

1 **Degradation of the Mitchell River fluvial megafan by alluvial gully**
2 **erosion increased by post-European land use change, Queensland,**
3 **Australia**

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10

11 **Abstract**

12 Along low gradient rivers in northern Australia, there is widespread gully erosion into
13 unconfined alluvial deposits of active and inactive floodplains. On the Mitchell River fluvial
14 megafan in northern Queensland, river incision and fan-head trenching into Pleistocene and
15 Holocene megafan units with sodic soils created the potential energy for a secondary cycle of
16 erosion. In this study, rates of alluvial gully erosion into incipiently-unstable channel banks
17 and/or pre-existing floodplain features were quantified to assess the influence of land use
18 change following European settlement. Alluvial gully scarp retreat rates were quantified at 18
19 sites across the megafan using recent GPS surveys and historic air photos, demonstrating rapid
20 increases in gully area of 1.2 to 10 times their 1949 values. Extrapolation of gully area growth
21 trends backward in time suggested that the current widespread phase of gulying initiated
22 between 1880 and 1950, which is post-European settlement. This is supported by young
23 optically stimulated luminescence (OSL) dates of gully inset-floodplain deposits, LiDAR terrain
24 analysis, historic explorer accounts of earlier gully types, and archival records of cattle numbers
25 and land management. It is deduced that intense cattle grazing and associated disturbance
26 concentrated in the riparian zones during the dry season promoted gully erosion in the wet
27 season along steep banks, adjacent floodplain hollows and precursor gullies. This is a result of
28 reduced native grass cover, increased physical disturbance of soils, and the concentration of
29 water runoff along cattle tracks, in addition to fire regime modifications, episodic drought, and
30 the establishment of exotic weed and grass species. Geomorphic processes operating over
31 geologic time across the fluvial megafan predisposed the landscape to being pushed by land
32 used change across an intrinsically close geomorphic threshold towards instability. The
33 evolution of these alluvial gullies is discussed in terms of their initiation, development, future
34 growth, and stabilisation, and the numerous natural and anthropogenic factors influencing their
35 erosion.

36 **Keywords:** alluvial gully erosion, air photograph interpretation, OSL dating, geomorphic
37 thresholds.

1 **Highlights**

- 2 ❖ Alluvial gully erosion into floodplains is widespread across northern Australia.
- 3 ❖ River incision into megafans creates the potential energy for new erosion cycles.
- 4 ❖ Air photo and OSL data demonstrate rapid gully expansion post-European settlement.
- 5 ❖ Cattle grazing increases erosion into incipiently-unstable floodplain features.
- 6 ❖ Natural and anthropogenic factors influence geomorphic thresholds and gully evolution.

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1. Introduction

Gully erosion is a global phenomenon, a major cause of severe land degradation, and an important source of sediment pollution that reduces water quality and degrades aquatic ecosystems (Lal, 1992; Poesen et al., 2003; Valentin et al., 2005). In northern Australia, there is widespread alluvial gully erosion (*sensu* Brooks et al., 2009) into unconfined alluvial deposits on active and inactive floodplains and fluvial megafans (Simpson and Douth, 1977; Payne et al., 1979; Condon, 1986; Brooks et al., 2009; McCloskey, 2010; Sattar, 2011; Shellberg et al., 2013a,b). Alluvial gullies eroding into large floodplain and megafan surfaces are a distinct end member along a continuum of gully form–process associations that are different from colluvial hillslope gullies, soft-rock badlands, and valley-bottom cut-and-fill channels in semi-confined floodplains (Brooks et al., 2009). Alluvial gully initiation and evolution can span across spatial and temporal scales in floodplain environments, from small anthropogenically enhanced alluvial gullies (e.g., Vandekerckhove et al., 2001, 2003) to large alluvial gully tributaries cut into floodplains during sea level lowstands and inundated by backwater during highstands (e.g., Mertes and Dunne, 2008; Parker et al., 2008). The existence of alluvial gullies indicates that large floodplains and fluvial megafans are not consistently depositional environments through time, but rather temporary stores of sediment along fluvial process domains (Schumm, 1977) that are subject to erosion cell dynamics (Pickup, 1985, 1991) at a variety of spatial and temporal scales.

On the 31,000 km² Mitchell River fluvial megafan on Cape York Peninsula in northern Queensland (Fig. 1), a minimum area of 12,900 ha of alluvial gully erosion and 5,560 km of active gully front length were mapped using remote sensing (Brooks et al., 2009; Fig. 2). These areas of de-vegetated eroded sub-soils were concentrated in dispersible floodplain soils adjacent to incised main channels, and covered 0.4% of the megafan area and up to 10% of the local floodplain area. Using preliminary head scarp retreat data (GPS) from 2005 to 2007 at distributed gullies, along with scarp height and perimeter measurements, Brooks et al. (2008) estimated that these gullies erode ~ 5 Mt yr⁻¹ of alluvial soil from the megafan. Shellberg et al. (2013b) measured sediment yields of 89 to 363 t ha⁻¹ yr⁻¹ (2009–2010) at a stream gauge in a 33 ha gullied catchment (WPGC2a this study) on the Mitchell megafan. The degree to which these high erosion rates represent natural or human accelerated conditions is an important research question, toward which this current study will provide supporting data. Since soil erosion threatens the sustainability of the local cattle industry, aquatic ecosystems and the cultural use of water bodies, understanding rates of gully erosion pre- and post-European settlement is important to define past human land use impacts and the sensitivity of the landscape to further development.

1 Savanna catchments across northern Australia have undergone major land use changes from
2 traditional Aboriginal management to widespread cattle grazing on unimproved rangelands
3 since European settlement in the 1800s. Major alterations in grass cover, woodland thickening,
4 exotic vegetation species, and fire regimes have resulted (Neldner et al., 1997; Fensham and
5 Skull, 1999; Crowley and Garnett, 1998, 2000; Sharp and Whittaker, 2003; Bowman et al.,
6 2004; Sharp and Bowman, 2004). Many assessments have documented, but not fully quantified,
7 changes in sheet and gully erosion and sediment yield as a result of cattle grazing and/or
8 European settlement in northern Australia (Medcalff, 1944; Payne et al., 1979; Condon, 1986;
9 Wasson et al., 2002, 2010; Bartley et al. 2007, 2010; McCloskey, 2010; Hancock and Evans,
10 2010). Other sediment tracing studies in northern Australia have shown that current sediment
11 loads are dominated by sub-surface erosion (typically >90%) from primarily gully erosion,
12 channel erosion, deep rilling and scalded soils (Hughes, et al., 2009; Caitcheon et al., 2012;
13 Wilkinson et al., 2013; Hancock et al., 2014; Olley et al., 2013); but to date few studies have
14 looked at how these rates and processes of erosion have changed through time. Elsewhere in
15 south-eastern Australia, sediment yields clearly increased from accelerated soil, gully, and
16 channel erosion associated with post-European land use (Condon et al., 1969; Eyles, 1977;
17 Wasson and Galloway, 1986; Pickup, 1991; Prosser and Winchester, 1996; Brooks and
18 Brierley, 1997; Wasson et al., 1998; Fanning, 1999; Olley and Wasson, 2003; Rustomji and
19 Pietsch, 2007).

20 The main objectives of this study were to investigate the growth rates of alluvial gullies and
21 their evolution over time, and the stability of floodplain features and their threshold response to
22 disturbance. More specific research objectives were to 1) quantify how alluvial gully erosion
23 rates have changed over different time scales along the Mitchell River fluvial megafan, 2)
24 develop projections of gully erosion growth and duration into the future, 3) examine the form
25 and evolution of alluvial gullies using Light Detection and Ranging (LiDAR) terrain analysis, 4)
26 interpret early European explorer observations and potential post-European land use impacts
27 from settlement, 5) discuss the stability of floodplains and fluvial megafans influenced by
28 natural and anthropogenic factors, and 6) describe a threshold response to disturbance – the
29 widespread initiation of alluvial gully erosion.

30 **2. Regional setting and land use history**

31 The Mitchell River fluvial megafan (31,000 km²) in northern Queensland, Australia, consists of
32 nested fluvial fans (>150 km in radius) and river floodplains concentrated in the lower half of
33 the Mitchell River catchment (71,630 km²; Brooks et al., 2009). Major geomorphic units of the
34 megafan were deposited from the Pliocene to the Holocene, but were especially active in the
35 late Pleistocene during major sedimentation periods (Galloway et al., 1970; Grimes and Douth,
36 1978; Nanson et al., 1992; Fig. 1). Sea levels in the Gulf of Carpentaria, at the mouth of the

1 Mitchell River, reached their minimum of 120 m below the present level during the late
2 Pleistocene (~18,000 years ago), rose to their Holocene maximum of 1.5 m above the present
3 level at 5,500 years ago, and have since fallen to their present level (Chappel et al. 1982; Chivas
4 et al. 2001). The current tidal range is 2–3 m in the Mitchell estuary, which extends 20 km
5 inland along the 350 km total length of the Mitchell fluvial megafan.

6 During the very late Pleistocene and Holocene, river incision and fan-head trenching into the
7 fluvial megafan, and backfilled floodplain units upstream, occurred as the likely combined
8 result of base level changes, reductions in sediment supply, and climate variability (Kershaw,
9 1978; Chappell et al., 1982; Nanson et al., 1992). This incision shifted the hydrologic apex of
10 the megafan from near the Lynd River confluence (Pleistocene apex) to below the Palmer River
11 confluence (Holocene apex of the Mitchell fan-delta) (Figs. 1 and 2). More recently, the active
12 distributaries of the Holocene fan-delta and deltaic estuary have prograded into the Gulf of
13 Carpentaria during the last 5,500 years (Nanson et al., 2013). River incision into both
14 Pleistocene and Holocene megafan units at different times increased the local relative relief and
15 potential energy between the river channel thalweg and high floodplain (Brooks et al., 2009;
16 Shellberg et al., 2013a), which increased the possibility of secondary cycles of erosion (*sensu*
17 Pickup, 1985) by alluvial gully erosion initiating at steep channel banks.

18 A majority of alluvial gullies are located within 4 km of main creek and river channels, and are
19 concentrated in the upstream incised sections of the Pleistocene megafan where relative relief is
20 greatest (Brooks et al., 2009) (Fig. 2). Pleistocene high floodplains proximal to the river channel
21 are dominated by fine-grained (fine sand, silt and clay) dispersible sodic soils with high
22 percentages of exchangeable sodium (Isbell et al., 1968; Galloway et al., 1970; Shellberg et al.,
23 2013a). Alluvial gullies are also widespread along channel banks and floodplains of the active
24 Holocene fan, albeit of reduced density and size due to lower relief and less weathered soils
25 (Fig. 2). Large portions of distal Pleistocene megafan units (Fig. 1) are less active currently in
26 terms of erosion and deposition due to reduced connectivity to main river channels, low relief,
27 and increased clay content in soils.

28 The Mitchell River catchment currently has a monsoonal, wet–dry tropical climate that receives
29 >80% of its annual rainfall and river runoff from December to March. Annual rainfall in the
30 lower catchment averages 1015 mm and varies between 500 and 2000 mm (ABOM, 2015) (Fig.
31 3a). Storm rainfall intensity and erosivity are moderately high (Shellberg et al., 2013a), as are
32 potential (1700 to 2000 mm yr⁻¹) and actual (600 to 900 mm yr⁻¹) evapotranspiration (ABOM,
33 2015). Inter-annual rainfall totals are variable in the Mitchell catchment, with multi-year wet
34 and dry phases that are influenced by cycles of El Niño-Southern Oscillation (ENSO) and
35 Interdecadal Pacific Oscillation (IPO) (Lough, 1991; Risbey et al., 2009) (Fig. 3b).

1 Aboriginal people have managed the Mitchell catchment for tens of thousands of years (Sharp
2 1934). The first European explorers traveled through the catchment in the mid-1800s (Gilbert,
3 1845; Leichhardt, 1847; Jardine and Jardine, 1867). In 1872, gold was discovered near
4 Palmerville (Hann, 1872) (Fig. 2). Pastoralism followed soon after across the savanna
5 woodlands of the lower catchment. The number of introduced cattle increased to > 40,000 head
6 over the subsequent 140 years (Fig. 4), as reported in historic archives of herd data for the
7 Wrotham Park Aggregation cattle station (9973 km²; Fig. 2; Edye and Gillard, 1985; Arnold,
8 1997; QSA, 2008), which now consists of Wrotham Park, Gamboola, Gamboola South,
9 Highbury, and Drumduff Stations. These herd size trends generally followed total cattle
10 numbers across Queensland (Fig. 2; ABS, 2008). Low-density cattle grazing (1 beast per 20 ha
11 on average) across open range has been the predominant land use (Edye and Gillard, 1985;
12 Arnold, 1997). However, cattle density (>1 beast per 8 ha) and impacts were concentrated along
13 river, creek, and lagoon frontages, where animals congregated for water and feed during the
14 long dry season and cattle drives (QSA, 2008). Over time, thousands of kilometers of fences
15 have been installed across the megafan, but primarily are used to divide very large paddocks and
16 seldom to protect waterways or river frontage from grazing.

17 All of the early European explorers along the lower Mitchell River (Gilbert, 1845; Leichhardt
18 1847; Jardine and Jardine, 1867; Hann, 1872) anecdotally described fluvial features including
19 floodplain drainage ‘hollows’, ‘gullies’ and ‘creeks’ near the ‘steep banks’ of the rivers. Their
20 definitions and use are open to interpretation (Shellberg, 2011). For example, Leichhardt (1847)
21 wrote that “*the [floodplain] was interrupted by gullies and deep creeks, which [were] the*
22 *outlets of the waters collecting on the [floodplain]*”. Gilbert (1845) wrote that they had “*to keep*
23 *well back [from the river] to avoid the deep gullies frequent on the immediate banks*”. Hann
24 (1872) wrote that “*the many gullies and broken country made it impossible to travel [along the*
25 *river bank]*”. Gilbert (1845) and Jardine and Jardine (1867) also used the term ‘broken’ country
26 in contrast to open flats that were easy to ride horses through. The explorers’ anecdotal
27 observations provide a backdrop for more in depth geomorphic quantification and interpretation
28 of gully evolution along the Mitchell fluvial megafan.

29 **3. Methods**

30 *3.1 Recent and historic gully erosion rates and area expansion*

31 Across the Mitchell River megafan, a representative subset of 18 alluvial gullies were selected
32 for analysis based on the mapped spatial distribution of gullies and field reconnaissance of
33 randomly selected sites (Brooks et al., 2008, 2009; Fig. 2). Gullies initiated by fence lines and
34 roads were not included as study sites. Three gully complexes (WPGC2, HBGC1, and KWGC2)
35 on main channel banks were selected as intensively monitored sites on the upper, middle, and
36 lower sections of the megafan along a continuum of geologic age (Pleistocene to Holocene),

1 river incision and local relative relief decreasing in the downstream direction (Brooks et al.,
2 2009), which are reported on here and elsewhere (Shellberg, 2011; Shellberg et al., 2013a,b).

3 Recent annual surveys (2005–2010) of alluvial gully fronts (scarps) were conducted at the 18
4 study sites (Fig. 2) using differential GPS (Trimble with Omnistar High Precision). In combined
5 total, ~ 50,040 m of scarp front were surveyed with GPS each year. Horizontal accuracy
6 depended on signal strength and vegetation cover, but was typically 10–15 cm and always less
7 than 50 cm. Error margins in gully area were calculated by buffering each survey line by ± 0.50
8 m, with any area changes within the buffer overlap omitted from final calculations. The average
9 linear erosion rate (m yr^{-1}) for each gully for each year was calculated as the area of change
10 (m^2) between any two survey-years divided by the survey length (m) of active gully perimeter at
11 the later time period.

12 Air photographs of the same sites were used to assess the historic location and rates of gully
13 front erosion. The earliest photographs were from 1949 or 1955, with the average number of
14 photos per site between 1949–2006 being 5 and ranging from 3 to 7. The photo scale ranged
15 from 1:20,000 to 1:85,000, with the first (1949, 1:23,900) and last photos (2006, 1:20,000)
16 having the largest scales. High resolution (2400 dpi) digital copies were clipped to the general
17 gully area ($< 4 \text{ km}^2$). Photos were georectified backward through time in a GIS (e.g., Hughes et
18 al., 2006), starting with GPS surveys and LiDAR data (where available) to rectify 2006 photos.
19 For each photo, a minimum of six ground control points were used that were consistently
20 identifiable between photos; these were most often large trees but also fence lines, roads, and
21 stable fluvial features. A first-order polynomial georectification was used along with a cubic
22 convolution resampling of pixels (Hughes et al., 2006).

23 For each gully and photo year, the gully head scarp location was digitized from rectified photos.
24 In total for the 18 sites, ~ 43,160 m of scarp front was digitized for each photo year. Error
25 margins for the gully scarp location and gully area were estimated from the total root mean
26 square errors (*RMSE*) for the rectified photos (e.g., Hughes et al., 2006), which averaged 1.39 m
27 and ranged from 0.36 to 3.32 m. Repeat digitisation of scarp edges from photos indicated that
28 scarps could be consistently located within ± 2 – 3 m as compared to GPS and LiDAR surveys.
29 Therefore, each digitized line was buffered by ± 2 m if obtained from high resolution photos ($<$
30 1:30,000) and ± 3 m for coarser resolution photos ($>$ 1:30,000). Area changes within the buffer
31 overlap were omitted from final calculations. Annual average linear erosion rates (m yr^{-1}) were
32 calculated similar to GPS methods above.

33 The change in the bare eroded gully area over time (1949–2010) was determined for different
34 sites using the combination of historic photo and recent GPS data. The zero area or starting
35 point for each gully was located at the confluence of the gully channel with a mainstem river,

1 lagoon, or large creek. In a few cases, the transition between bare gully complexes and their
2 narrow outlet channels that traverse dense riparian zones could not be mapped using historic air
3 photos, resulting in these areas being omitted from the analysis.

4 According to disturbance, response and relaxation theory (Schumm, 1977; Graf, 1977), it was
5 initially hypothesized that increasing trends in gully area over time would follow negative-
6 exponential rates of change that are common in unstable channels (Graf, 1977; Simon, 1992;
7 Rutherford et al., 1997; Wu et al., 2012). A modified negative exponential function was fitted to
8 the data for each gully:

$$\frac{A}{A_0} = a + be^{(-kt)} \quad (1)$$

10 where A is the exposed gully area at time t , A_0 is the initial gully area at $t = 0$, a and b are
11 dimensionless coefficients determined by regression, k is a coefficient determined by regression
12 that defines the rate of change in gully area over time, and t is the time (yr) since the initial
13 starting point or the first air photograph. When k is very small the equation approaches linearity,
14 as dictated by the data trend and goodness of fit determined by the coefficient of determination
15 (r^2).

16 3.2 Past gully erosion chronologies from OSL dating

17 To quantify timing and rates of sediment deposition (and thus ‘upstream’ erosion) within
18 gullies, alluvial sediment samples were collected in 2009 from vertical cut banks of incised
19 outlet channels within two gully complexes (WPGC2 and HBGC1) (Fig. 2). Samples were
20 dated using single-grain optically stimulated luminescence (OSL) (Aitken, 1998; Olley et al.,
21 2004; Pietsch, 2009). OSL dating was not conducted at KWGC2 because air photograph
22 evidence clearly indicated that the gully erosion was less than 100 years old, and ^{14}C dating (not
23 reported here) was used in a separate study to date recent tree colonization into the gully
24 (Shellberg 2011).

25 At both WPGC2 and HBGC1, a gully cross-section was located for sampling downstream of the
26 major gully erosion but upstream of river backwater conditions, to isolate gully outwash
27 sediment. Major sedimentary units (i.e., Pleistocene megafan sediment and Holocene gully
28 sediment) were defined in one or more vertical profiles along or near each cross-section and
29 sampled for OSL dating. Ten discrete OSL sediment samples at WPGC2 and four at HBGC1
30 were collected (Table 1). The measured OSL burial ages were used to interpret the timing of
31 sediment deposition within the gullies, and infer erosion timing and gully evolution. In addition,
32 the vertical distances between samples in a profile and the sample ages were used to estimate
33 sedimentation rates for different sedimentary units, and thus infer changes in erosion rates over
34 time.

1 Single-grain OSL dating of quartz grains (180–212 μm) followed the techniques and
2 instrumentation of Olley et al. (2004) and Pietsch (2009) to determine the burial age (years
3 before present, BP, or the year of sampling in 2009) from the equivalent dose (D_e , Gy) the
4 buried grain(s) received cumulatively over time and the total dose rate (D_r , Gy yr^{-1}) received
5 from radiation in the surrounding environment. The dose rate was calculated from soil
6 radionuclide activities measured using gamma spectrometry (Murray et al., 1987), using
7 conversion factors from Stokes et al. (2003), and beta-dose attenuation factors from Mejdahl
8 (1979). For all samples, a long-term average water content of $5 \pm 5\%$ was used for this
9 seasonally dry climate. A modified single-aliquot regenerative-dose (SAR) protocol (Olley et
10 al., 2004) was used to determine the dose response curve and D_e for each grain. Between 600
11 and 1700 single grains were analysed for each sample, with these yielding on average 6% that
12 passed our commonly used acceptance criteria (see Pietsch, 2009; Pietsch et al., 2015).
13 Overdispersed grain dose populations were observed in all cases, which we interpreted as being
14 primarily a result of partial bleaching; hence burial doses were calculated using the minimum
15 age model (and its unlogged variant for very low dose samples) with an assumed underlying
16 overdispersion of the grain dose population immediately after burial of 10% (see Arnold et al.,
17 2009; Galbraith and Roberts, 2012). For two samples (WP13 and WP07), the majority of grains
18 acting as reliable dosimeters were observed to have doses in excess of the saturation point of
19 their respective growth curves. For these two samples, we used the average onset of saturation
20 as an indicative minimum possible burial dose, and hence the ages thus calculated are taken as
21 minimum ages only.

22 3.3 *Projections of future gully growth and duration*

23 Future projections of gully growth at the three intensively monitored gully sites
24 (WPGC2, HBGC1, and KWGC2; Fig. 2) was assessed from over 50 longitudinal
25 profiles of the channel thalweg elevation at each site extracted from Light Detection and
26 Ranging (LiDAR) DEM data. These data were collected in 2008 and DEMs (1 m^2 grid)
27 were generated from point data using the natural neighbour interpolation model. Each
28 profile radiated out from the main channel along individual dendritic tributaries and
29 extended through the gully scarp zone onto the flat terrain of the river high-floodplain.
30 Future projections of the spatial expansion of gully area were made by forward-trending
31 the slope of the outlet channel, common to all tributaries, through the scarp zone and
32 into the uneroded alluvial plain. This assumes that the sand-bed gully-outlet channels
33 are at an equilibrium slope or grade (*sensu* Mackin, 1948; Lane, 1955) due to abundant
34 sand bed-material supplied from gully scarp failure during monsoon rains (Brooks et al.,
35 2009; Shellberg et al., 2013a,b; Rose et al., 2015). It also assumes that over-steepened
36 scarp fronts will flatten over time toward a graded slope, due to the unconfined nature
37 of the high-floodplain. The ultimate erosion extent of the gully was located where the

1 projected graded slope intersected the elevation of the relatively flat uneroded
2 floodplain or the surface of another topographic feature. However, since the channel-
3 slope within each gully was a sinuous thalweg slope rather than a straight-line valley-
4 slope, the calculated straight distance from the current scarp edge to the future estimated
5 scarp endpoint was adjusted to a straight-line valley distance by dividing this distance
6 by the sinuosity of the outlet channel.

7 The form of gully area growth trajectories and trends into the future are unknown and
8 could follow linear, negative exponential or other functions depending on internal gully
9 evolution processes and/or future climatic forcing. Linear trends using 1949–2010 area
10 data were initially used to estimate the minimum time when the gully scarp would reach
11 a graded slope in all directions by projecting trends into the future until the relative
12 gully area (A/A_0) spatially projected by the profile extensions was reached. Negative
13 exponential trends using 1949–2010 area data alternatively were used to project the
14 time to reach a graded slope, assuming that expansion rates continue to relax over time
15 as observed at many sites. Projection uncertainties of both approaches are discussed.

16 *3.4 Analysing gully evolution from LiDAR data*

17 The 2008 LiDAR DEMs (1 m² grid) were analysed to examine the form and evolution of
18 alluvial gullies and floodplain hollows. A location-for-time substitution was adopted for alluvial
19 gullies at different stages of evolution (initiation, expansion, and stabilisation; Brooks et al.,
20 2009). Cross-section and longitudinal profile data extracted from LiDAR data were used to
21 compare hollow and gully forms and possible evolution over time. Site HBGC1 was selected as
22 a case study due to the presence of multiple forms of gullies and floodplain hollows, and having
23 been passed directly by Leichhardt and Gilbert in 1845 (Fig. 2).

24 **4. Results**

25 *4.1 Recent and historic gully erosion rates and area expansion*

26 Recent GPS surveys (2005–2010) documented the more or less consistent annual growth rates
27 of alluvial gully area (Fig. 5). However, linear erosion rates were variable within individual
28 gully scarps, with the highest rates at distinct lobes or alcoves of water convergence (in
29 planform) compared to inter-lobe zones along more linear scarps (Fig. 5). Maximum retreat
30 rates regularly exceeded 1 m yr⁻¹, with extreme values > 10 m yr⁻¹ (Brooks et al., 2009;
31 Shellberg et al., 2013a,b). Inter-lobe zones were more stable with rates < 0.5 m yr⁻¹.

32 Historical air photographs documented the longer term growth of alluvial gullies, demonstrating
33 that these gullies can consume large areas of floodplain margins consistently through time (Fig.
34 6). Early phases of gully growth were predominantly linear headward retreat. Subsequently,

1 lateral widening expanded gully growth to develop amphitheatre shaped gully complexes that
2 were as wide as they were long (Brooks et al., 2009) (Fig. 6).

3 Annual average scarp retreat rates varied by year, period, site, and measurement method (Fig.
4 7). The median rate of annual average scarp retreat (area change / scarp perimeter) from recent
5 GPS surveys (2005–2010; 18 sites; 41 time steps; 50,040 m of scarp) was 0.23 m yr⁻¹ compared
6 to 0.37 m yr⁻¹ from historic air photos (1949–2006; 18 sites; 58 time steps; 43,163 m of scarp).
7 The historic air photos (1949–2006) vs. recent GPS (2005–2010) distributions were
8 significantly different from each other ($p = 0.001$, $\alpha = 0.05$; non-parametric Kruskal-Wallis one-
9 way analysis of variance; Fig. 7). For additional analysis of the nature of the form of the gully
10 growth model, the historical air photo period (1949–2006) was split into two periods (1949–
11 1975 and 1975–2006) with equal sample sizes based on air photo availability. These two
12 distributions were marginally different ($p = 0.058$, $\alpha = 0.05$). When the two periods of historical
13 air photo (1949–1975 and 1975–2006) and the period of recent GPS (2005–2010) were
14 compared, the results were significantly different ($p < 0.001$; $\alpha = 0.05$; Fig. 7).

15 The combined scarp location data from historic air photos and recent GPS surveys showed
16 progressive growth of all 18 gully complexes over time (Fig. 8a). Relative gully area (A/A_0) for
17 individual gullies increased from 1.2 to 10 times their initial 1949 areas. Trend results were the
18 same whether the recent GPS data were included or excluded from the historical air photo data.
19 The estimated error in gully area for any given year was relatively small compared to the
20 magnitude of area change over the 60 years (Fig. 8).

21 Fitting the negative exponential function to the combined data indicated that erosion rates varied
22 from negative exponential to near linear depending on the site. The values of the coefficient k
23 (0.0007 to 0.0028) were small (near linear), but allowed for the exploration of the degree of
24 linearity in the data without assuming a linear function. Values of r^2 were high (average $r^2 =$
25 0.981, range 0.872 to 0.999). Although many sites had declining growth rates over time (Fig.
26 8b), due to the low sample size (average 5, range 3 to 7) and short time frame (< 60 years),
27 linear and logarithmic functions also fit the data well (average $r^2 = 0.979$ and 0.976,
28 respectively).

29 Sites with the highest erosion rates (m yr⁻¹) and greatest relative expansion ($A/A_0 > \sim 2$) had the
30 smallest k -values in the exponential function, suggesting near linear areal expansion. Head scarp
31 retreat was dominated by undercutting and mass failure of soil blocks at these sites (Brooks et
32 al., 2009). For these fast growing gullies, extrapolation of gully area growth trends backward in
33 time ($A/A_0 \ll 1$) suggests that the time frame for initiation was between 1910 and 1950, i.e. after
34 the introduction of cattle (Fig. 8a). Often these gullies had the most identifiable starting points
35 near the banks of rivers or lagoons.

1 In contrast, sites with low erosion rates (m yr^{-1}) and small relative expansion ($A/A_0 < \sim 2$) had
2 larger k-values, suggesting non-linear trends with rapid initial growth and slower growth over
3 time. Head scarp retreat was dominated by direct rainfall and fluting and carving of the gully
4 front face at these sites (Brooks et al., 2009). These slower growing gullies had less identifiable
5 starting points and indeterminate initiation times before 1900, but consistent with the period of
6 European settlement (Fig. 8b).

7 4.2 Gully erosion chronologies from OSL dating

8 Measured OSL burial ages (Fig. 9; Table 1) were used to interpret the timing and rates of gully
9 evolution before and after European settlement (*circa* 1872). At WPGC2 (Figs. 2 and 6a), OSL
10 samples obtained from three vertical profiles (2, 3, and 5) located along a cross-section transect
11 through the lower gully (Fig. 10), with one additional nearby profile (7) (Table 1). Example
12 radial plots of D_e data for profile 5 are included in Fig. 9. Profile 5 in WPGC2b consisted of
13 three sedimentary units (Fig. 11). The lower Unit C consisted of massive indurated silt/clay
14 deposited in the Pleistocene during the construction of the fluvial megafan ($>35,000$ yr BP;
15 Table 1: WP13). Unit B was deposited above an unconformity with Unit C. Unit B was an
16 indurated silty-clay deposit that lack visible sedimentary structures, and infilled a floodplain
17 hollow or swale on the surface of Unit C with silt, clay and organic material in a low energy
18 environment (Fig. 10). The top of Unit B was the pre-European soil surface (180–515 yr BP;
19 Table 1: WP-11 to 12), as also indicated by a buried (in situ) tree which grew on top of Unit B
20 (Fig. 11a). The laminated silt and Fe/Mn (ferricrete) nodules of Unit A were deposited
21 following European settlement (90 yr BP; Table 1: WP-10) and eroded from sheet and/or
22 shallow gully erosion in the upslope catchment.

23 At profile 7 upstream in WPGC2a, OSL data from a thinner section of unit A confirmed that its
24 deposition initiated 100 yr BP (Table 1: WP-19) at the bottom of the unit and buried the older
25 unit B immediately underneath (125 yr BP; Table 1: WP-20). At profiles 2 and 3 in WPGC2a
26 (Fig. 10), the unconsolidated fill units Aa to Ac of small inset floodplains within the gully were
27 deposited following European settlement (15–70 yr BP; Table 1: WP-03 to 05). These deposits
28 overly a major unconformity that was exposed by gully erosion cutting into the indurated
29 Pleistocene sediments of unit C ($>35,000$ yr BP; Table 1: WP-07).

30 These OSL data at WPGC2 demonstrate a complex response to gully evolution – from initial
31 shallow erosion to deposition within hollows and finally deep gully incision – all in response to
32 disturbance associated with land use change to cattle grazing. To aid this interpretation and
33 enable estimates to be made of the magnitude of changes, pre- and post-European sedimentation
34 rates were calculated for different units using the vertical distances between samples in a profile
35 and the estimated sample ages and uncertainty. The pre-European deposition rates within Unit B
36 at profile 5 in WPGC2 were 1.2 ± 0.14 mm yr^{-1} (Table 1: between WP-11 and 12). Whereas,

1 post-European deposition rates of Unit A ranged from $5.5 \pm 0.6 \text{ mm yr}^{-1}$ at profile 5 (Table 1:
2 between WP-11 and surface) to $6.4 \pm 3.1 \text{ mm yr}^{-1}$ at profile 7 (Table 1: between WP-19 and
3 20), five times higher than pre-European rates.

4 At the HBGC1 site (Figs. 2 and 13), OSL dates of gully inset-floodplain deposits were less than
5 100 years old (Table 1: HB-01 to 05) and overlaid an indurated ferricrete knickpoint (Figs. 12b
6 and 13) presumably from the Pleistocene (but not dated). Holocene deposits appear to have been
7 either evacuated from this gully or buried and not found. Further drilling or excavation would be
8 needed for additional dating analysis. Post-European deposition rates in HBGC1 were $7.1 \pm$
9 0.65 mm yr^{-1} during the construction of the gully inset-floodplain (Table 1: HB-01 to 05),
10 which are comparable to WPGC2.

11 *4.3 Projections of future gully growth and duration*

12 Gully-thalweg longitudinal-profiles extracted from LiDAR DEM's (Fig. 12) generally displayed
13 graded thalweg slopes over finite distances up to the immediate scarp zone where the profiles
14 were over-steepened. However for HBGC1 and KWGC2 (Fig. 12b,c), the channel profiles were
15 interrupted by indurated ferricrete at depth. For HBGC1 (Fig. 12b), the channel slope above the
16 indurated ferricrete knickpoint was used for profile extension because 1) the knickpoint was a
17 permanent feature influencing the upstream channel grade and scarp retreat, and 2) the over-
18 steepened convex profile below the knickpoint was not in equilibrium due to cut and fill
19 processes associated with both river sedimentation. For KWGC2 (Fig. 12c), the steeper channel
20 slope below the knickpoint was used for profile extension because 1) the indurated knickpoint
21 was actively failing and temporary, and 2) the slope of the profile below the knick point
22 matched the channel slope a few hundred meters below the gully scarps.

23 Temporal estimates of when the gully scarp would reach a graded profile in all directions
24 differed between study sites and trend projection method. The fastest observed rates of gully
25 area expansion were at WPGC2 (Fig. 8), where linear rates projected into the future until a
26 graded profile was reached suggested that the gully would erode for at least another 260 years
27 after 2010 until the year 2270, with an ultimate size 42 times its 1949 size (Fig. 12a,d). If
28 negative exponential trends are used for projections, this changed to 290 years until a graded
29 profile was reached. At KWGC2, both linear and negative exponential trends suggested that the
30 gully would erode for at least another 260 years until the year 2270, to 24 times its 1958 size. In
31 contrast, linear trends at HBGC1 projected erosion for at least ~1200 years, while negative
32 exponential trends projected erosion for ~1700 years. The low rates of expansion at HBGC1ab
33 ($A/A_0 < \sim 2$; Fig. 8) and the lower slope used to project profiles into the floodplain suggested that
34 HBGC1 would only grow to 13 times its 1949 size.

1 4.4 Gully evolution from LiDAR data

2 At HBGC1 using a location-for-time substitution of gully form and evolution, cross-sections
3 through the main gully (A–A') were compared to several adjacent large (B–B') and small (C–
4 C') hollows (Fig. 13). These cross-sections demonstrate the transformation of uneroded shallow
5 hollows into dissected gully complexes through lateral and vertical expansion (Fig. 14). The
6 longitudinal profile of the main HBGC1 channel was also compared to the profile of a rounded
7 bank gully (HBGC99) without a connection to an upslope hollow (Figs. 12b and 13). The
8 HBGC99 bank gully profile is imminently unstable, with head cuts starting to migrate upstream,
9 and is much steeper compared to the HBGC1 profile that already has incised into the floodplain
10 and upstream hollow. The incision of HBGC1 was likely contingent on its connection to the
11 upstream hollow, while HBGC99 had its headwaters captured by the development of the
12 HBGC1 catchment. Early stages of gullying were also observed on the immediate banks of the
13 river, where bank gullies have been initiated from local disturbances (rills, stock tracks, roads,
14 and bank erosion; Fig. 13).

15 5. Discussion

16 5.1 Gully erosion rates and area expansion

17 Delineating long sections of alluvial gully scarp fronts using recent GPS surveys and historical
18 air photographs was effective for quantifying the variability in annual scarp retreat across many
19 sites over short to medium time periods. Average linear rates of gully erosion within the
20 Mitchell megafan (0.02 to 1.7 m yr⁻¹) were within the same order of magnitude to the most
21 comparable study of medium-term alluvial gully erosion rates (0.02–0.26 m yr⁻¹) measured by
22 Marzloff et al. (2011) in Spain. Due to difficulty detecting subtle scarp change over short time
23 periods due to inherent measurement error, other technologies will also be useful in measuring
24 intra- and inter-annual change at gully scarps, such as time-lapse photography (Shellberg et al,
25 2013a), low-altitude large-scale aerial photographs (Marzloff et al., 2011) and/or or high
26 resolution terrestrial laser scanning (Shellberg and Brooks, 2013).

27 Scarp retreat rates at alluvial gullies are known to vary by time scale and measurement method
28 (Marzloff et al., 2011; Shellberg et al., 2013b). The differences between erosion rates measured
29 from historic air photos and recent GPS (Fig. 7) could be a result of exponential decline in
30 erosion rates, changes in rainfall drivers, vegetation resistance, soil erodibility and/or inherent
31 differences in measurement methods and time scales. One half of the 18 gully sites had negative
32 exponential trends in aerial expansion over the historical period (Fig. 8b) that would have
33 influenced rate distributions (1949–1975 and 1975–2006; Fig. 7). Inter-annual, annual and
34 decadal rainfall totals are variable within a consistent range at these study sites and known to
35 influence scarp retreat rates (Shellberg et al., 2013a,b; Fig. 3). The drought in the 1980s could
36 have influenced the lower rates between 1975–2006, but the drought was preceded and followed

1 by wet periods in the mid-1970s and late-1990s onward. The scale and method accuracy of the
2 scarp perimeter measurements could also be a factor. For a given gully area, the GPS method
3 measures longer, more convoluted gully perimeters compared to coarser air photograph
4 measurements. This could potentially reduce average erosion rates, but could also be offset by
5 increased area measurement. More detailed investigations will be needed to assess all these
6 factors, but we do not consider these to be of significance in terms of the conclusions arising out
7 of this study.

8 Extrapolation of area trends back in time demonstrated that many large alluvial gully complexes
9 were post-European features (Fig. 8). Extrapolations were less certain for the slowest growing
10 gullies, complicated by the lack of air photo data before 1949 and uncertainty in choice of
11 mathematical model. For all cases, it is possible that the available data over a finite period
12 (1949–2010) might bias the trend toward a more linear form, and omit any rapid erosion rates
13 immediately after disturbance (e.g., Graf, 1977; Simon, 1992; Rutherford et al., 1997).

14 Within supply-limited colluvial gullies and hillslopes, numerous researchers have documented
15 negative-exponential decline in growth due to sediment exhaustion over time or bedrock control
16 (Graf, 1977; Rutherford et al., 1997; Olley and Wasson, 2003; Rustomji and Pietsch, 2007).
17 Other gully researchers have assumed linear trends where there was insufficient basis to
18 determine otherwise, where small sample sizes (three to four air photos) limited data
19 exploration, or actual linear trends were present from detailed analysis (Shepard 2010; Saxton et
20 al., 2012; Brooks et al. 2013). In this Mitchell gully study, both negative exponential trends and
21 linear trends in area growth were observed from detailed analysis of photos each decade
22 between 1949–2010, as well as the estimation of area error margins and *RMSE*. The benefit of
23 the negative exponential function used here is that the coefficient k can be used to explore the
24 degree of linearity in the data, and project the time (or half-life) until stabilisation. The k values
25 (0.0007 to 0.0028) observed in these alluvial gullies were smaller than those observed or
26 modelled in other studies (Graf, 1977; Simon, 1992; Rutherford et al., 1997), resulting in both
27 near linear trends and longer relaxation times after disturbance, and negative exponential trends
28 with faster initial growth and slower growth over time.

29 Alluvial gully erosion into dispersible floodplain soils on the Mitchell megafan is typically
30 unconfined both horizontally and vertically (Brooks et al. 2009). Both gully elongation and
31 lateral expansion can provide a relatively continuous supply of sediment at the transport limit,
32 with sediment yield highly correlated to monsoonal rainfall and scarp retreat (Shellberg et al.,
33 2013b). This can lead to near linear growth over time until grade stabilisation occurs in all
34 directions for periods of several 100s to 1000s of years. However, some vertical confinement
35 can be provided by bedrock or indurated ferricrete layers, which could have influenced sediment
36 availability and aerial growth rates at sites with the slowest rates and strongest exponential

1 decline (Fig. 8b). From a long-term sediment supply perspective, the fact that alluvial gullies
2 can potentially contribute sediment at the transport limit (Shellberg et al., 2013b; Rose et al.,
3 2015) is a contrast to many colluvial gullies that tend to be self-limiting over timescales of a
4 century or less (e.g. Graf, 1977; Olley and Wasson, 2003).

5 5.2 *Gully erosion chronologies from OSL dating*

6 Optically stimulated luminescence dating revealed that there was a major change in erosion and
7 sedimentation patterns near and after the time of European settlement and introduction of cattle
8 grazing (*circa* 1872). At WPGC2, initial shallow erosion following disturbance deposited
9 sediment within floodplain hollows, with subsequent deep gully incision following a complex
10 response to disturbance (*sensu* Schumm, 1973, 1979). While earlier forms of floodplain channel
11 erosion and drainage hollows existed on the Mitchell floodplain during the Holocene, the rates
12 of sedimentation post-European settlement at WPGC2 were five times higher than pre-European
13 erosion rates within preceding drainage hollows. Similar gully sedimentary units, OSL dates,
14 and post-European shifts in deposition rates (0.5 mm yr^{-1} pre-European; 14 mm yr^{-1} post-
15 European) have been documented in gully profiles in the adjacent Normanby River catchment
16 (Brooks et al. 2013; Pietsch et al., 2015). These stratigraphic data define the shift from the
17 Holocene to the Anthropocene in northern Australia (*sensu* Waters et al., 2016).

18 5.3 *Projections of future gully growth and duration*

19 The future spatial and temporal projections of gully area growth – using the concept of an
20 equilibrium grade or slope and constant average linear retreat rates – represented a minimum
21 estimate in space and time for gully scarps to stabilize. These estimates of continued erosion for
22 several hundred years are reasonable from our understanding of alluvial gully evolution, but
23 many uncertainties are embedded in these estimates. Actual growth trends over the next few
24 hundred years will be influenced by non-static hydro-climatic and geomorphic conditions.
25 Stabilisation could take longer if exponential decline in growth occurs, sites are re-disturbed by
26 external forcing, and/or a reduction in sediment supply from graded scarp slopes creates
27 sediment transport imbalances that reinitiate incision. Future climate change scenarios in
28 northern Australia are uncertain, but increased rainfall intensity during extreme events could
29 accelerate erosion rates with unknown consequences. However for immediate land management
30 purposes, it is clear from these growth projections that alluvial gullies will remain chronic
31 features on the landscape for at least several hundred years once initiated by natural and/or
32 anthropogenic factors, unless erosion is mitigated by land management intervention (Shellberg
33 and Brooks, 2013).

34 5.4 *Gully evolution: Reconciling quantitative data and explorer observations*

35 Location-for-time terrain analysis using LiDAR data demonstrated that alluvial gullies can
36 evolve from incipient gullies on channel banks into massive alluvial gully complexes (Brooks et

1 al., 2009). At HBGC1, extrapolation of gully area trends back in time and OSL data suggested
2 that the upper part of the dissected gully complex was not eroded in 1845 when Leichhardt and
3 Gilbert passed this location. However, both journal records (Gilbert, 1845; Leichhardt, 1847)
4 and LiDAR data indicate that rounded fluvial features (floodplain hollows and precursor gullies
5 on steep river banks) were likely present in 1845. It is deduced that incipiently unstable bank
6 gullies, adjacent floodplain hollows, and other inherited (antecedent) features co-evolved and
7 incised into the massive gully complexes during the post-European period. The initiation of
8 gullying into river banks, precursor gullies, and floodplain hollows was dependent on natural
9 and anthropogenic disturbance factors that triggered incision into these unstable features.

10 *5.5 Sediment production from alluvial gullies across the megafan*

11 The erosion rate data presented here can be used to update earlier estimates of sediment
12 production from alluvial gullies in the Mitchell catchment (Brooks et al., 2008, 2009; Rustomji
13 et al., 2010). These calculations are based on recent and historic median rates of annual scarp
14 retreat, catchment gully distribution, gully scarp perimeter measurements, scarp heights
15 correlated to relative relief and downriver floodplain elevation, and soil bulk densities. It is now
16 estimated that $\sim 6.3 \text{ Mt yr}^{-1}$ of sand, silt, and clay were eroded historically (1949-2006) from
17 alluvial gullies, compared to $\sim 3.9 \text{ Mt yr}^{-1}$ recently (2005–2010). There is still uncertainty in
18 these data due to the spatial and temporal variability in scarp retreat rates and the accuracy of
19 mapping the density of all alluvial gullies at the landscape scale (Brooks et al., 2008, 2009;
20 Shellberg et al., 2013a,b). However, compared to other components of the Mitchell catchment
21 sediment budget or sediment yield estimates at downstream gauges (Brooks et al., 2008;
22 Rustomji et al., 2010; Shellberg, 2011; Shellberg et al., 2013b), these alluvial gullies are a major
23 component of the sediment budget. Independent sediment tracing research in the Mitchell
24 catchment has confirmed that sub-surface soils from gully erosion, channel erosion, deep rilling
25 and scalded soils dominate the fine sediment budget (Caitcheon et al., 2012).

26 *5.6 Gully initiation and geomorphic thresholds*

27 Understanding the possible mechanisms that contributed to the acceleration of gully initiation
28 and erosion following European settlement requires a process-based analysis of geomorphic
29 change, which is provided here. The initiation of gully erosion and channel incision is
30 influenced by internal and external factors that can exceed geomorphic thresholds resulting in
31 instability and landform change (e.g., Schumm and Hadley, 1957; Schumm, 1973, 1979; Cooke
32 and Reeves, 1976; Graf, 1979; Prosser et al., 1994; Prosser and Slade, 1994; Tucker et al.,
33 2006). Long-term factors include climate, geology, soil type, weathering, relief, base level,
34 slope angles, sediment storage volume, and inherited or antecedent terrain. Factors influential
35 over shorter time periods include fluctuations in rainfall and hydrology, changes in vegetation
36 cover and resistance, and anthropogenic land use (Schumm and Lichty, 1965; Phillips, 2010).

1 The over-steepened bank slopes along channels of the upper Mitchell megafan are a result of
2 fan-head trenching since the late-Pleistocene (Grimes and Douth, 1978; Fig. 1). This incision
3 could have been influenced by changes in base level (Chappell et al., 1982; Nanson et al.,
4 2013), reductions in sediment supply in the Holocene after a major period of floodplain and fan
5 sedimentation during the Last Glacial Maximum (Nanson et al., 1992; Thomas et al., 2001), and
6 changes to rainfall and water runoff as the current monsoonal climate regime developed
7 (Kershaw, 1978; Kershaw and Nanson, 1993). The reduced connectivity of flood water with the
8 megafan surface after incision (Shellberg et al., 2013a) transformed the high floodplain from an
9 aggrading to a degrading environment. Incision and tropical weathering through the Holocene
10 made available large volumes of dispersible sodic soils (Isbell et al., 1968; Galloway et al.,
11 1970). The potential for alluvial gully erosion increased where the local relative relief and bank
12 slope was greatest and coincident with these highly dispersible soils (Brooks et al., 2009;
13 Shellberg et al., 2013a).

14 The inherited (antecedent) floodplain terrain adjacent to river channels on the Mitchell megafan
15 influenced the potential for gully initiation and propagation. These inherited features include
16 shallow flood drainage hollows, steep rounded gullies on immediate river banks, fluvial levees,
17 paleo-channels and lagoons, and larger creeks. Their spatial distribution is highly contingent on
18 the local evolution of the floodplain or megafan surface (e.g., Wilkinson et al., 2006; Phillips
19 and Slattery, 2008). While inherited floodplain features are not requisite for gully initiation or
20 expansion (Brooks et al., 2009), they can be especially unstable components of the landscape.
21 These topographic irregularities are preferential locations for surface- or soil-water draining off
22 the floodplain, often have unique soil conditions, are preferential cattle grazing areas or
23 migration routes, and thus are inherently prone to degradation by gully incision.

24 The monsoonal climate of the Cape York Peninsula has been relatively stable over the last
25 6000-years following the Last Glacial Maximum compared to longer-term glacial-interglacial
26 cycles (Kershaw 1978; Kershaw and Nanson 1993). However, decadal fluctuations in climate
27 due to ENSO cycles (Lough, 1991; Risbey et al., 2009; Fig. 3) are a signature of the current
28 climate, with additional variability in the occurrence of tropical cyclones. In the Mitchell
29 catchment, Nott et al. (2007) measured oxygen isotope ratios in limestone stalagmites as a
30 rainfall proxy and documented that cyclone landing frequency and magnitude were relatively
31 high from AD 1400 and 1800, and comparatively low from AD 1800–2000 during the period
32 when a majority of these alluvial gullies initiated. The floodplain sediment into which these
33 alluvial gullies are eroding has an age > 35,000 years BP, and has persisted mostly intact
34 through the Holocene despite river and major tributary incision. Therefore, while climate
35 variability is no doubt important, it is not a new phenomenon, and cannot alone explain the
36 recent synchronous incision and acceleration of alluvial gulying across the Mitchell megafan

1 (this study), the neighbouring Normanby catchment (Brooks et al., 2013; Shellberg and Brooks
2 2013) and other floodplains across northern Australia (Condon, 1986; McCloskey, 2010) during
3 the last 100 years of European settlement and land use.

4 The kinetic energy from rainfall, in-channel and overbank river discharge, and floodplain
5 drainage is the main driver for alluvial gully erosion initiation and propagation. Monsoonal
6 convective storms in the Mitchell catchment have moderately high rainfall intensity and
7 erosivity that dominate rill initiation and gully erosion processes (Shellberg et al., 2013a). Wet
8 and dry cycles at the storm, annual, and decadal scale can influence the kinetic energy available
9 for erosion (Lough, 1991; Nott et al., 2007; Risbey et al., 2009; Shellberg et al., 2013a).
10 Extreme rainfall events, such as from tropical cyclones (Nott et al., 2007), can lead to large-
11 scale flooding along rivers that can also play a role in alluvial gully initiation and propagation.
12 River backwater and overbank flooding into floodplain hollows was observed to increase gully
13 erosion at KWGC2 (Shellberg et al., 2013a), but this is not a prerequisite for gully activity;
14 rather it can add to ubiquitous rainfall driven erosion. Scour of floodplain drainage channels can
15 occur during flood drawdown, as can failure of bank slumps from water seepage. Bank erosion
16 is widespread along the lower Mitchell River (Brooks et al., 2008). Linear bank retreat could
17 initiate ‘continuous scarp front’ gullies (Brooks et al., 2009), as well as destabilize adjacent
18 floodplain drainage channels.

19 The stability of valley floors and initiation of gulying depends on the balance between the
20 critical shear stress of flowing water needed to entrain sediment and the resisting and energy
21 dissipating factors of vegetative cover. Reduced vegetative cover or biomass for a given
22 hydrological regime can induce channel incision and gulying (Graf, 1979; Prosser and Slade,
23 1994). Both natural factors (such as drought and fire) and anthropogenic land use can influence
24 vegetative cover and thresholds of gully erosion. The initiation of gully erosion corresponding
25 with vegetation disturbance after the introduction of cattle has been observed on other alluvial
26 plains and valleys in Australia (e.g., Eyles, 1977; Condon, 1986; Pickup, 1991; Prosser and
27 Winchester, 1996; Pringle et al., 2006).

28 Major land use change from traditional Aboriginal management to cattle grazing (Fig. 4)
29 undoubtedly disturbed the soil and native grass of riparian woodlands across the Mitchell
30 megafan. Mismanagement of cattle and the landscape was widespread (QSA, 2008; Shellberg,
31 2011), as described for the Wrotham Park Aggregation: “*no property in the North has been*
32 *maintained or cared for worse, and this includes the quality of cattle and horses, together with*
33 *plant and improvements*” (W. Reid, Queensland Primary Producers Co-op, 3rd Dec 1963; QSA,
34 2008).

1 Along the Mitchell River, cattle congregated in riparian zones for water access and grass feed
2 from fertile soils, and were concentrated along river stock routes during cattle drives (QSA,
3 2008). Grazing, and soil disturbance by cattle hoofs, reduced native perennial grass cover and
4 vigour that were essential for stabilizing dispersible soils (Shellberg and Brooks, 2013). Soil
5 disturbance and the reduction of soil organic cover promoted the scalding of sodic soils, loss of
6 biological crusts, soil compaction, reduced infiltration, and accelerated water runoff, as
7 observed in other tropical rangelands (e.g., Bridge et al., 1983; McIvor et al., 1995; Dunne et al.,
8 2011). Dense and deep cattle tracks (pads) traversed steep banks down to water holes, cut into
9 the fragile soils, and channelled overland flow from rainfall and floodwater into gullies (e.g.,
10 Condon, 1986; Brooks et al, 2009; Shellberg and Brooks, 2013). Cattle tracks also followed the
11 easiest path to water; in many cases this was down incipiently-unstable floodplain hollows and
12 rounded bank gullies. Weed invasion into riparian zones became commonplace by the 1920s
13 (QSA, 2008; Shellberg, 2011). Major changes to the fire regime also occurred, with a shift from
14 low-intensity early-dry season fires and mosaic burning by Aboriginal people, toward greater
15 fire suppression by pastoralists with limited use of fire in the early-dry and early-wet seasons to
16 control cattle and maximize feed, but not maintain grass cover or vigour (Hann, 1872; Crowley
17 and Garnett, 2000).

18 The initiation and propagation of alluvial gullies across the Mitchell megafan were undoubtedly
19 influenced by multiple synergistic factors. The long-term evolution of the Mitchell megafan and
20 inherited floodplain features provided the inherent gully erosion potential, while shorter-term
21 hydro-climatic drivers and land use impacts on vegetative cover and soil erosion resistance
22 helped push the landscape across a stability threshold. For example, the rapid increase of cattle
23 in the lower Mitchell after 1900 (Fig. 4) was coincident with several years of above average
24 rainfall (Fig. 3). Cattle numbers remained relatively high into the subsequent dry phase in the
25 late 1910s, both of which likely reduced grass cover and increased the effective kinetic energy
26 of rainfall impacting soil. These natural climate variations could have exacerbated the erosional
27 impacts of cattle that were not destocked from sensitive areas during long dry seasons and
28 drought years, similar to elsewhere in Australia (McKeon et al., 2004; Stafford Smith et al.,
29 2007).

30 **6. Conclusions**

31 Along the Mitchell fluvial megafan, historic trends in alluvial gully area extrapolated back in
32 time suggested that most large alluvial gully complexes are post-European features. OSL dating
33 quantified an increase in gully deposition rates after the introduction of cattle grazing and land
34 use change, following a complex response of initial soil stripping, deposition in hollows, and
35 then deep gully incision. LiDAR terrain analysis, OSL data, and air photos suggested that
36 incipiently unstable bank gullies and floodplain hollows observed by European explorers

1 subsequently coevolved and incised into sediments deposited >35,000 BP to become the
2 massive gully complexes observable today. While uncertainty remains in defining the exact
3 processes and mechanisms for triggering gully initiation, both natural (extreme rainfall, floods,
4 and drought) and anthropogenic (grazing, fire, weeds, and roads) disturbance factors likely
5 worked synergistically to erode unstable landscape features. Once initiated, these gullies will
6 continue to erode large areas of riparian landscape for hundreds if not thousands of years.

7 This study has obvious implications for improving land management across northern Australia
8 and beyond. A major paradigm shift in grazing land management has long been needed (e.g.,
9 Winter, 1990), in order to maintain native grass health and cover, reduce soil disturbance and
10 erosion, re-introduce sustainable fire regimes, reduce exotic and woody weed invasion, and
11 adjust to climate variability (Stafford Smith et al., 2007). Improved land management would see
12 cattle excluded or spelled from riparian zones and steep banks and associated hollows across
13 wide areas of river frontage (>4 km, Brooks et al. 2009) via fencing, off-stream water point
14 development and/or improved pasture conditions away from river frontage. This will reduce the
15 initiation of new alluvial gullies, slow gully erosion rates where already initiated, and aid in
16 passive or proactive gully rehabilitation efforts (Shellberg and Brooks, 2013).

17 This study demonstrates the vulnerability of floodplains and megafans to gully erosion. The
18 nature and extent of alluvial gulying should be investigated in more detail on other floodplains
19 and megafans globally, as well as their sensitivity to degradation from intrinsic and extrinsic
20 variables, land use change, and future climate change. Our understanding of floodplains and
21 megafans as predominantly depositional environments needs to change to incorporate
22 deposition and erosion cell dynamics over a variety of spatial and temporal scales along the
23 (dis)continuum of process domains, channel evolution, and antecedent alluvial morphology.

24 **Acknowledgements**

25 The Tropical Rivers and Coastal Knowledge (TRaCK) program, Caring for Our Country
26 program, Northern Gulf NRM Group, Land & Water Australia, and Griffith University funded
27 this project. Terry Culpitt and staff at the Queensland Department of Environment and Resource
28 Management provided historic air photograph support. Jorg Hacker and Wolfgang Lieff from
29 Airborne Research Australia acquired and processed the airborne LiDAR data. Ken McMillan
30 and Chris Leslie at CSIRO and Daniel Borombovits and Jon Olley at Griffith University
31 provided OSL support and advice. Field assistance was provided by the Kowanyama Rangers,
32 Kris Jaeger, Garrett Bean and Ariane Hefferan. Project support was provided by Deb Eastop,
33 Brynn Mathews and Bill Sokolich at the Mitchell River Watershed Management Group, and
34 Noeline Ikin and Tim Hoogwerf at the Northern Gulf NRM Group. Cultural guidance by
35 Aboriginal Traditional Owners was provided by the late Vivian Lane for Gugu Mini country
36 and by Willie Banjo and the Kowanyama Rangers for Yir Yoront country. We especially thank

1 the managers of Wrotham Park, Highbury and Dunbar Stations and the Kowanyama Aboriginal
2 Land Office for property access and the time to discuss the management, challenges, and beauty
3 of the lower Mitchell catchment. Critical but constructive reviews by Justin Wilkinson and
4 several anonymous reviewers improved the manuscript.

1 **References**

- 2 Aitken, M.J., 1998. *Introduction to Optical Dating: Dating of Quaternary Sediments by the Use of*
3 *Photon-stimulated Luminescence*. Clarendon Press, 280 pp.
- 4 Arnold, G., 1997. Grazier experience with Stylosanthes technology. III. Wrotham Park, 1963-1988.
5 *Tropical Grasslands*, 31, 522-526.
- 6 Arnold, L.J., Roberts, R.G., Galbraith, R.F., DeLong, S.B., 2009. A revised burial dose estimation
7 procedure for optical dating of young and modern-age sediments. *Quaternary Geochronology*, 4,
8 306-325.
- 9 ABOM (Australian Bureau of Meteorology), 2015. *Climate Data*. Accessed online in
10 2015 at: <http://www.bom.gov.au/climate/>
- 11 ABS (Australian Bureau of Statistics), 2008. *7124.0- Historical Selected Agriculture Commodities, by*
12 *State (1861 to Present), Total cattle numbers*. Australian Bureau of Statistics.
- 13 Bartley, R., Hawdon, A., Post, D.A., Roth, C.H., 2007. A sediment budget for a grazed semi-arid
14 catchment in the Burdekin basin, Australia. *Geomorphology*, 87, 302-321.
- 15 Bartley, R., Wilkinson, S.N., Hawdon, A.A., Abbott, B.N., Post, D.A., 2010. Impacts of improved
16 grazing land management on sediment yields Part 2: Catchment response. *Journal of Hydrology*,
17 389, 249-259.
- 18 Bowman, D.M.J.S., Sharp, B.R. and Zoppi, U., 2004. Isotopic (¹³C and ¹⁴C) evidence supporting the
19 transformative effect of cattle on north Australian vegetation. *Journal of Biogeography*, 31,
20 1373-1375.
- 21 Bridge, B.J., Mott, J.J. and Hartigan, R.J., 1983. The formation of degraded areas in the dry savanna
22 woodlands of Northern Australia. *Australian Journal of Soil Research*, 21, 91-104.
- 23 Brooks, A.P. and Brierley, G.J., 1997. Geomorphic responses of lower Bega River to catchment
24 disturbance, 1851-1926. *Geomorphology*, 18, 291-304.
- 25 Brooks, A.P., Spencer J., Shellberg J.G., Knight J., Lymburner L., 2008. Using remote sensing to quantify
26 sediment budget components in a large tropical river - Mitchell River, Gulf of Carpentaria. In
27 *Sediment Dynamics in Changing Environments* (Proceedings of a symposium held in
28 Christchurch, New Zealand, December 2008). IAHS Publ. 325, pp. 225-236.
- 29 Brooks, A.P., Shellberg, J.G., Spencer, J. and Knight, J., 2009. Alluvial gully erosion: an example from
30 the Mitchell fluvial megafan, Queensland, Australia. *Earth Surface Processes and Landforms*,
31 34, 1951-1969. With 2010 Erratum, *Earth Surface Processes and Landforms*, 35, 242-245.
- 32 Brooks, A., Spencer, J., Olley, J., Pietsch, T., Borombovits, D., Curwen, G., Shellberg, J., Howley, C.,
33 Gleeson, A., Simon, A., Bankhead, N., Klimetz, D., Eslami-Endargoli, L., Bourgeault, A., 2013.
34 *An Empirically-Based Sediment Budget for the Normanby Basin: Sediment Sources, Sinks, and*
35 *Drivers on the Cape York Savannah*. Griffith University, Australian Rivers Institute, Final
36 Report for the Australian Government Caring for Our Country - Reef Rescue Program Available
37 at: <http://www.capeyorkwaterquality.info/downloads>.
- 38 Caitcheon, G.C., Olley, J.M., Pantus, F., Hancock, G. and Leslie, C., 2012. The dominant erosion
39 processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT),
40 Mitchell (Qld) and Flinders (Qld) Rivers. *Geomorphology*, 151-152, 188-195.
- 41 Chappell, J., Rhodes, E.G., Thom, B.G. and Wolanski, E., 1982. Hydro-isostasy and the sea-level isobase
42 of 5500 BP in North Queensland, Australia. *Marine Geology*, 49(1-2), 81-90.
- 43 Chivas, A.R., Garcia, A., van der Kaars, S., Couapel, M.J.J., Holt, S., Reeves, J.M., Wheeler, D.J.,
44 Switzer, A.D., Murray-Wallace, C.V., Banerjee, D., Price, D.M., Wang, S.X., Pearson, G.,
45 Edgar, N.T., Beaufort, L., De Deckker, P., Lawson, E. and Cecil, C.B., 2001. Sea-level and
46 environmental changes since the last interglacial in the Gulf of Carpentaria, Australia: an
47 overview. *Quaternary International*, 83-5: 19-46.
- 48 Condon, R.W., 1986. *A Reconnaissance Erosion Survey of part of the Victoria River District, N.T.*,
49 Hassall & Associates, Canberra.
- 50 Condon, R.W., Newman, J.C. and Cunningham, G.M., 1969. Soil erosion and pasture degeneration in
51 Central Australia: Part 1 - Soil erosion and degeneration of pastures and topfeeds. *Journal of the Soil*
52 *Conservation Service of New South Wales*, 25, 47-92. Cooke, R.U. and Reeves, R., 1976.
53 *Arroyos and Environmental Change in the American South-West*. Clarendon Press, London.
- 54 Crowley, G.M. and Garnett, S.T., 1998. Vegetation change in the grasslands and grassy woodlands of
55 east-central Cape York Peninsula, Australia. *Pacific Conservation Biology*, 4(2), 132-148.
- 56 Crowley, G.M. and Garnett, S.T., 2000. Changing fire management in the pastoral lands of Cape York
57 Peninsula of Northeast Australia, 1623 to 1996. *Australian Geographical Studies*, 38(1), 10-26.
- 58 Dunne, T., Western, D. and Dietrich, W.E., 2011. Effects of cattle trampling on vegetation,
59 infiltration, and erosion in a tropical rangeland. *Journal of Arid Environments*, 75(1), 58-69.
- 60 Edye, L.A. and Gillard, P., 1985. Pasture improvement in semi-arid tropical savannas: a practical example

- 1 in northern Queensland. In: J.C. Tothill and J.J. Mott (Editors), *Ecology and Management of the*
2 *World's Savannas*. Australian Academy of Science, Canberra, ACT, pp. 303-309.
- 3 Eyles, R.J., 1977. Changes in drainage networks since 1820, Southern Tablelands, N.S.W. *Australian*
4 *Geographer*, 13, 377-386.
- 5 Fanning, P.C., 1999. Recent landscape history in arid western New South Wales, Australia: a model for
6 regional change. *Geomorphology*, 29(3-4), 191-209.
- 7 Fensham, R.J. and Skull, S.D., 1999. Before cattle: A comparative floristic study of Eucalyptus savanna
8 grazed by macropods and cattle in north Queensland, Australia. *Biotropica*, 31(1), 37-47.
- 9 Galbraith, R.F., Roberts, R.G., 2012. Statistical aspects of equivalent dose and error calculation and
10 display in OSL dating: An overview and some recommendations. *Quaternary Geochronology*,
11 11, 1-27.
- 12 Galloway, R.W., Gunn, R.H. and Story, R., 1970. *Lands of the Mitchell-Normanby Area, Queensland*.
13 CSIRO, Land Research Series 26, 1-101.
- 14 Gilbert, J., 1845. *Diary of the Port Essington Expedition, 18 Sept. 1844 - 28 June 1845*. Mitchell
15 Library: State Library of New South Wales, 226 pp.
- 16 Graf, W.L., 1977. The rate law in fluvial geomorphology. *American Journal of Science*, 277, 178-91.
- 17 Graf, W.L., 1979. The development of montane arroyos and gullies. *Earth Surface Processes*, 4, 1-14.
- 18 Grimes, K.G. and Douth, H.F., 1978. The late Cainozoic evolution of the Carpentaria Plains, Northern
19 Queensland. *BMR Journal of Australian Geology and Geophysics*, 3, 101-112.
- 20 Hancock, G.R. and Evans, K.G., 2010. Gully, channel and hillslope erosion – an assessment for a
21 traditionally managed catchment. *Earth Surface Processes and Landforms*, 35: 1468-1479.
- 22 Hancock, G. J., S. N. Wilkinson, A. A. Hawdon and R. J. Keen, 2014. Use of fallout tracers ⁷Be, ²¹⁰Pb
23 and ¹³⁷Cs to distinguish the form of sub-surface soil erosion delivering sediment to rivers in
24 large catchments. *Hydrological Processes* 28(12), 3855-3874.
- 25 Hann, W., 1872. *Expedition of Exploration to the Endeavour River, Cape York Peninsula, 1872*.
26 Reconstructed from his diary and two notebooks by Harry Clarke, 1982, with an introduction by
27 Helen Mays, 81 pp.
- 28 Hughes, M.L., McDowell, P.F., Marcus, W.A., 2006. Accuracy assessment of georectified aerial
29 photographs: Implications for measuring lateral channel movement in a GIS. *Geomorphology*,
30 74, 1-16.
- 31 Hughes, A., Olley J.M, Croke, J., and Webster, I., 2009. Determining floodplain sedimentation rates
32 using ¹³⁷Cs in a low fallout environment dominated by channel- and cultivation-derived
33 sediment inputs, central Queensland. *Australia Journal of Environmental Radioactivity* 100,
34 858–86.
- 35 Isbell, R.F., Webb, A.A. and Murtha, G.G., 1968. *Atlas of Australian Soils - Explanatory Data for Sheet 7*
36 *North Queensland*. CSIRO and Melbourne University Press, Victoria.
- 37 Jardine, F. and Jardine, A., 1867. *Narrative of the overland expedition of the Messrs. Jardine, from*
38 *Rockhampton to Cape York, Northern Queensland, 1864-1865*. Compiled from the journals of
39 the brothers, and edited by Frederick J. Byerley (engineer of roads, northern division of
40 Queensland). J.W. Buxton Publisher, Brisbane. Available at www.gutenberg.net
- 41 Jones, D.A., Wang, W. and Fawcett, R., 2009. High-quality spatial climate data-sets for Australia.
42 *Australian Meteorological and Oceanographic Journal*, 58 (233-248).
- 43 Kershaw, A.P., 1978. Record of last interglacial cycle from northeast Queensland. *Nature*, 272, 159-61.
- 44 Kershaw, A.P. and Nanson, G.C., 1993. The last full glacial cycle in the Australian region. *Global and*
45 *Planetary Change*, 7, 1-9.
- 46 Lal, R., 1992. Restoring land degraded by gully erosion in the tropics. *Advances in Soil Science*, 17,
47 123-151.
- 48 Lane, E.W., 1955. Design of stable channels. *Transactions of the American Society of Civil Engineers*,
49 120, 1234-1279.
- 50 Leichhardt, L., 1847. *Journal of an Overland Expedition in Australia: from Moreton Bay to Port*
51 *Essington, a distance of upwards of 3000 miles, during the years 1844-1845*. T&W Boone,
52 London, 544 pp.
- 53 Lough, J.M., 1991. Rainfall variations in Queensland, Australia: 1891-1986. *International Journal of*
54 *Climatology*, 11(7), 745-768.
- 55 Mackin, J.H., 1948. Concept of the graded river. *Geological Society of America Bulletin*, 59, 463-512.
- 56 Marzolf, I., Ries, J.B., Poesen, J., 2011. Short-term versus medium-term monitoring for detecting gully-
57 erosion variability in a Mediterranean environment. *Earth Surface Processes and Landforms*,
58 36(12), 1604–1623.
- 59 McCloskey, G.L., 2010. *Riparian Erosion Morphology, Processes and Causes along the Victoria River,*
60 *Northern Territory, Australia*. Charles Darwin University, PhD Thesis, pp. 200.
- 61 McIvor, J.G., Williams, J. and Gardener, C.J., 1995. Pasture management influences runoff and soil
62 movement in the semi-arid tropics. *Australian Journal of Experimental Agriculture*, 35, 55-65.

- 1 McKeon, G., Hall, W., Henry, B., Stone, G. and Watson, I., 2004. *Pasture degradation and recovery in*
2 *Australia's rangelands: learning from history*. Queensland Dept. of Natural Resources, Mines
3 and Energy, Indooroopilly, Qld., 256 pp.
- 4 Medcalf, F.G., 1944. *Soil Erosion Reconnaissance of the Ord River Valley and Watershed*. Report to the
5 Department of Lands and Surveys, Western Australia.
- 6 Mejdahl, V., 1979. Thermoluminescence dating: beta-dose attenuation in quartz grains. *Archaeometry*,
7 21(1), 61-72.
- 8 Mertes, L.A.K. and Dunne, T., 2008. Effects of tectonism, climate change, and sea-level change on the
9 form and behaviour of the modern Amazon river and its floodplain. In: A. Gupta (Editor), *Large*
10 *Rivers: Geomorphology and Management*. John Wiley and Sons, West Sussex, UK, pp. 115-
11 144.
- 12 Murray, A.S., Marten, R., Johnston, A. and Martin, P., 1987. Analysis for naturally occurring
13 radionuclides at environmental concentrations by gamma spectrometry. *Journal of*
14 *Radioanalytical and Nuclear Chemistry, Articles*, 115(2), 263-288.
- 15 Nanson, G.C., Price, D.M. and Short, S.A., 1992. Wetting and drying of Australia over the past 300 ka.
16 *Geology*, 20, 791-4.
- 17 Nanson, R.A., Vakarelov, B.K., Ainsworth, R.B., Williams, F.M., Price, D.M., 2013. Evolution of a
18 Holocene, mixed-process, forced regressive shoreline: The Mitchell River delta, Queensland,
19 Australia. *Marine Geology*, 339 22-43.
- 20 Neldner, V.J., Stanton, J.P., Fensham, R.J. and Clarkson, J.R., 1997. The natural grasslands of Cape York
21 Peninsula, Australia. Description, distribution and conservation status. *Biological Conservation*,
22 81(1-2), 121-136.
- 23 Nott, J., Haig, J., Neil, H. and Gillieson, D., 2007. Greater frequency variability of landfalling tropical
24 cyclones at centennial compared to seasonal and decadal scales. *Earth and Planetary Science*
25 *Letters*, 255(3-4), 367-372.
- 26 Olley, J.M. and Wasson, R.J., 2003. Changes in the flux of sediment in the Upper Murrumbidgee
27 catchment, Southeastern Australia, since European settlement. *Hydrological Processes*, 17(16),
28 3307-3320.
- 29 Olley, J.M., Pietsch, T. and Roberts, R.G., 2004. Optical dating of Holocene sediments from a variety of
30 geomorphic setting using single grains of quartz. *Geomorphology*, 60, 337-358.
- 31 Olley, J., Brooks, A., Spencer, J., Pietsch, T., Borombovits, D., 2013. Subsoil erosion dominates the
32 supply of fine sediment to rivers draining into Princess Charlotte Bay, Australia. *Journal of*
33 *Environmental Radioactivity*, 124, 121-129.
- 34 Parker, G., Muto, T., Akamatsu, Y., Dietrich, W.E. and Lauer, J.W., 2008. Unravelling the conundrum
35 of river response to rising sea-level from laboratory to field. Part II. The Fly–Strickland River
36 system, Papua New Guinea. *Sedimentology*, 55, 1657–1686.
- 37 Payne, A.L., Kubicki, A., Wilcox, D.G. and Short, L.C., 1979. *A Report on the Erosion and Range*
38 *Condition in the West Kimberley Area of Western Australia*, Department of Agriculture of
39 Western Australia, Technical Bulletin No. 42., pp. 52.
- 40 Phillips, J.D., 2010. Relative importance of intrinsic, extrinsic, and anthropic factors in the geomorphic
41 zonation of the Trinity River, Texas. *Journal of the American Water Resources Association*,
42 46(4), 807-823.
- 43 Phillips, J.D., Slattery, M.C., 2008. Antecedent alluvial morphology and sea level controls on form-
44 process transition zones in the lower Trinity River, Texas. *River Research and Applications*, 24,
45 293-309.
- 46 Pickup, G., 1985. The erosion cell: a geomorphic approach to landscape classification in range
47 assessment. *Australian Rangeland Journal*, 7(2), 114-121.
- 48 Pickup, G., 1991. Event frequency and landscape stability on the floodplain systems of arid Central
49 Australia. *Quaternary Science Reviews*, 10, 463-473.
- 50 Pietsch, T.J., 2009. Optically stimulated luminescence dating of young (<500 years old) sediments:
51 Testing estimates of burial dose. *Quaternary Geochronology*, 4(5), 406-422.
- 52 Pietsch, T.J., Brooks, A.P., Spencer, J., Olley, J.M., Borombovits, D. 2015. Age, distribution, and
53 significance within a sediment budget, of in-channel depositional surfaces in the Normanby
54 River, Queensland, Australia. *Geomorphology*, 239, 17-40.
- 55 Poesen, J., Valentin, C., Nachtergaele, J. and Verstraeten, G., 2003. Gully erosion and environmental
56 change: importance and research needs. *Catena*, 50(2-4), 91-133.
- 57 Pringle, H.J.R., Watson, I.W. and Tinley, K.L., 2006. Landscape improvement, or ongoing degradation
58 reconciling apparent contradictions from the arid rangelands of Western Australia. *Landscape*
59 *Ecology*, 21(8), 1267-1279.
- 60 Prosser, I.P., Chappell, J. and Gillespie, R., 1994. Holocene valley aggradation and gully erosion in
61 headwater catchments, south-eastern highlands of Australia. *Earth Surface Processes and*
62 *Landforms*, 19, 465-480.

- 1 Prosser, I.P. and Slade, C.J., 1994. Gully formation and the role of valley-floor vegetation, Southeastern
2 Australia. *Geology*, 22(12), 1127-1130.
- 3 Prosser, I.P. and Winchester, S.J., 1996. History and processes of gully initiation and development in
4 eastern Australia. *Zeitschrift für Geomorphologie, Suppl Bnd*, 105, 91 - 109.
- 5 QSA (Queensland State Archives), 2008. *Pastoral Run Files for Wrotham Park, Gamboola, Gamboola*
6 *South, Highbury, and Drumduff Cattle Stations*, Accessed in 2008 in Runcorn Queensland:
7 <http://www.archivessearch.qld.gov.au>.
- 8 Risbey, J.S., Pook, M.J., McIntosh, P.C., Wheeler, M.C. and Hendon, H.H., 2009. On the remote drivers
9 of rainfall variability in Australia. *Monthly Weather Review*, 137, 3233-3253.
- 10 Rose, C.W., Shellberg, J.G., Brooks, A.P., 2015. Modelling suspended sediment concentration and load
11 in a transport-limited alluvial gully in northern Queensland, Australia. *Earth Surface Processes*
12 *and Landforms*, 40(10), 1291-1303.
- 13 Rustomji, P. and Pietsch, T., 2007. Alluvial sedimentation rates from southeastern Australia indicate post-
14 European settlement landscape recovery. *Geomorphology*, 90, 73-90.
- 15 Rustomji, P., Shellberg, J., Brooks, A., Spencer, J. and Caitcheon, G. 2010. *A Catchment Sediment and*
16 *Nutrient Budget for The Mitchell River, Queensland*. A report to the Tropical Rivers and Coastal
17 Knowledge (TRaCK) Research Program. CSIRO Water for a Healthy Country National
18 Research Flagship. 119 pp. Available at: <http://track.gov.au/publications/registry/876>.
- 19 Rutherford, I.D., Prosser, I.P. and Davis, J., 1997. Simple approaches to predicting rates and extent of
20 gully development. In: S.S.Y. Wang, E.J. Langendoen and F.D.J. Shields (Editors), *Proceedings*
21 *of the Conference on Management of Landscapes Disturbed by Channel Incision*. The Centre for
22 Computational Hydroscience and engineering. The University of Mississippi, pp. 1124-1130.
- 23 Sattar, F., 2011. Geoinformatics Based Framework for Three Dimensional Gully Mapping and Erosion
24 Volume Calculation. PhD Dissertation, School of Environment and Life Sciences, Charles
25 Darwin University, Australia, 191 pp.
- 26 Saxton, N.E., Olley, J.M., Smith, S., Ward, D.P., Rose, C.W., 2012. Gully erosion in sub-tropical south-
27 east Queensland, Australia. *Geomorphology*, 173-174, 80-87.
- 28 Schumm, S.A. and Hadley, R.F., 1957. Arroyos and the semiarid cycle of erosion. *American Journal of*
29 *Science*, 255, 161-74.
- 30 Schumm, S.A. and Lichty, R.W., 1965. Space, time and causality in geomorphology. *American Journal*
31 *of Science*, 263, 110 - 119.
- 32 Schumm, S.A., 1973. Geomorphic thresholds and complex response of drainage systems. In: M.
33 Morisawa (Editor), *Fluvial Geomorphology*. Allen and Unwin, London, pp. 299-310.
- 34 Schumm, S.A., 1977. *The Fluvial System*. Wiley, New York.
- 35 Schumm, S.A., 1979. Geomorphic thresholds: the concept and its applications. *Transactions Institute*
36 *British Geographers*, 4, 485 - 515.
- 37 Sharp, R.L., 1934. *The Social Organisation of the Yir Yoront Tribe, Cape York Peninsula*. PhD
38 Dissertation, Harvard University.
- 39 Sharp, B.R. and Whittaker, R.J., 2003. The irreversible cattle-driven transformation of a seasonally
40 flooded Australian savanna. *Journal of Biogeography*, 30, 783-802.
- 41 Sharp, B.R. and Bowman, D.M.J.S., 2004. Net woody vegetation increase confined to seasonally
42 inundated lowlands in an Australian tropical savanna, Victoria River District, Northern
43 Territory. *Austral Ecology*, 29, 667-683.
- 44 Shepherd, R., 2010. Changes in gully erosion along the Upper Burdekin River frontage in north
45 Queensland. In: D.J. Eldridge, C. Waters (Eds.), *Proceedings of the 16th Biennial Conference of*
46 *the Australian Rangeland Society*. Australian Rangeland Society, Perth.
- 47 Shellberg, J.G. 2011. *Alluvial Gully Erosion Rates and Processes Across the Mitchell River Fluvial*
48 *Megafan in Northern Queensland, Australia*. Griffith University, PhD Dissertation, Brisbane,
49 Australia, 248pp.
- 50 Shellberg, J.G., Brooks, A.P., Spencer, J. and Ward, D., 2013a. The hydrogeomorphic influences on
51 alluvial gully erosion along the Mitchell River fluvial megafan, northern Australia. *Hydrological*
52 *Processes*, 27(7), 1086-1104.
- 53 Shellberg, J.G., Brooks, A.P. and Rose, C.W., 2013b. Sediment production and yield from an alluvial
54 gully in northern Queensland, Australia. *Earth Surface Processes and Landforms*, 38, 1765-
55 1778.
- 56 Shellberg, J.G. and Brooks, A.P., 2013. *Alluvial Gully Prevention and Rehabilitation Options for*
57 *Reducing Sediment Loads in the Normanby Catchment and Northern Australia*. Griffith
58 University, Australian Rivers Institute, Final Report for the Australian Government's Caring for
59 our Country - Reef Rescue Initiative, 312pp.
60 <http://www.capeyorkwaterquality.info/references/cywq-223>.
- 61 Simpson, C.J. and Douth, H.F., 1977. The 1974 wet-season flooding of the southern Carpentaria Plains,
62 northwest Queensland. *BMR Journal of Australian Geology and Geophysics*, 2, 43-51.

- 1 Simon, A., 1992. Energy, time and channel evolution in catastrophically disturbed fluvial systems.
2 *Geomorphology*, 5, 345-372.
- 3 Stafford Smith, D.M., McKeon, G.M., Watson, I.W., Henry, B.K., Stone, G.S., Hall, W.B. and Howden,
4 S.M., 2007. Learning from episodes of degradation and recovery in variable Australian
5 rangelands. *Proceedings of the National Academy of Sciences of the United States of America*,
6 104(52), 20691.
- 7 Stokes, S., Ingram, S., Aitken, M.J., Sirocko, F., Anderson, R., Leuschner, D., 2003. Alternative
8 chronologies for Late Quaternary (Last Interglacial-Holocene) deep sea sediments via optical
9 dating of silt-sized quartz. *Quaternary Science Reviews*, 22(8-9), 925-941.
- 10 Thomas, M.F., Nott, J., Price, D.M., 2001. Late Quaternary stream sedimentation in the humid tropics: a
11 review with new data from NE Queensland, Australia. *Geomorphology*, 39(1-2), 53-68.
- 12 Tucker, G.E., Arnold, L., Bras, R.L., Flores, H., Istanbuluoglu, E. and Solyom, P., 2006. Headwater
13 channel dynamics in semiarid rangelands, Colorado high plains, USA. *Geological Society of
14 America Bulletin*, 118(7/8), 959-974.
- 15 Valentin, C., Poesen, J. and Li, Y., 2005. Gully erosion: Impacts, factors and control. *Catena*, 63(2-3),
16 132-153.
- 17 Vandekerckhove, L., Gyssels, G., Poesen, J. and Oostwoud Wijdenes, D., 2001. Short-term bank gully
18 retreat rates in Mediterranean environments. *Catena*, 44(2), 133-161.
- 19 Vandekerckhove, L., Poesen, J. and Govers, G., 2003. Medium-term gully headcut retreat rates in
20 southeast Spain determined from aerial photographs and ground measurements. *Catena*, 50(2-4),
21 329-352.
- 22 Wasson, R.J. and Galloway, R.W., 1986. Sediment yield in the Barrier Range before and after European
23 settlement. *Australian Rangelands Journal*, 8(2), 79-90.
- 24 Wasson, R.J., Mazari, R.K., Starr, B. and Clifton, G., 1998. The recent history of erosion and
25 sedimentation on the Southern Tablelands of southeastern Australia: sediment flux dominated
26 by channel incision. *Geomorphology*, 24, 291-308.
- 27 Wasson, R.J., Caitcheon, G., Murray, A.S., McCulloch, M. and Quade, J., 2002. Sourcing sediment using
28 multiple tracers in the catchment of Lake Argyle, Northwestern Australia. *Environmental
29 Management*, 29(5), 634-646.
- 30 Wasson, R.J., Furlonger, L., Parry, D., Pietsch, T., Valentine, E. and Williams, D., 2010. Sediment
31 sources and channel dynamics, Daly River, Northern Australia. *Geomorphology*, 114, 161-174.
- 32 Waters, C.N., Zalasiewicz, J., Summerhayes, C., Barnosky, A.D., Poirier, C., Gałuszka, A., Cearreta, A.,
33 Edgeworth, M., Ellis, E.C., Ellis, M., Jeandel, C., Leinfelder, R., McNeill, J.R., Richter, D.d.,
34 Steffen, W., Syvitski, J., Vidas, D., Waprich, M., Williams, M., Zhisheng, A., Grinevald, J.,
35 Odada, E., Oreskes, N., Wolfe, A.P., 2016. The Anthropocene is functionally and
36 stratigraphically distinct from the Holocene. *Science*, 351(6269).
- 37 Wilkinson, J.M., Marshall, L.G. and Lundberg, J.G., 2006. River behavior on megafans and potential
38 influences on diversification and distribution of aquatic organisms. *Journal of South American
39 Earth Sciences*, 21(1-2), 151-172.
- 40 Wilkinson, S.N., Hancock, G.J., Bartley, R., Hawdon, A.A., Keen, R.J., 2013. Using sediment tracing to
41 assess processes and spatial patterns of erosion in grazed rangelands, Burdekin River basin,
42 Australia. *Agriculture, Ecosystems and Environment*, 180, 90-102.
- 43 Winter, W.H., 1990. Australia's northern savannas: a time for change in management philosophy. *Journal
44 of Biogeography*, 17, 525-529.
- 45 Wu, B., Zheng, S. and Thorne, C., 2012. A general framework for using the rate law to simulate
46 morphological response to disturbance in the fluvial system. *Progress in Physical Geography*,
47 36(5), 575-597.

Tables

Table 1 OSL sample ages (years before 2009) from WPGC2 and HBGC1. Radionuclide values (Bq kg^{-1}) were used to determine the dose rate, Grains is number of grains accepted for equivalent dose calculation and the number of grains analysed, D_e (Gy) is the equivalent dose, D_r (Gy kyr^{-1}) is the total dose rate, and Age (yr) is the burial age in years. Ages and uncertainties were rounded to the nearest 10 yrs when the age is < 100 yrs, and 20 yrs where the age is between 100 and 1000 yrs.

| Site | Code | Profile | Unit | Depth (cm) | ^{238}U | ^{226}Ra | ^{210}Pb | ^{232}Th | ^{40}K | Grains (n) | D_e (Gy) | D_r (Gy kyr^{-1}) | Age (yr) |
|--------|-------|---------|------|------------|------------------|-------------------|-------------------|-------------------|------------------|------------|------------------|--------------------------------|--------------|
| WPGC2a | WP-03 | 2 | Ab | 45 | 51.9 ± 2.9 | 49.8 ± 0.7 | 40.5 ± 3.6 | 75.7 ± 3.4 | 530.6 ± 12.2 | 49/1000 | 0.27 ± 0.03 | 3.67 ± 0.35 | 70 ± 15 |
| WPGC2a | WP-04 | 2 | Ac | 65 | 52.9 ± 1.9 | 48.2 ± 0.6 | 42.7 ± 2.4 | 74.7 ± 1.5 | 510.9 ± 11.1 | 77/1300 | 0.27 ± 0.04 | 3.66 ± 0.35 | 70 ± 15 |
| WPGC2a | WP-05 | 3 | Aa | 30 | 76.6 ± 2.4 | 92.6 ± 1.1 | 67.3 ± 3.0 | 88.8 ± 21.9 | 492.3 ± 10.6 | 56/1500 | 0.06 ± 0.03 | 3.95 ± 0.39 | 15 ± 10 |
| WPGC2a | WP-07 | 3 | C | 75 | 54.1 ± 2.8 | 62.7 ± 0.9 | 49.1 ± 3.6 | 72.4 ± 10.0 | 689.6 ± 16.4 | 23/600 | >150 | 4.38 ± 0.41 | >35,000 |
| WPGC2b | WP-10 | 5 | A | 50 | 50.9 ± 2.7 | 49.7 ± 0.7 | 41.9 ± 3.4 | 60.6 ± 14.1 | 553.8 ± 13.6 | 109/1700 | 0.36 ± 0.02 | 3.86 ± 0.34 | 90 ± 10 |
| WPGC2b | WP-11 | 5 | B | 80 | 55.2 ± 2.1 | 48.9 ± 0.7 | 43.0 ± 2.7 | 72.2 ± 2.4 | 525.9 ± 12.1 | 77/1600 | 0.67 ± 0.04 | 3.71 ± 0.35 | 180 ± 20 |
| WPGC2b | WP-12 | 5 | B | 120 | 55.7 ± 2.0 | 51.7 ± 0.7 | 46.5 ± 2.2 | 75.7 ± 0.9 | 564.2 ± 12.0 | 70/1200 | 2.00 ± 0.08 | 3.88 ± 0.36 | 515 ± 60 |
| WPGC2b | WP-13 | 5 | C | 160 | 50.4 ± 1.6 | 45.8 ± 0.6 | 45.7 ± 2.2 | 82.2 ± 5.4 | 590.6 ± 12.4 | 87/1000 | >150 | 3.94 ± 0.37 | >35,000 |
| WPGC2a | WP-19 | 7 | A | 51 | 80.3 ± 2.6 | 114.0 ± 1.4 | 79.3 ± 3.5 | 76.9 ± 11.9 | 596.2 ± 12.7 | 74/1300 | 0.49 ± 0.02 | 4.79 ± 0.47 | 100 ± 10 |
| WPGC2a | WP-20 | 7 | B | 67 | 52.2 ± 2.5 | 50.9 ± 0.7 | 44.2 ± 2.7 | 74.4 ± 2.7 | 516.0 ± 11.9 | 59/1500 | 0.46 ± 0.02 | 3.68 ± 0.35 | 125 ± 20 |
| HBGC1 | HB-01 | 1 | A | 6 | 65.8 ± 2.1 | 58.2 ± 0.7 | 66.3 ± 2.6 | 92.6 ± 1.1 | 247.1 ± 5.6 | 68/1000 | 0.01 ± 0.005 | 3.64 ± 0.38 | 5 ± 5 |
| HBGC1 | HB-02 | 1 | B | 20 | $62.4 \pm$ | $59.4 \pm$ | $58.5 \pm$ | $95.4 \pm$ | 220.1 | 71/1000 | 0.06 ± 0.02 | 3.48 ± 0.37 | 20 ± 10 |

| | | | | | | | | | | | | | |
|-------|-------|---|---|----|----------------|----------------|----------------|----------------|-----------------|---------|-----------------|-----------------|-------------|
| HBGC1 | HB-04 | 1 | D | 35 | 2.2 | 0.8 | 2.5 | 1.3 | ± 5.3 | 77/1000 | 0.06 ± 0.01 | 2.17 ± 0.21 | 30 ± 10 |
| | | | | | 37.9 ± 1.4 | 30.2 ± 0.4 | 30.8 ± 1.6 | 45.2 ± 0.6 | 220.0 ± 5.1 | | | | |
| HBGC1 | HB-05 | 1 | E | 45 | 44.1 \pm | 38.0 \pm | 38.2 \pm | 58.0 \pm | 240.4 | 94/1000 | 0.15 ± 0.01 | 2.57 ± 0.26 | 60 ± 10 |
| | | | | | 1.6 | 0.5 | 1.9 | 1.0 | ± 5.5 | | | | |

Figures

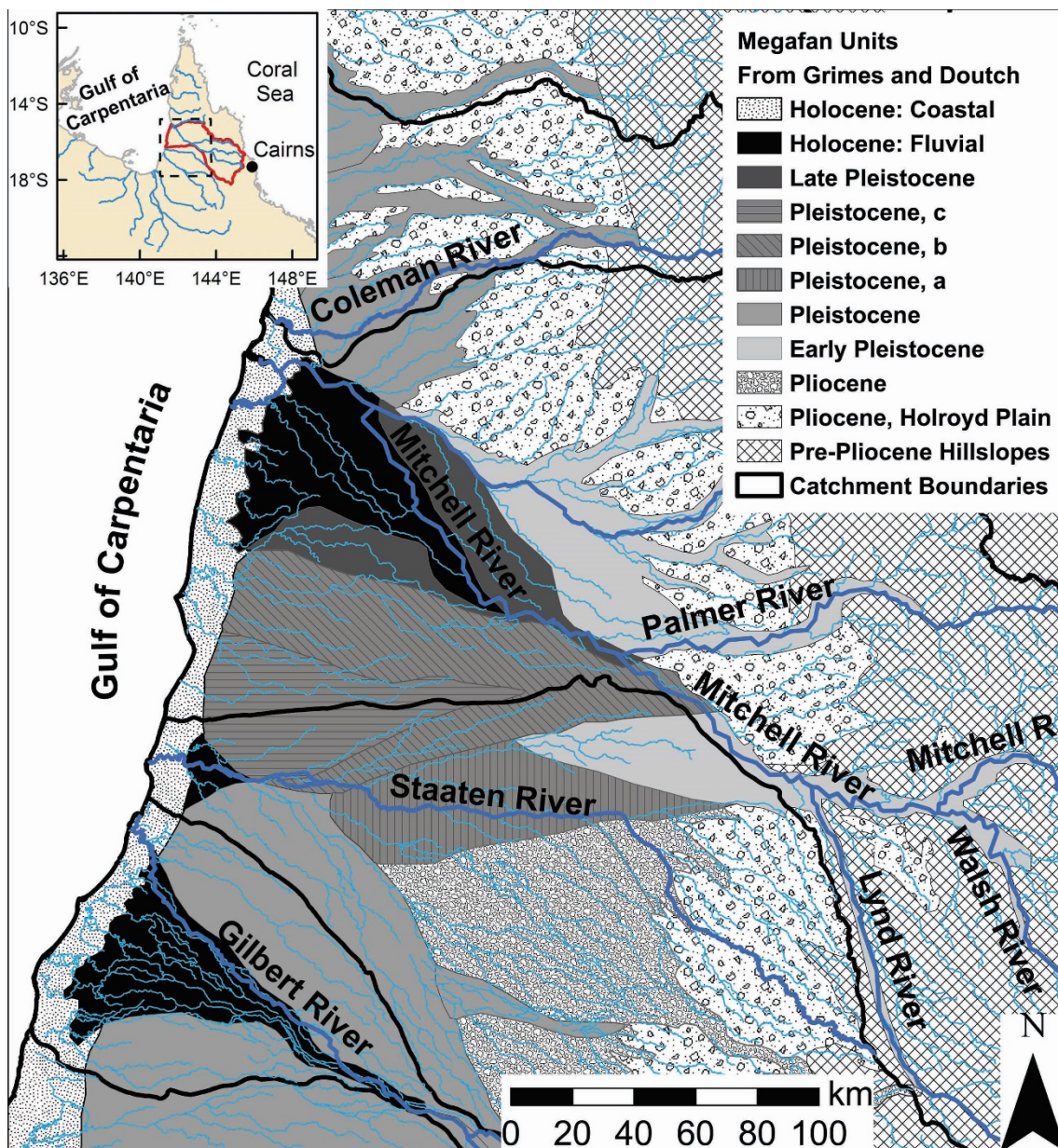


Fig. 1. Location and evolution of the Mitchell and Gilbert megafans from the Pliocene to Holocene (modified from Grimes and Douth, 1978). The inset map of northern Queensland, Australia, shows the large map extent and the Mitchell catchment boundary.

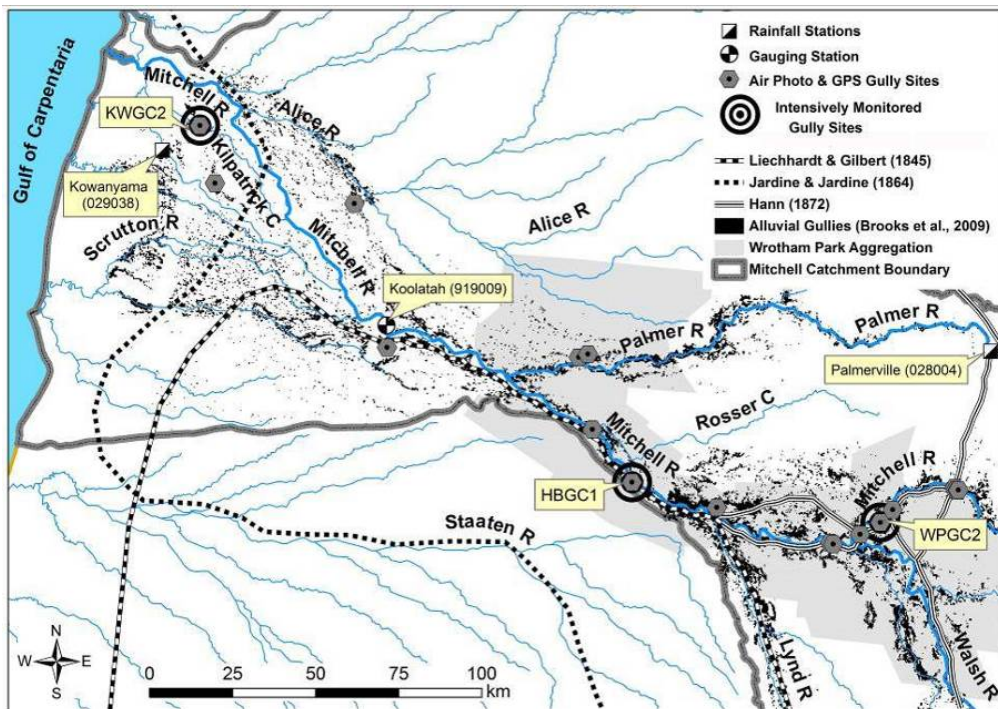


Fig. 2. Study area, gully sites, and monitoring stations along the lower Mitchell River fluvial megafan, along with the distribution of alluvial gullies, tracks of European explorers, and the extent of the Wrotham Park Aggregation cattle station. Several gully site symbols are hidden due to close proximity to others.

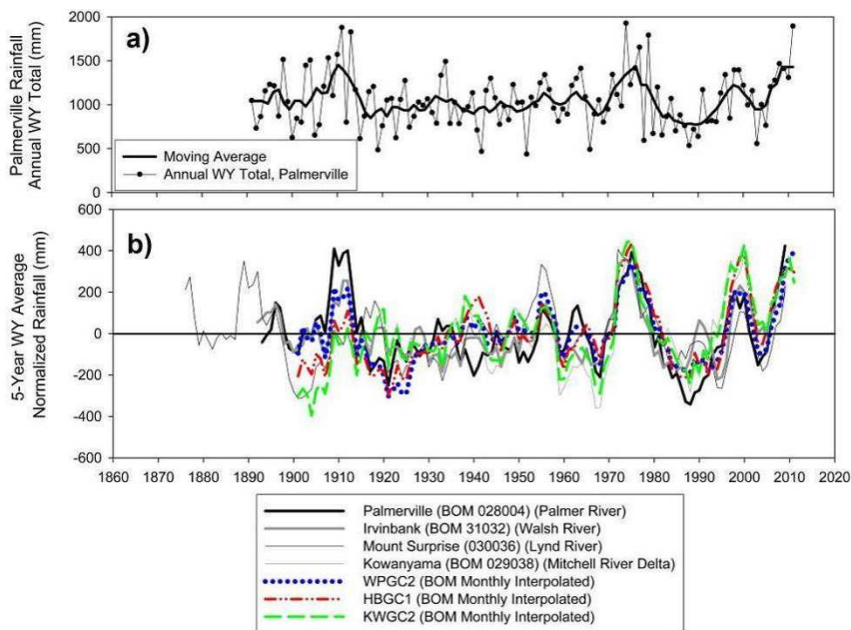


Fig. 3. Historic trends of a) rainfall totals by water year (WY, Oct to Sept) for Palmerville Station (028004) in the Mitchell catchment (Fig. 2), and b) normalized rainfall totals (WY, 5-year moving average divided by mean) for catchment rainfall stations and interpolated data (ABOM monthly data, 1900–2011; Jones et al., 2009) for main gully sites (Fig. 2).

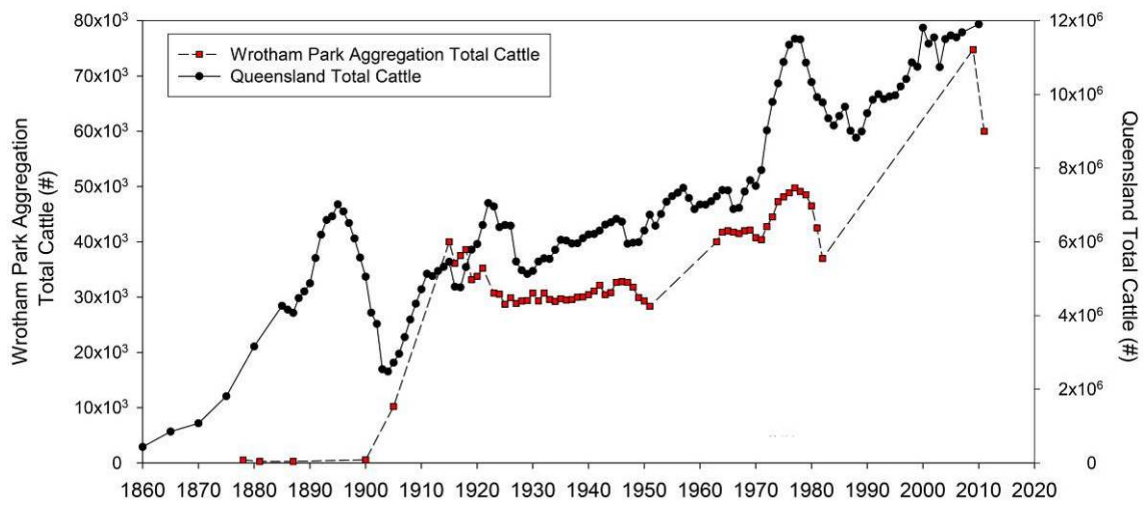


Fig. 4. Historic archive trends in reported cattle numbers for 1) the State of Queensland (ABS, 2008), and 2) the historic Wrotham Park Aggregation cattle station (Fig. 2) on the Mitchell megafan (QSA, 2008; Edey and Gillard, 1985; Arnold, 1997; pers. comm. with station managers, 2008).

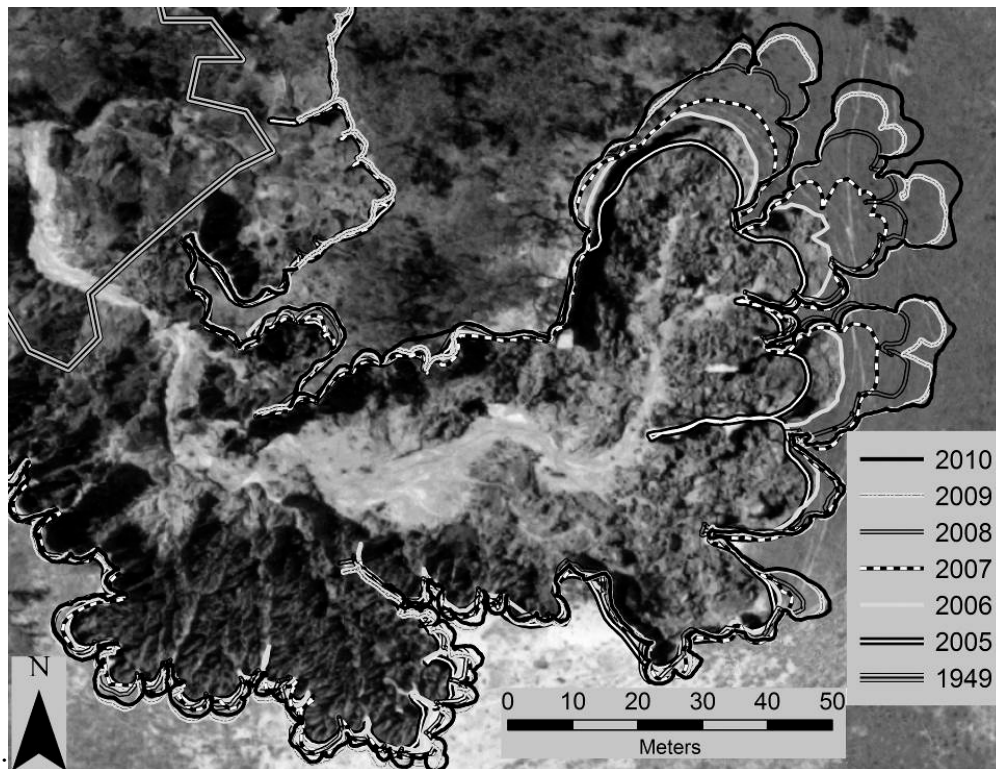


Fig. 5. Annual gully scarp location between 2005 and 2010 at WPGC3 measured using GPS, with approximate, 1949 position from historic air photo and recent 2006 photo in background.

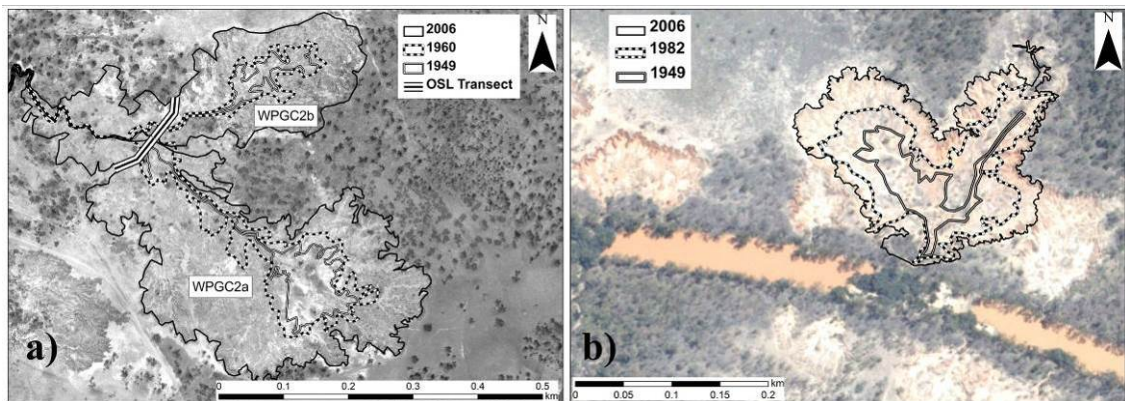


Fig. 6. Changes in gully scarp location from 1949 to 2006 at a) Wrotham Park (WPGC2) with the OSL cross-section location (see Fig. 10), and b) Highbury (HBGC2) where gully sediment infilled the previously free flowing lagoon channel between 1982 and 2006.

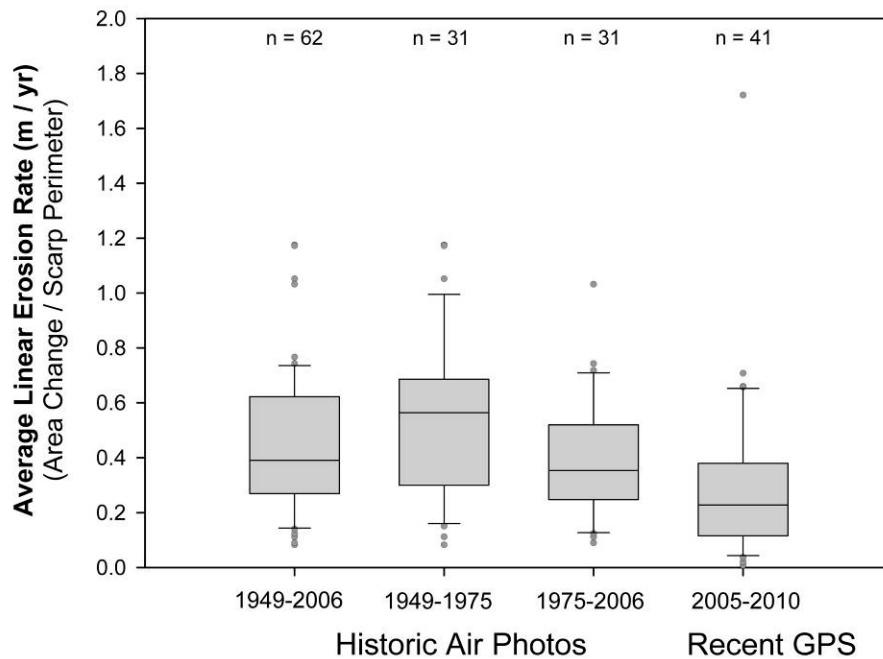


Fig. 7. Comparison of annual average linear erosion rates (area change / scarp perimeter, m yr^{-1}) measured from historic air photos and recent GPS surveys. Sample sizes (n) represent the total number of measurements between individual years (time steps) for all gullies within the overall time period. Boxes represent 25th, 50th, 75th percentiles, whiskers represent 5th and 95th percentiles, and points represent outliers.

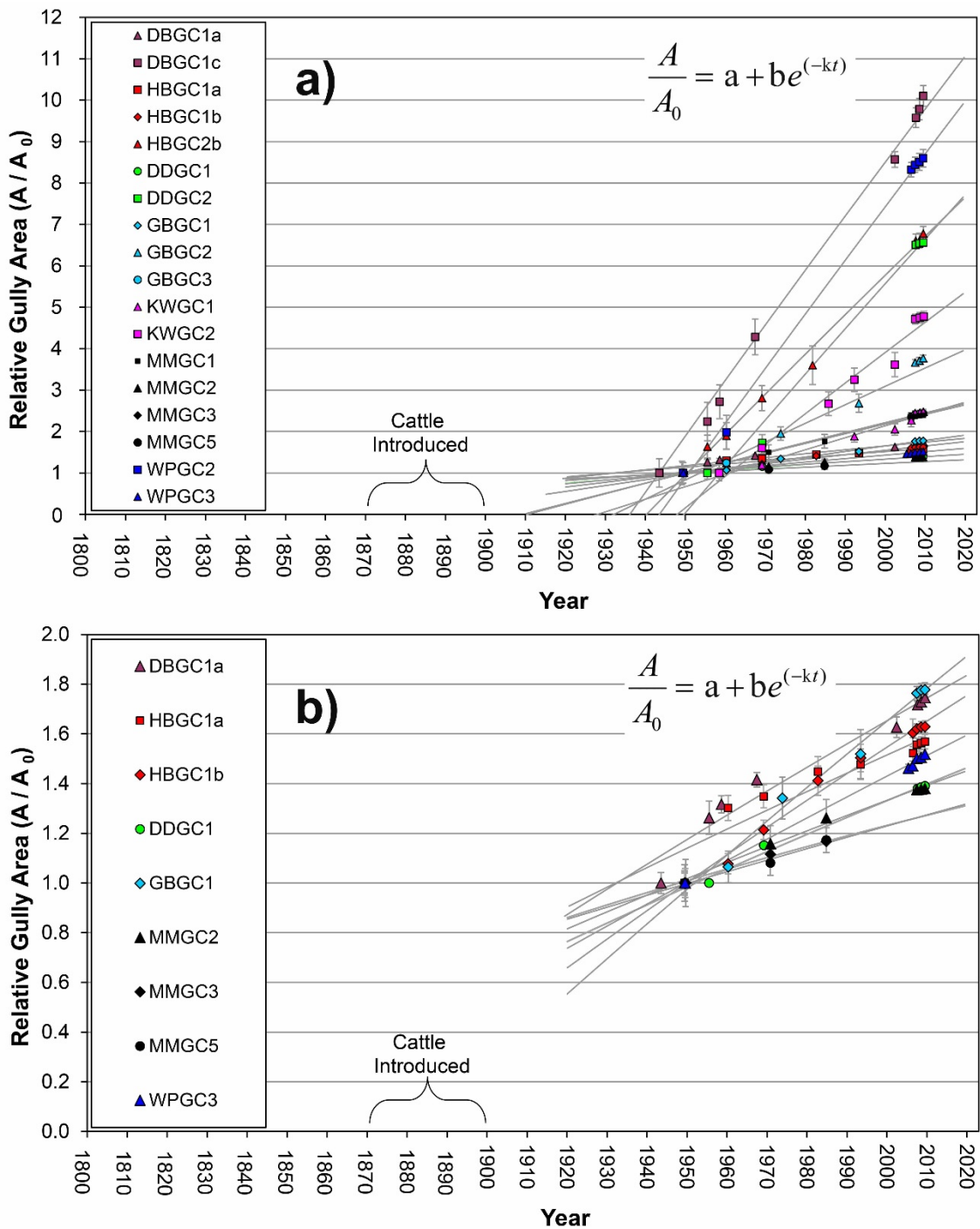


Fig. 8. Relative changes in gully area (A/A_0) over time for a) all 18 gully sites (Fig. 2), and b) a subset of 9 sites with $A/A_0 < 2$. A negative exponential function was fitted to the data using historical air photos (1949–2006) and recent GPS surveys (2005–2010). Error bars correlate to horizontal errors of ± 2 to 3 m for historic photos and ± 50 cm for recent GPS.

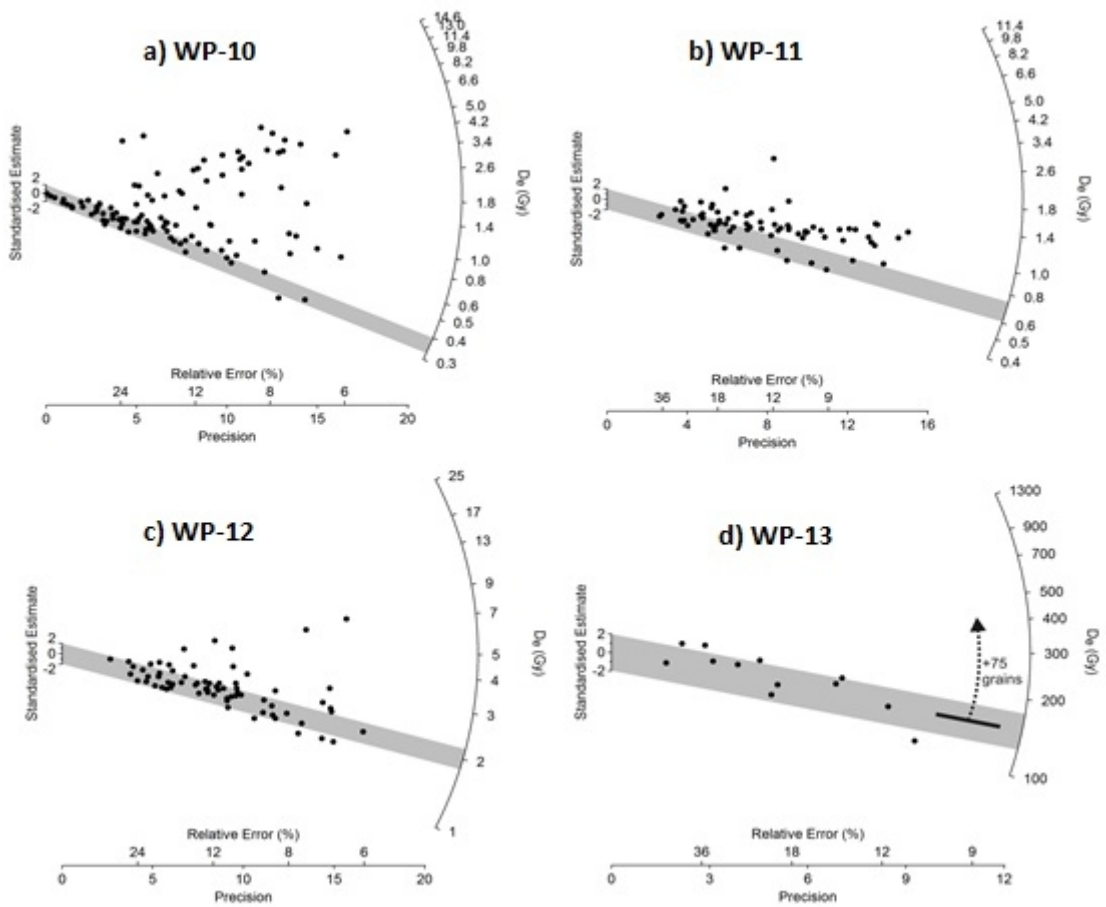


Fig. 9. Radial plots of equivalent dose (D_e) data for samples a) WP-10, b) WP-11, c) WP-12, and d) WP-13 at profile 5 at WPGC2b. The x -axis plots the relative standard error (%) and its reciprocal, precision, while the shaded area represents the 2σ confidence interval for the D_e estimate. For WP-13, 75 grains had doses at or above their respective saturation points of ~ 150 Gy, as indicated by dashed arrow.

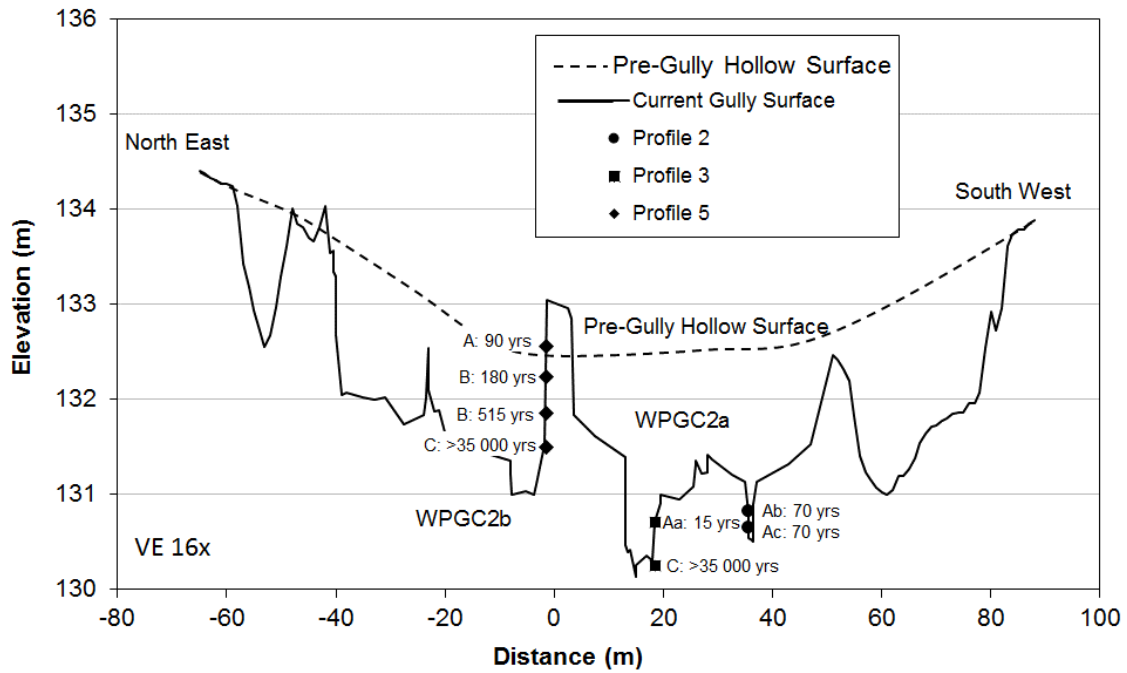


Fig. 10. Cross-sectional transect through WPGC2 with locations of vertical profiles, OSL sample locations, OSL ages (years BP), and the approximate location of the pre-gully hollow surface. See Fig. 6a for planform location.

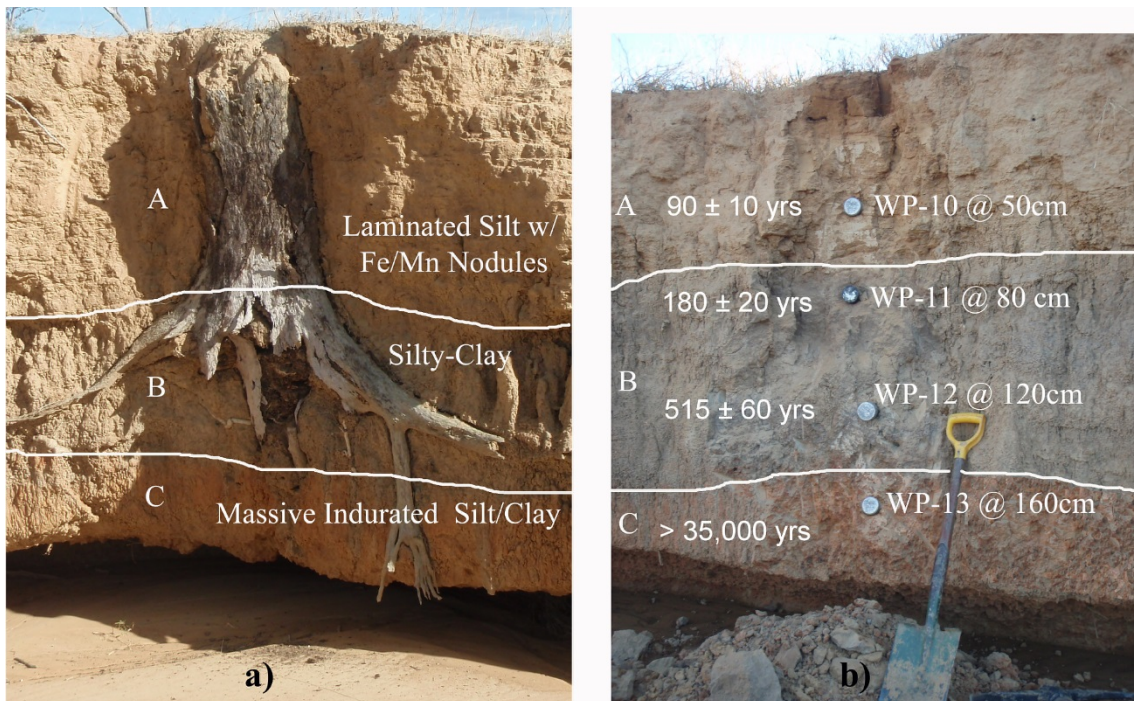


Fig. 11. Profile 5 at WPGC2b showing a) stratigraphic units and a buried tree 5m upstream from OSL sample locations, and b) the same stratigraphic units, OSL sample locations, and measured burial ages (years BP) 5 m downstream from a).

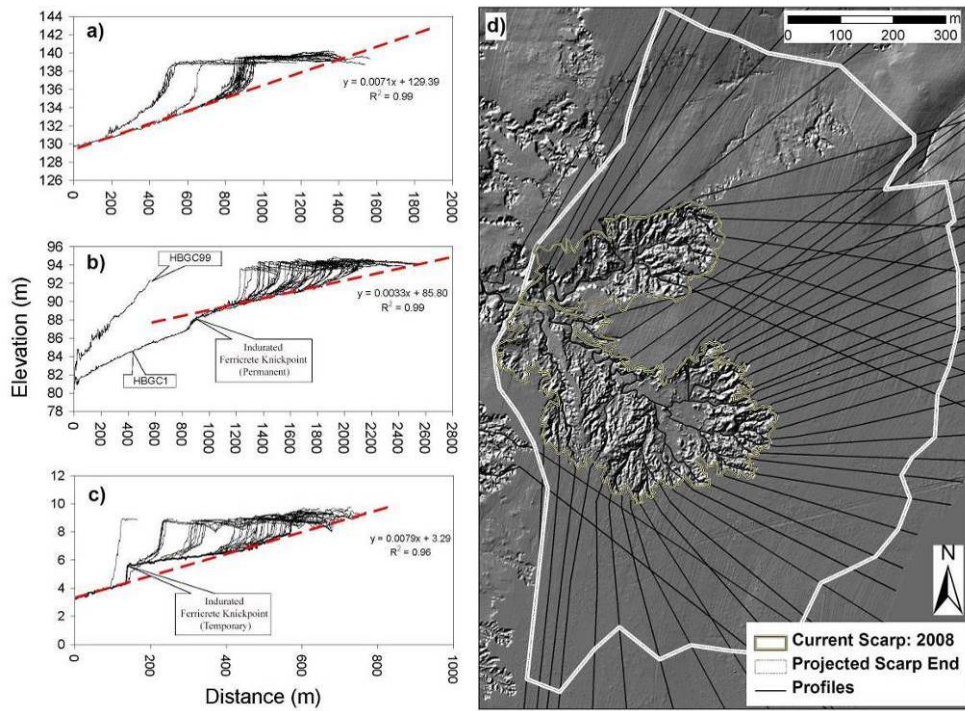


Fig. 12. Longitudinal profiles of channel thalwegs (black lines) extracted from LiDAR for a) WPGC2, b) HBGC1 and HBGC99 (bank gully), and c) KWGC2, with trend lines of thalweg slopes (dotted lines) extended beyond the scarp zone to intersection points with the river high-floodplain surface. d) WPGC2 LiDAR hillshade DEM, longitudinal profile (thalweg) extraction lines, current gully extent, and future projection of gully extent.

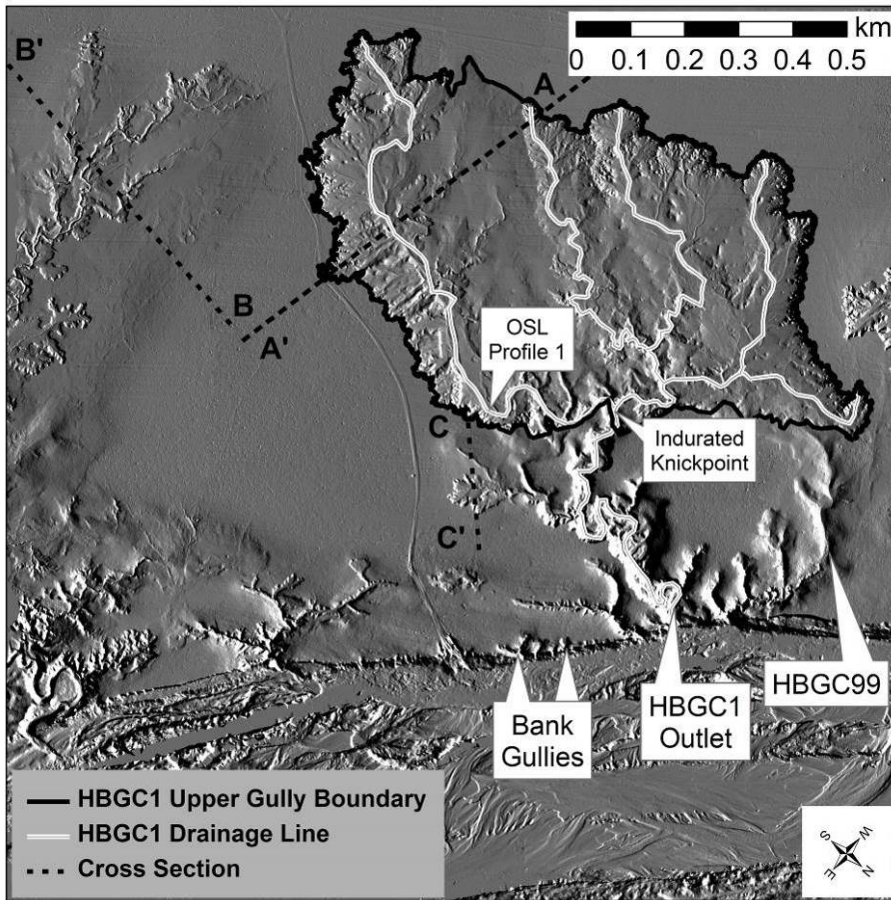


Fig. 13. LiDAR hillshade map of the left bank of the Mitchell River at HBGC1, with locations of cross-sections (Fig. 14), OSL sample location (Table 1) and the upper scarp boundary of HBGC1 above the indurated knickpoint (Fig. 12b) and main outlet channel.

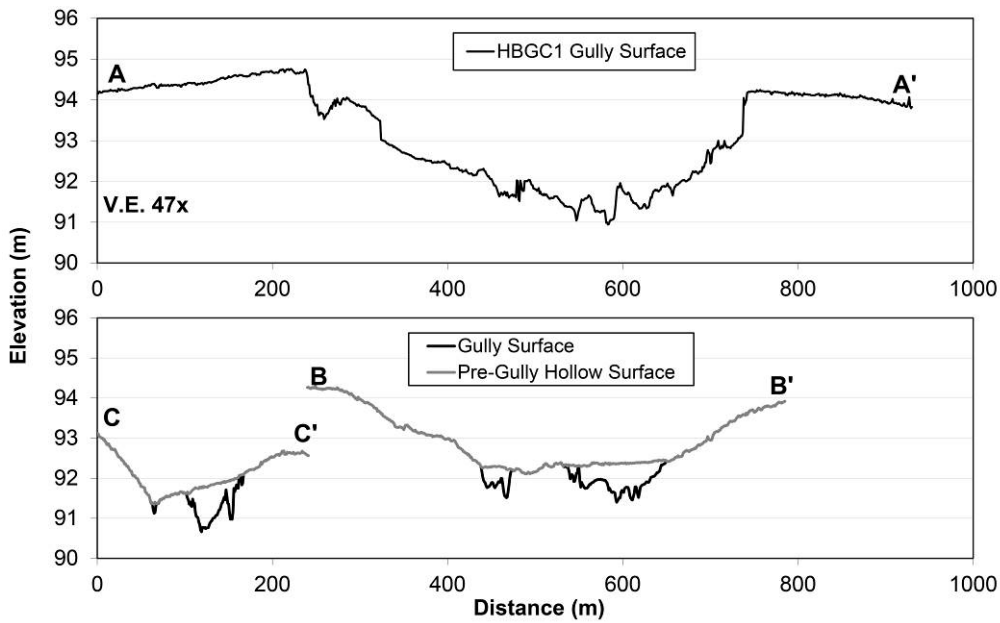


Fig. 14. Elevation cross-sections (looking downstream) from A to A' (HBGC1), B to B' and C to C' in Fig. 13.