil loss is of critical significance and in which studies to pinpoint the causes and consequences of soil erosion are of immense importance.

New England possesses a series of internally draining lake basins, known locally as lagoons. Most of these have remained hydrologically active over the last century or more and thus provide ideal sites in which to use lake sediments as a means of reconstructing records of soil loss over time. We have recorded in excess of 50 lagoons on the central and southern part of the Tablelands alone (Fig. 1). The sediments trapped in several of these have been studied (Haworth, 1994; Gale et al., 1995, 2004; Haworth et al., 1999; Gale and Haworth, 2002). The longest and most complete record comes from Little Llangothlin Lagoon (Fig. 1), and it is that record that is considered here.

Little Llangothlin Lagoon lies 18 km northeast by north of Guyra at an altitude of 1360 m and is one of a cluster of lagoons located close to the highest part of the Tablelands. The catchment is largely composed of basalt, although the underlying granite is exposed along the northern divide. The lagoon is dammed by a kilometre-long sand lunette on its eastern side. The lake has no natural outlet and consequently acts as an efficient trap for material mobilised on the catchment surrounds (Fig. 2).

The lagoon covers an area of 1.17 km^2, with a catchment area of 3.23 km^2. The small size of the catchment and the short hillslopes leading to the lake mean that transport routes between the slopes, the channels and the basin are few and short. This minimises the potential for sediment storage on the catchment slopes and means that sedimentation in the lake is likely to take place relatively rapidly after the occurrence of erosion on the catchment. The sedimentary record therefore probably represents a near-complete and near-instantaneous response to events in the catchment area. Rates of wind erosion and deposition in the area are negligible (Woods, 1984; McTainsh and Pitblado, 1987) and this has probably been the case since the time of European settlement. The depositional record in the lagoon is thus likely to reflect water-borne sediment transport.

The annual average rainfall at Braeside, 5 km to the north of the lagoon, is 1051 mm (White, 1986). Unfortunately, this record covers only 15 years and so does not provide a picture of secular variations in climate. The three stations on the Tablelands within a 40 km radius of the lake (Guyra, Glen Innes and Wandsworth) display similar trends over the last century, suggesting that they are all influenced by the same rainfall regime (Haworth, 1994). Significantly, the records from Armidale, 50 km to the south, which extend back to 1857, also follow the same pattern. The Armidale record may thus be cautiously used as an index of rainfall variation across the central part of the Tablelands for the past 140 years.

3. The history of land use in the catchment

Little is known of pre-European land use in the catchment. The conventional account is that the

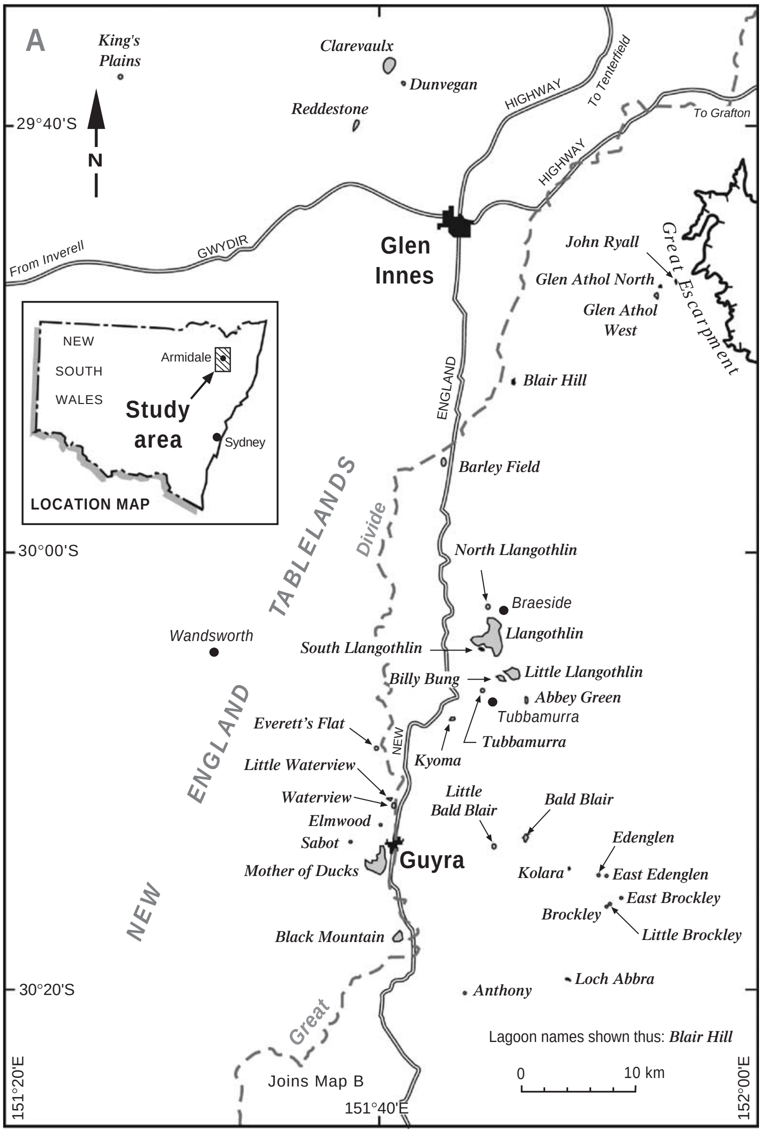

Fig. 1. The (A) central and (B) southern parts of the New England Tablelands of northeast New South Wales showing the location of internally-draining lakes and wetlands.

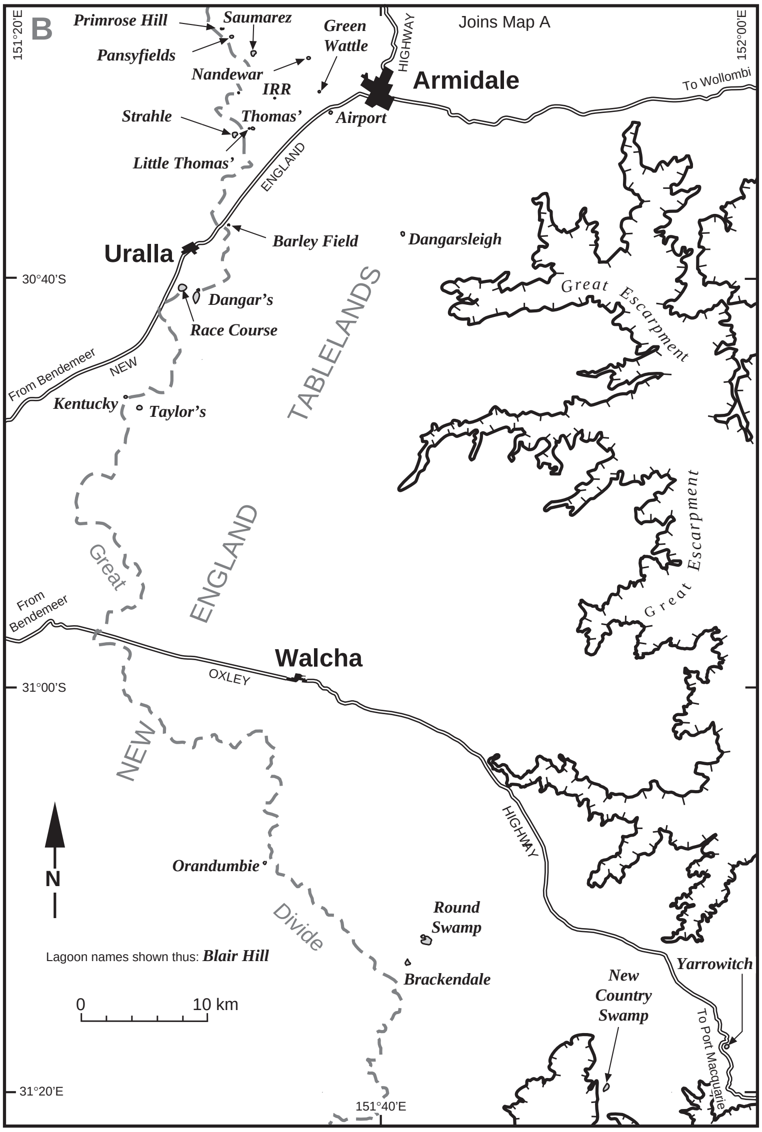

Fig. 1 (*continued*).

Aboriginal population of the Tablelands was very low (Macdonald, 1842; Markham, 1851) and that conditions here were too harsh to support a dense population (McBryde, 1974, 1976, 1977; Belshaw, 1978). However, scatters of artefacts can be found in the catchment, particularly around the lunette (Davidson, 1982; Gale, unpublished observations), and it seems unlikely that the concentration of resources represented by this and other lagoons would not have been intensively exploited by Aborigines (Godwin, 1990).

The history of colonial land use in the catchment is reviewed by Gale et al. (1995) and Gale and Haworth (2002) and is summarised here. Although there is some evidence of earlier European contact, the environmental impacts of this were limited and the documentary tradition is that the Llangothlin run was first taken up by Thomas Perry in 1837. Perry left

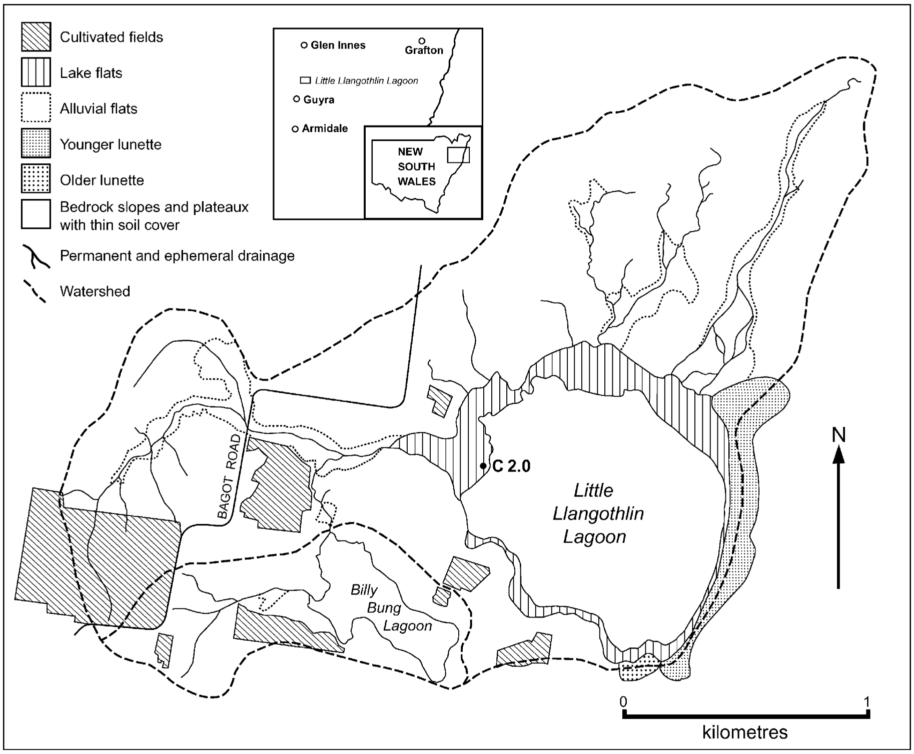

Fig. 2. The catchment of Little Llangothlin Lagoon, Guyra, northeast New South Wales. Mapping based on field surveys and 1984 aerial photographs.

Llangothlin in the early 1840s, and the station appears to have been owned first by Arthur Maister, who went bankrupt in 1844, and subsequently by William Rawson, who occupied the run until at least 1847. The squatterage was taken up by Charles Codrington sometime between 1847 and 1851, from whom it was purchased by Thomas Bagot in 1861.

The first squatters ran sheep on the property. By 1845, Rawson grazed 4000 sheep on 20 000 ha. The flock had increased to 5000 by June 1846 and to 6000 by November of the same year. Cattle were also run on the catchment, although the earliest known reference to this is from 1848. During Bagot's ownership, however, the property was run largely as a cattle station and about 7000 head of cattle were depastured on the run in 1877 (Wanderer, 1877). Apart from this, little is known of stocking rates on the property. In 1848, however, each sheep grazed an average of 1.79 ha throughout New England as a whole. This had fallen to 1.37 ha in 1857, to 0.8 ha in 1884 and to between 0.4 and 0.6 ha in 1891–1892. Cattle stocking rates increased similarly, from one animal per 17 ha in 1848 to one per 6 ha in 1884.

The Crown Lands Alienation and Crown Lands Occupation Acts were enacted in 1861 and significantly amended in 1875. One aim of these was to promote closer settlement of rural lands. Nevertheless, the legislation appears to have had little impact on the catchment of Little Llangothlin Lagoon until late in the century. By 1878, only 445 of the original 20 000 ha of pastoral lease had been alienated and Bagot himself appears to have owned most of these. However, Bagot went bankrupt in 1879 (Anon, 1879; Walker, 1963), and the subdivision plans of 1895–1898 show the catchment beginning to be divided into a series of blocks, usually of 16 ha. Throughout New England, closer settlement in the later decades of the nineteenth century was associated with wholesale ringbarking, clearing and general tree destruction (McElhone, 1881; Campbell, 1907). The numbers living in the catchment must have increased significantly during this period, although figures are hard to come by. One measure comes from the population of the village of Tubbamurra, which lies just outside the catchment. Tubbamurra was a product of the late nineteenth century subdivision of rural land. First mentioned in the postal records of 1896–1897 and listed as containing 14 households in 1898–1899, it had increased to 32 households by 1916. By the 1940s, the number of households had fallen to between 20 and 22 (Anon, 1896–1897 to 1950). Numbers have diminished since then to the present total of four. It is probable that subdivision was associated with an increase in the area of the catchment under crops. The sale of seed potatoes was a profitable business on the Tablelands as early as 1852 (Norton, 1903), and it is likely that potatoes were amongst the first crops grown by the smallholders. By 1920, 22 ha of the Ben Lomond estate (as Llangothlin had become known) were under potatoes (Sommerlad, 1922) and the crop is still grown today in the western part of the catchment. The area was also affected by the nationwide rabbit plague of the late nineteenth and early twentieth centuries. Although they did not reach the area until the turn of the century (Cameron, 1975), rabbits became a serious pest from 1909 (Johnson and Jarman, 1975), with numbers apparently peaking in the 1920s (Cameron, 1975).

By 1910, much of the western part of the catchment had been consolidated into a single dairy farm, which was further enlarged over the succeeding decades (C. Looker, Guyra Branch, New South Wales Farmers' Association, 1991, personal communication). Today, only a single household remains in the catchment.

In 1942, the Navy Bean Board was formed in Guyra to supply navy beans, mainly for United States troops. A cannery was built in the town and much of the land in the catchment was taken up to supply it with beans. Special farm machinery was purchased for the project from Lend Lease funds and aerial photographs taken in 1943 show large parts of the catchment under crops.

Shortage of manpower during the second world war resulted in an increase in the mechanisation of farms in the district, although fuel was rationed and charcoal gas was used extensively. Nevertheless, even after the war, farm machinery remained in short supply in the region. During the 1950s, however, the number of tractors on the Tablelands increased dramatically, reaching a maximum by the early 1960s. Phosphatic fertilisers also began to be applied to pastures, particularly after 1950, when the first aerial application of superphosphate undertaken in Australia occurred at Walcha, 100 km south of the lagoon.

In 1979, the lagoon was gazetted as a Nature Reserve and agricultural activities around the lake were gradually wound down until 1989, when the grazing lease on the lagoon finally expired. The western parts of the catchment are still farmed, however, mainly for potatoes.

4. Methods

In order to determine the quantity of sediment trapped in the lake basin over given periods of time, more than 50 cores were taken from 37 stations across Little Llangothlin Lagoon. Sampling was based on a 200-m grid aligned along the main axis of the lake, although several cores from intermediate sites were also taken in areas of particular interest. With one exception, all the cores were taken using 50-mm diameter plastic tubing. This allowed the measurement of downcore variations in volume-specific magnetic susceptibility to be made without extruding the cores from their sleeves. Measurements were taken at 20-mm intervals down each core following procedures similar to those described by Gale and Hoare (1991). Using this information, it has proved possible to trace stratigraphic features across the entire lake basin (Fig. 3). Since sediment stratigraphies could be correlated across the entire area of the basin, only a single site needed to be studied in detail. The longest and highest resolution record came from site C2.0, located on the distal edge of the delta formed by the largest stream flowing into the basin (Fig. 2), and this was therefore chosen as the site of the master cores. In order to obtain sufficient material for analysis, two cores were taken from within 2 m of each other at this site. The original 50-mm diameter core was subsampled at 20- or 40-mm intervals following the procedures outlined by Gale et al. (1995). Loss on ignition, low-field mass-specific magnetic susceptibility and frequency-dependent magnetic susceptibility were measured on each sample following the methods described by Gale

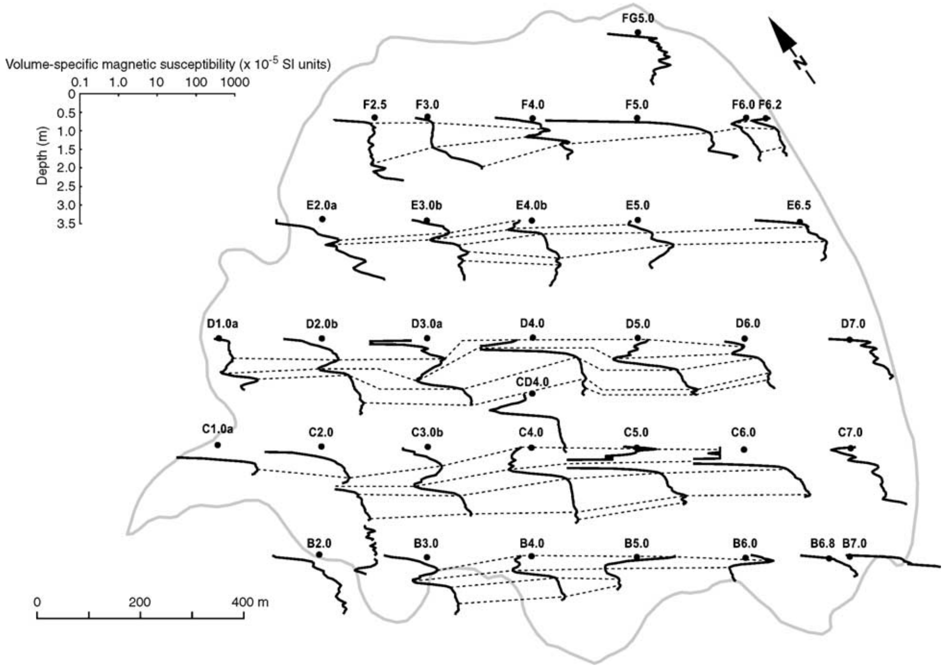

Fig. 3. The correlation of stratigraphic features in the sediments of Little Llangothlin Lagoon, Guyra, northeast New South Wales on the basis of measurements of volume-specific magnetic susceptibility made on cores taken from the basin. The magnetic susceptibility signal of several of the marginal cores cannot be tied in to those in the rest of the basin. It is likely that this is because of the exposure of these sites at times of low lake levels, resulting in phases of non-deposition and the modification of the susceptibility signal as a result of weathering.

and Hoare (1991). A second core, of 90-mm diameter, was subsampled at 40-mm intervals using the same procedures. Dry bulk density, loss on ignition, mineral bulk density and unsupported ^{210}Pb activity were determined on each sample as described by Gale et al. (1995). The two cores were correlated by comparison of downcore measurements of mass magnetic susceptibility and loss on ignition (Gale et al., 1995).

The results of the ^{210}Pb analysis were used to construct a high-resolution chronology for core C2.0, dating back over 180 years. This record was successfully checked and calibrated using palynological and geochemical indicators of well-dated historical events in the catchment (Gale et al., 1995).

5. Rates of lake sedimentation and catchment denudation

The ^{210}Pb date of 1836±7 on the master core corresponds with a major change in the magnetic susceptibility of the lake sediments. This coincides with the official date of arrival of Europeans in the catchment in 1837. The corresponding magnetostratigraphic feature, which can be traced clearly right across the lagoon, may thus be used as a marker to enable the depth of sediment laid down in the basin since the time of European settlement to be determined (Fig. 4). The pattern is one of largely fluvial input, with deltaic accumulations around the mouths of the inlet streams and over a metre of sediment deposited on the proximal parts of the deltas.

The total volume of sediment laid down in the basin since 1837 is 657 000 m^3. Extrapolating from the measurements of mineral bulk density made on the 90-mm core (that is, measurements that ignore the contribution of plant organic matter to the sediments), the total mass of mineral matter deposited in the lagoon basin since European contact is 134 000 t. This procedure adopts the conservative assumption that the plant organic content of the sediments is entirely the product of vegetative growth in the lake itself and does not represent material eroded into the lake basin. Observation of

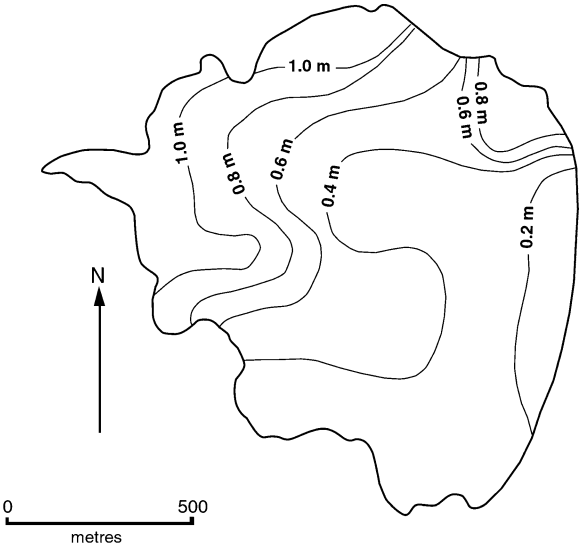

Fig. 4. The depth of sediment deposited in Little Llangothlin Lagoon, Guyra, northeast New South Wales since European contact.

the modern lake indicates that this assessment is likely to be correct.

Measures of lake sedimentation can be used to obtain a crude measure of catchment denudation. This requires the assumption that all the material eroded from the catchment is transported to the lake basin. In the case of Little Llangothlin with its short, steep catchment slopes and lack of sediment stores on the catchment sides, this assessment is probably not unreasonable. Nevertheless, this procedure almost certainly underestimates erosion since a small proportion of eroded material is likely to be stored on the catchment sides.

A minimum minerogenic denudation rate of 41 500 t km^{-2} across the catchment may thus be estimated. This is equivalent to a mean annual mineral loss of at least 269 t km^{-2} for the period since European settlement. To place this figure in context, it may be compared with modern sediment yields. The rate lies at the top end of yields from catchments throughout New South Wales (Olive and Walker, 1982; Olive and Rieger, 1986). However, perhaps the best comparison is with the large data set of modern sediment yields from the uplands of southeastern Australia assembled by Wasson (1994). The mean post-contact minerogenic denudation rate at Little Llangothlin is an order of magnitude greater than the mean rate for a catchment of this size (although it still lies within the extreme range of values recorded). Part of the explanation for this difference may lie with the inefficient delivery of sediment from fluvial basins, which underestimates the amount of erosion occurring, although there is no evidence from Wasson's results that hillslope plots display systematically higher yields than those from river basins.

Although of interest, this crude estimate of mean annual erosion rates over a period of more than 150 years fails to provide the information necessary for answering the questions posed in Section 1. A means of obtaining more detailed data is to use the high-resolution chronological record from site C2.0. The similarity of the susceptibility plots from sites across the basin demonstrates that a similar pattern of deposition was experienced right across the lagoon (Fig. 3). The pattern of deposition at C2.0 is thus unlikely to be a consequence simply of localised sedimentation and must instead reflect the operation of catchment-wide erosional processes. The chronology from site C2.0 therefore allows basin-wide variations in the accumulation of mineral matter over time to be determined (Fig. 5). These reveal three distinct episodes of sedimentation:

(i) A pre-European episode (c. 1806–1836) characterised by a mean basin-wide minerogenic sedimentation rate of 70 t $km^{-2}a^{-1}$. On the basis of the assumptions made above, this is equivalent to a minimum minerogenic erosion rate of 25 t $km^{-2}a^{-1}$.

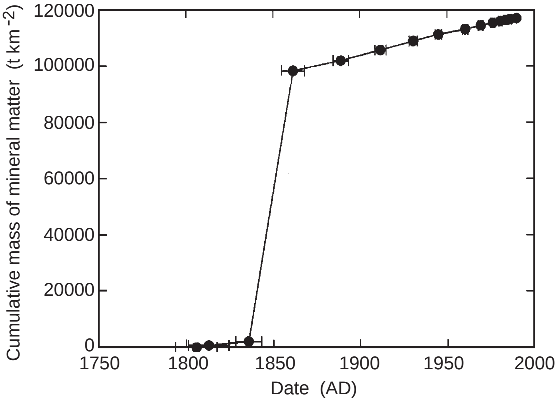

Fig. 5. The cumulative mass of mineral matter laid down in the basin of Little Llangothlin Lagoon, Guyra, northeast New South Wales in the period c. 1806–1990.

(ii) An immediate post-contact episode (c. 1836–1861) characterised by a mean basin-wide minerogenic sedimentation rate of 3770 t $\text{km}^{-2}\text{a}^{-1}$, equivalent to a minimum minerogenic erosion rate of 1360 t $\text{km}^{-2}\text{a}^{-1}$.

(iii) The period from the middle of the nineteenth century onwards (c. 1861–1990) characterised by a mean basin-wide minerogenic sedimentation rate of 145 t $\text{km}^{-2}\text{a}^{-1}$, equivalent to a minimum minerogenic erosion rate of 52 t $\text{km}^{-2}\text{a}^{-1}$.

The high-resolution chronology reveals a dramatically different pattern to that of the mean situation for the last 150 years. First, sedimentation rates increased by a factor of 50 within a year or two of European settlement in the catchment. The impact of hard-hooved stock, the clearance of tree cover, the cultivation of home paddocks and the alteration of drainage patterns must all have contributed to a massive increase in catchment-wide soil loss and lake sedimentation. Almost 85% of post-contact sedimentation took place in the first quarter of a century of European land use.

Equally dramatic, however, is the sharp drop in sedimentation rates that occurred in the second half of the nineteenth century. Not only are these rates of the same magnitude as those that prevailed prior to the arrival of Europeans at the site, but they are remarkably constant over time, being maintained right up to the present day. The minimum minerogenic erosion rate in the catchment for the period c. 1861–1990 is 52 t $\text{km}^{-2}\text{a}^{-1}$. This is comparable with modern and recent rates recorded for catchments of this size throughout upland southeast Australia (Wasson, 1994).

One explanation for the change to low and constant sedimentation rates could be that the period since 1861 has been characterised by stable environmental conditions and by few climatic extremes. There is little evidence of this, however. Cornish (1977) identified an abrupt increase of almost 20% in summer rainfall on the Tablelands after 1945, for example, and Pittock (1975) noted a major increase in annual rainfall totals after 1945–1946 over much of eastern Australia. Kraus (1955) showed that annual rainfall along the eastern edge of the continent decreased at the end of the nineteenth century, increasing again after 1945, and Deacon (1953) and Gentilli (1971) demonstrated that mean annual rainfalls decreased by 50–75 mm on the Tablelands between 1881–1910 and 1911–1940. Detailed analysis of New England rainfall records reveals a positive residual mass balance from at least the middle of the nineteenth century until around 1895. This was followed by a negative balance until 1947 and a positive balance since then (Foley, 1957).

A similar pattern is revealed by a study of runoff records. The rivers of the northern part of the state experienced a shift from a drought-dominated regime in the first part of the twentieth century to a flood-dominated regime after the mid-late 1940s, and there is evidence that flood-dominated conditions prevailed from 1857 until the end of the nineteenth century (Erskine and Warner, 1988; Riley, 1988). In the absence of long records of runoff, the record of precipitation from Armidale may be used to provide a measure of streamflow across the New England Tablelands. Clusters of very wet months are likely to be associated with moderate to severe flooding. Following Page and Carden (1998), those months receiving >150 mm and >200 mm of rainfall are plotted on Fig. 6. This reveals marked variations in precipitation, with concentrations of high monthly rainfalls occurring in 1861–1866, 1887–1897, 1947–1959 and 1970–1978. This pattern is more complex than but broadly in accord with the alternation of flood- and drought-dominated regimes identified elsewhere, indicating that similar regime shifts may have been experienced right across the northern part of the state (see also Brizga et al., 1993). Such oscillations in runoff suggest that environmental stability is unlikely to be the explanation of the highly constant rates of sedimentation experienced in Little Llangothlin Lagoon since 1861.

A second explanation for the low and stable rates of soil loss could be that the intensity of land use declined markedly in the period after c. 1861. There is little support for this thesis, however. Indeed, stocking rates in the region continued to climb, widespread and intensive cultivation of the catchment began, and the density of the population on the land increased up until the first world war.

A third possibility is that the reduction in rates of soil erosion was the consequence of the introduction

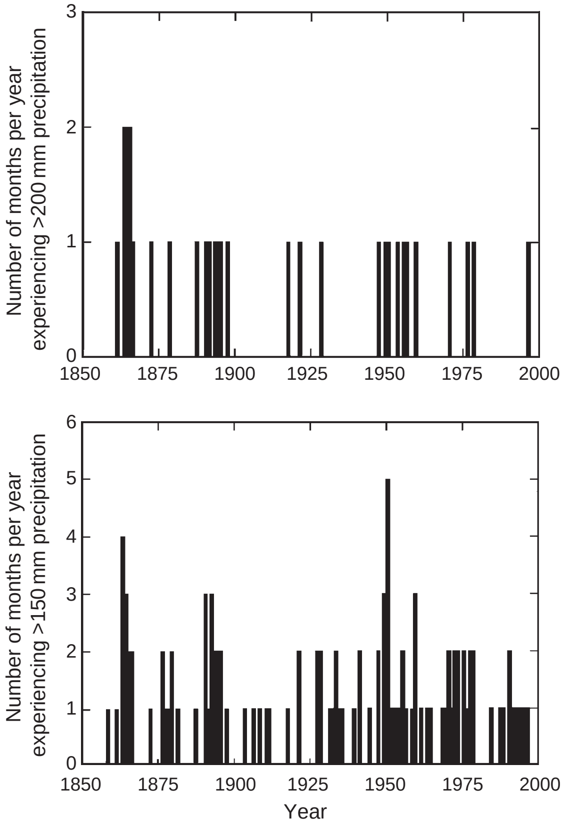

Fig. 6. The incidence of high precipitation monthly rainfall at Armidale, northeast New South Wales, 1857–1996. Clusters of very wet months are likely to provide a surrogate for moderate to severe flood events. Note that there are no data for the years 1867–1870 and that the data for the years 1857, 1860, 1871 and 1877 are incomplete.

of soil conservation measures during the second half of the nineteenth century. In fact, clearance occurred apace during this period. From the 1840s to the early 1900s, the principal means of improving pastures were ringbarking, draining and burning, and it was not until the twentieth century that more enlightened methods of pasture improvement began to be used (Wright, 1964).

Two other hypotheses for the changing pattern of soil erosion over time are worthy of more detailed consideration. First, sedimentation in the lake may have moved from a transport-controlled regime, in which the amount of material eroded from the catchment surface depended on the activity of erosional and transporting mechanisms, to one in which sedimentation was limited by the rate at which catchment material was made available for transport into the lake. Second, the high, early colonial rates of erosion may have been associated with the extension and deepening of the drainage net during the initial phase of European contact. The subsequent establishment of a new drainage net equilibrium may have reduced soil loss to a low and stable level. These hypotheses are considered in the following sections.

6. Transport- and supply-limitation of erosion

The phenomenon of supply-limitation, whereby the quantity of material available for erosion is dictated by the rate at which Earth materials are broken down by weathering (Gilbert, 1877), may provide an explanation for the record of sediment yield at Little Llangothlin. The basin experienced a high rate of deposition in the decades immediately after initial catchment disturbance, followed by over a century of significantly lower and highly constant sedimentation. The initial disturbance may have depleted the catchment of transportable material with the result that subsequent erosion has been controlled, not by the processes of erosion and transport, but by the rate at which erodible material is being produced on the catchment slopes by weathering and/or pedogenesis.

There is a range of mechanisms that may have driven these processes. In particular, the arrival of hard-hooved domestic herbivores may have resulted in overgrazing and soil compaction, causing falling infiltration capacities, greater runoff and enhanced erosion (Gale, 2003). The loss of the more erodible topsoils may have reduced rates of erosion until a self-limiting balance was achieved between the availability of surface material for detachment by erosion and the rate at which new material for erosion is formed at the base of the soil. In such a situation, the availability of detachable material at the surface is dependent on the availability of weatherable material immediately below the surface that may be modified into a form suitable for erosion, and ultimately on the availability of material at the base of the profile being weathered from the substrate.

7. Drainage net extension

An alternative hypothesis is that compaction of the ground surface by hard-hooved stock, the digging of drainage channels and the clearance of vegetation during the initial phase of European contact would have increased overland flow and encouraged gully development. Rapid extension and deepening of the drainage net would have resulted in high rates of erosion in the catchment. Within a short period, however, the drainage net would have established a new equilibrium in which the gullies transported only that material eroded from their beds and walls. As a result, erosion would have declined to a low and relatively constant level.

Studies of drainage net development throw some light on the processes involved here and the rates at which they operate. Morisawa (1964) showed that some of the channels developed on a newly uplifted lake floor reached a steady-state planform within two years, although it is not clear from her text whether cross-sections also remained stable after this time. Graf (1977) demonstrated that the length of newly-formed gullies increases in a negative exponential fashion; that is, there is an early phase of rapid enlargement that becomes progressively slower as the system approaches a steady state. In his examples, the half-life of gully enlargement was 15–19 years, comparable with the timescales required were the model to be applied to Little Llangothlin. Finally, very similar patterns of negative exponential growth have been noted in hardware models of drainage network extension (Schumm et al., 1987).

Support for the drainage net extension hypothesis comes from southeast Australian studies that argue that the initiation of gullying frequently occurred shortly after the arrival of Europeans in a catchment. The rate of change of cross-section shapes and depths slowed in the twentieth century, reaching a new equilibrium state, with the result that the channels have become less significant sources of sediment (see, for example, Eyles, 1977; Starr, 1989; Prosser, 1991; Srikanthan and Wasson, 1993; Wasson et al., 1998). This may explain, for example, the declining sedimentation rate in Burrinjuck Reservoir in southeast New South Wales after 1954 (Wasson and Clark, 1985; Wasson et al., 1987).

Other work has demonstrated that, in the absence of major catchment destabilisation, erosion in gullied catchments is limited to the gullies themselves (see, for example, Starr, 1989; Olley et al., 1993; Wasson, 1994). This has been quantified by Wallbrink et al. (1996) who showed that >90% of the suspended sediment load of the Murrumbidgee River in southeast Australia comes from gully and channel erosion rather than sheet or rill erosion. Similarly, Wasson et al. (1998), from evidence obtained from a number of catchments on the Southern Tablelands of New South Wales, estimated that only about 2–5% of the sediment that reached the channels came from sheet and rill erosion of hillslopes; the remainder came from channel incision and bank erosion. The implication of this research is thus that in catchments with stable gully systems, erosion will be restricted to the gullies themselves and sediment yields will be low.

8. Discussion

In the following sections we assemble evidence to test the supply-limitation and drainage net extension hypotheses.

8.1. Rates of regolith formation

If the supply-limitation hypothesis were correct, then rates of sedimentation in the lagoon would be determined by rates of regolith formation on the catchment. Little information is available on rates of soil formation in Australia, and most of this is from studies of alluvium. Nevertheless, the estimated rates cluster around 30 mm ka^{-1} or 0.04 kg $m^{-2}a^{-1}$ (Walker and Coventry, 1976; Costin, 1980; Walker, 1981; Edwards, 1988, 1991). If the rate of pedogenesis at Little Llangothlin were equal to estimated rates elsewhere in southeast Australia and if the rate of soil erosion were equal to the rate of soil formation, the rate of sedimentation in the lake would be 0.11 kg $m^{-2}a^{-1}$. This figure assumes no change in sediment storage on the catchment slopes. This value is similar to the mean rate of sedimentation of 0.14 kg $m^{-2}a^{-1}$ that has prevailed in the catchment since c. 1861. Clearly, there is a large number of assumptions involved here, but the important point is that the equivalence between the rate of soil formation and the rate of sedimentation means that the supply-controlled mechanism of soil erosion is an entirely feasible one in this situation.

8.2. Provenance of sediment in the lagoon

The implication of both the sediment exhaustion model and the gullying thesis is that the bulk of the material eroded into the lake during the mid-nineteenth century episode of rapid erosion would be made up of subsoil rather than topsoil. Irrespective of whether erosion was a consequence of deep gullying or catchment-wide stripping, it must have largely involved the erosion of subsoil material. Two sources of evidence provide clues to the provenance of the sediments in the lake. First, those sediments lying between 1.12 and 0.52 m in the 90-mm core from site C2.0 (laid down between approximately 1835 and 1860) possess a small deficit of excess ^{210}Pb (Gale et al., 1995). They must therefore have been derived largely from materials that had been isolated from $^{210}\text{Pb}_{\text{excess}}$ accumulation; in other words, from rocks and regolith lying below the catchment surface. The bulk of this sediment must therefore have come from subsurface materials rather than topsoils (Gale et al., 1995).

Second, the sediments from between 0.96 and 0.32 m in the 50-mm core (equivalent to 1.08 to 0.40 m in the 90-mm core and deposited between approximately 1840 and 1910; Gale et al., 1995) possess a relatively high mass-specific magnetic susceptibility and a zero to low frequency-dependent magnetic susceptibility (Fig. 7). This combination is strongly indicative of a magnetic mineral assemblage dominated by single and multidomain ferrimagnetic grains, and thus by the primary magnetic minerals characteristic of unweathered igneous rocks (Gale and Hoare, 1991). The only source of such material in the area is the relatively unweathered basalt and its associated regolith found beneath the catchment surface. Such material can only have reached the lake as a result of the erosion of relatively unweathered subsoils. Neither hypothesis is thus at odds with these two lines of evidence.

During the succeeding episode of lower rates of erosion, however, the character of the eroded material would have differed depending on which of the two models was operating. In the case of the gullying model, erosion would have continued to be from the bed and walls of the gullies, in other words, subsoil materials. By contrast, in the case of the supply-control model it would have been newly formed soils and newly weathered materials that would have been reworked into the lake basin. Such materials usually have moderate to high values of frequency-dependent magnetic susceptibility (Gale and Hoare, 1991), in other words, their magnetic characteristics would have been comparable with those deposited in the lake after

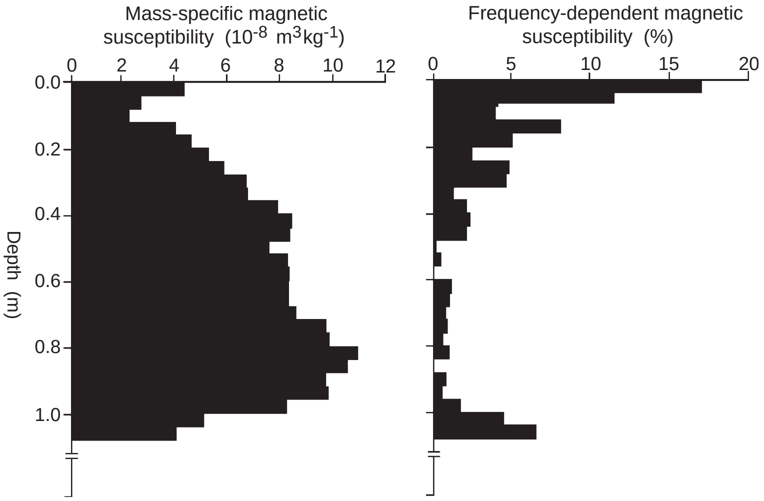

Fig. 7. The mass-specific magnetic susceptibility and frequency-dependent magnetic susceptibility of the upper part of the 50-mm core, C2.0, Little Llangothlin Lagoon, Guyra, northeast New South Wales.

c. 1861 (Fig. 7). But any differences in the character of the eroded materials would have been obscured once the sediments reached the lake. The basin, now shallow as a result of partial infilling, experienced high vegetation growth. The addition of plant organic matter to the mineral sediments diluted their high susceptibilities. Intermittent lowering of the lake levels exposed the sediments to weathering and pedogenesis, increasing frequency-dependent susceptibility, and lowered rates of sedimentation allowed the incorporation of significant levels of $^{210}Pb_{excess}$ to the lake sediments from atmospheric fallout. No reliable conclusions may therefore be drawn about sediment provenance for the period after the middle part of the nineteenth century.

8.3. The nature of the catchment slopes

If the gullying hypothesis were correct, the catchment should possess evidence of drainage net incision. Over 112 000 t of mineral matter would have been entrenched from the catchment in the first quarter of a century of European contact. Yet no trace of this episode can be observed in the modern landscape: there is no sign of gullying and, indeed, little sign that the catchment has ever experienced severe erosion. One possibility is that the gullies were infilled by land restoration and ploughing, particularly during the years of closer settlement in the late nineteenth and early twentieth centuries when much of the catchment was intensively cultivated. Yet there is no evidence of this either on the ground or on aerial photographs of the catchment. Nor have we discovered any documentary or oral evidence of gullying in the catchment. Moreover, although gullying is not unknown on the Tablelands, it is uncommon on basaltic terrains like those of Little Llangothlin (a point implicitly made by McGarity, 1977a).

If regolith formation were roughly balanced by erosion, as the supply-limitation hypothesis would imply, it might be thought that the catchment would consist largely of thin soils dominated by rock detritus. This is the picture presented by Parsons' (1988) detachability continuum, for example, which indicates that, at the weathering-limited end of the continuum, the catchment surface would consist of either coarse fragments on a rocky substrate or bare rock surfaces. Such conditions clearly do not exist at Little Llangothlin. But weathering limitation can also operate under conditions far less extreme and far more common than those posited by Parsons. Given the absence of rills or gullies in the catchment, the most likely mechanism of erosion is unconcentrated surface wash. This process is effectively weathering-limited because each rainstorm can readily detach and transport only a thin layer of debris loosened from the soil, mainly by cracking and drying; further erosion is much more difficult. Over time, therefore, the rate of removal depends not so much on the erosive process but on the rate of break-up of the surface between flows (Carson and Kirkby, 1972). In other words, it is limited by the rate at which weathering can occur.

A hundred and thirty-four thousand tonnes of mineral matter have accumulated in the basin since the arrival of Europeans. This is equivalent to the removal of 41.5 kg of mineral matter per square metre of the catchment. Would this have been sufficient to expose the subsoil to erosion? Expressing this as a mean depth of material eroded is not straightforward. First, the material on the catchment slopes would have included an unknown quantity of plant organic matter. Second, the dry bulk density of the pre-contact regolith is not known, although it is likely to have been very low in a landscape that had never been trampled by hard-hooved animals (Gale, 2003). John Oxley, the first European to cross the area, noted that the soils of the Tablelands frequently consisted of "... light black mould ... rich, dark mould [and] rich vegetable mould ..." (Oxley, 1820). Similarly, Norton (1886), although referring specifically to the slate country of New England, pointed out that "[t]he surface, no doubt, before it was stocked, was largely composed of decayed vegetable matter, the *debris* of falling leaves from the trees and smaller plants ...". The bulk density of the near-surface layers of uncultivated, but almost certainly trampled, krasnozems in southern Queensland averaged ~710±150 kg m^{-3} (McGarry, 1993) and it is likely that pre-contact values would have been considerably lower than this. Taking a likely range of values of 350–700 kg m^{-3}, the mean depth of soil removed would have been 6–12 cm, a figure that would have been higher if the organic content of the eroded material were taken into account or if erosion had been restricted to certain areas of the catchment. Given the thin nature of the soils in the catchment (Jessup, 1965; McGarity, 1977a,b), stripping is therefore likely to have been sufficient to expose the subsoil to erosion. The stripping hypothesis is thus not at odds with the evidence of sediment provenance.

Would the amount of material removed have been sufficient to allow gullies to develop? To determine this, we have to estimate what proportion of the catchment would have experienced gullying. Taking a notional range of 1–10%, and bearing in mind the unknowns and assumptions in the previous calculation, the possible range of mean gully depths would have been 0.6–11.9 m. This accords with gully depths elsewhere on the Tablelands and means that the bulk of the eroded material would have consisted of subsoil. The volume and character of the soil eroded are thus not incompatible with the operation of the gullying hypothesis.

8.4. Spatial pattern of lake sedimentation

The pattern of sedimentation in the lagoon is indicative of largely fluvial input, with deltaic accumulations around the mouths of the inlet streams and over a metre of sediment deposited on the proximal parts of the deltas (Fig. 4). At first sight, such a distribution would appear to provide support for the gullying hypothesis, with localised inputs of material to the basin being carried along the drainage lines. However, catchment-wide stripping would result in much the same pattern of deposition. In the western and northern parts of the catchment, downslope movements of material to the lake basin would be via drainage lines and the resultant deposition would have been at the mouths of the valleys draining into the basin. Direct delivery of material into the basin would have occurred only along the eastern and southwestern slopes. But here the contributing slopes are short and relatively little material would have been available for movement into the basin.

8.5. Temporal pattern of lake sedimentation

Both the supply-limitation and the gullying models predict a reduction in rates of erosion after the initial period of disturbance and adjustment. However, there are two important differences between the models. First, the transition itself takes place in different ways. The implication of the supply-limitation model is that there is a sharp change from transport-controlled to weathering-controlled rates of erosion at the instant at which erodible sources of catchment material are depleted. By contrast, observations of drainage net expansion show that the transition from high to low rates of erosion takes place exponentially (see, for example, Graf, 1977; Schumm et al., 1987).

Second, once the low erosion regime is reached, the models differ in the variability with which erosion occurs over time. In the case of the supply-limitation model, erosion rates are controlled by the rate at which new material is made available for transport. This is low and relatively constant, and the pattern of erosion is therefore relatively constant. In the case of the gullying model, gully expansion slows and erosion becomes largely a consequence of erosion of the gully itself. This is episodic and is governed by the incidence and magnitude of floods (Starr, 1989). The pattern of erosion is therefore episodic.

Discrimination between these two models is likely to be possible only in relatively small catchments that possess high-resolution chronologies of erosion. In large catchments, the pattern of denudation over time is likely to be smoothed as a result of the non-synchronous response of individual sub-catchments to disturbance. Similarly, without a high temporal resolution it is likely to be impossible to resolve the nature of the transition from high to low rates of erosion. The Little Llangothlin record meets both these requirements. The very well-dated record of lake sedimentation provides a close, although not necessarily direct, index of catchment erosion. There is no evidence of an exponential transition from high to low rates of sedimentation (Fig. 5). Although there is an unavoidable gap in the chronology for the first quarter of a century of European contact, this cannot disguise the fact that there is a sharp change from high rates of sedimentation to low and extremely constant rates of sedimentation. The change is clearly step-functional. The high resolution of the sedimentation record after c. 1861 (Fig. 5) makes it highly unlikely that the shape of this relationship is a consequence of chronological error.

Nor does the Little Llangothlin record contain evidence of variability of sedimentation over time within the low sedimentation regime (Fig. 5). This is despite the contemporaneous occurrence of high-magnitude events such as those revealed in Fig. 6. One explanation of this is that the resolution of the record is such that it would smooth the pattern of sedimentation so that peaks and troughs of erosion may not be discerned. This seems unlikely, however, particularly in the upper part of the core where the chronological precision is high (between ±1 and ±3 years at one standard deviation) and the dating errors are much less than the intervals between clusters of floods. The overwhelming evidence is thus that the behaviour of the Little Llangothlin catchment accords with the working of the supply-limitation model; the gullying model cannot be easily invoked to explain the temporal pattern of sedimentation in the lake.

9. Conclusions

9.1. Geomorphological processes

Two credible hypotheses have been advanced to explain the pattern of erosion and sedimentation at Little Llangothlin Lagoon. These are the gullying and the supply-limitation mechanisms. Much of the evidence available to test the competing hypotheses is equivocal; that is, it does not exclude the possibility of either mechanism operating. Nevertheless, the gullying model must be rejected: first because there is no evidence of past or present dissection of the catchment surface, second because gullying would seem incapable of providing the highly constant rate of sedimentation that has prevailed in the basin over the past century or more and third because the gullying model cannot explain the step change from high to low rates of sedimentation in the basin. Further support for the supply-limitation hypothesis comes from the concordance between likely rates of soil formation in the catchment and rates of sedimentation in the lagoon.

There may be several reasons why supply-limitation is particularly important in Australia (and this has been hinted at by Olive and Rieger, 1986 and Wasson, 1994). First, the continent is characterised by thin soils (Beckmann and Coventry, 1987) that may be easily stripped away, leaving erosion processes undersupplied with material. Second, the typically low rates of pedogenesis (Walker and Coventry, 1976; Costin, 1980; Walker, 1981; Beckmann and Coventry, 1987; Edwards, 1988, 1991) mean that material for erosion from hillslopes is produced only slowly, again leaving erosion processes undersupplied. Third, prior to European contact, many Australian soils appear to have been composed of uncompacted material of low bulk density, relatively high infiltration capacity and possessing a discontinuous grass cover (Gale, 2003). This was highly susceptible to erosion, and yielded high sediment yields until its removal reduced the supply of sediment to the system. Finally, many Australian soils have duplex characters with coarse-textured surface horizons overlying clay-rich subsoils (Olive and Walker, 1982). The upper horizons may be easily and rapidly eroded, leaving more resistant subsoils that are capable of impeding erosion by unconcentrated surface flows.

Wasson et al. (1998) have proposed that erosion in pastorally-dominated, low relief catchments in the mid- to high-latitudes operates along a spectrum, the two end members of which are gullying and slope erosion. They have suggested that rates of sediment loss in the slope erosion-dominated systems are closely related to the intensity of land use. Yet the results of this work reveal a more complex situation in which, after the initial phase of soil depletion, soil loss is controlled by the availability of material for detachment.

Finally, the dominance of slope processes at Little Llangothlin must be contrasted with the situation in the similar climatic and topographic environment of the Southern Tablelands of New South Wales. Wasson et al. (1998) have argued that, in the post-contact period, almost all the sediment yielded from catchments on the Southern Tablelands has been the product of gullying. One explanation of this dichotomy may lie in the nature of the substrates. The Southern Tablelands catchments are largely located on siliceous rocks, including granites and siliceous metasediments. Similar rocks on the New England Tablelands have also experienced gullying (McGarity, 1977a). Little Llangothlin, by contrast, is located on basalt and, like other basalt catchments in New England, has not been affected by gully erosion. This may be because the soils developed on the granites and siliceous metasediments often possess hard-setting surface horizons of low permeability (McGarity, 1977a). These increase runoff, increasing the likelihood of erosion and gully development.

9.2. Rates of soil loss

Immediately prior to the arrival of Europeans in the catchment of Little Llangothlin Lagoon, the mean rate of mineral denudation was 25 t $km^{-2}a^{-1}$. By contrast, the long-term, post-contact rate of soil loss has been at least 269 t $km^{-2}a^{-1}$, an order of magnitude higher. More significantly, the disturbance consequent upon the arrival of Europeans in the catchment had a massive and near-instantaneous impact, with a mean rate of erosion in the period c. 1836–1861 of 1360 t $km^{-2}a^{-1}$. Although such an increase is in accord with the findings of Wasson et al. (1996) that European impact in Australia has increased water borne sediment yield by 2–375 times, this figure is extraordinarily high. This is particularly so given that it represents an average over a quarter of a century and that rates are likely to have been far higher in individual years. It is also important to bear in mind that this erosion took place when the intensity of agricultural activity was extremely low by modern standards, with a single sheep pastured on every 1–5 ha (although shepherding may have meant that the numbers of sheep grazing small areas were relatively high for brief periods). The low density and uncompacted nature of pre-contact soils on the New England Tablelands has already been discussed (see Section 8.3). In such a sensitive environment, the trampling or loss of vegetation cover caused by even a small number of sheep might have left the soil so susceptible to erosion that it could be swept away by succeeding storms.

The high, early colonial rate of erosion was followed by an apparently sharp transition to a new, low and very constant rate of denudation, 52 t $km^{-2}a^{-1}$. Almost all the post-contact erosion thus took place in a very short period after initial disturbance: nearly 85% in no more than 25 years. The decline to low rates of erosion was not the result of the adoption of conservation measures, and it occurred despite massive changes in land use practice, changes in population density and climatic shifts. Thus, there have been great changes in land use and population density in the catchment in the period since c. 1861, but these seem to have had negligible impact on sedimentation rates. Similarly, high-magnitude natural events, such as floods and droughts, appear to have had little effect on erosion rates. Instead, the disturbance to the equilibrium of the natural system consequent upon the arrival of Europeans in the catchment appears to have made available sediment stores that were moved by the first large events to affect the catchment. Once these stores were depleted, event magnitude and land use appear to have become unimportant, with only a finite supply of material available to be moved by all events above a certain magnitude. Thus, erosion rates seem to have been governed largely by the availability or not of stores of regolith in the catchment.

9.3. Soil conservation

The findings of this research also have implications for soil conservation practice. First, conventional short-term monitoring of soil erosion is unlikely to allow investigators to recognise that low rates of soil loss at sites such as these are a consequence of the past depletion of sediment supplies. Instead, such results are likely to be interpreted as a product of relatively low levels of agricultural disturbance and/or good management practice. Such findings might lead researchers to conclude that similar land use practices may be introduced elsewhere with little impact on the land. Second, attempts to reduce rates of soil loss by changes in land-use practice or by the use of engineering methods such as contour banking and grassed waterways are likely to have minimal effect in such systems. This is because such measures attempt to reduce the capacity of transporting and erosive processes when these are already undersupplied with material. This could result in considerable expenditure for little or no minimisation of soil loss.

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