Late Quaternary biotic and abiotic controls on long-term sediment flux in a northern Australian tropical river system

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Abstract

The modern distribution of monsoonal rainforest in the Australian tropics is patchy and is mainly associated with river corridors and groundwater springs, which indicates a strong dependence on hydrologic and geomorphic conditions. While their present distribution is well known, very little data exists on past spatial and temporal dynamics of these ecosystems, or their medium- to longer-term

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controls. Factors such as (i) fire frequency and type, and/or (ii) hydroclimatic conditions (e.g. droughts) have been proposed to control riverine corridor rainforest extent. Recent observations, however, also suggest an additional (iii) geomorphic control induced by alluvial knickpoint migration. Sediment sequences provide valuable archives for the reconstruction of longer-term (i) floodplain sedimentary dynamics, (ii) local vegetation history, and (iii) catchment-wide fire histories. This study investigates such a sediment sequence at Wangi Creek, and shows that a phase of aggradation, lasting ~4000 years, was recently disrupted by channel incision and floodplain erosion. The aggradational phase is characterized by sand deposition with average vertical floodplain accretion rates of 0.8 cm/year and includes phases of soil development. The recent incisional phase has changed hydro-geomorphic conditions and caused widespread degradation of vegetation, erosion and lowering of the macro-channel surface. While there is no evidence in our data for an erosional event of similar magnitude since the onset of late Holocene floodplain aggradation, Wangi Creek experienced significant erosion and incision immediately before ~4000 years, providing the first evidence for a tropical cut-and-fill river system. We hence argue that phases of aggradation mainly controlled by biotic processes alternate and depend on feedbacks with incision phases controlled mainly by abiotic processes. The results show that eco-hydro-geomorphic feedbacks may play a crucial role in the medium to longer-term history of tropical fluvial systems and need to be considered when interpreting fluvial archives with regards to climate, fire or human induced change.

Introduction

Wet monsoonal rainforest (WMF) in tropical Northern Australia exists as discrete and isolated rainforest pockets in the vicinity of springs, or along river corridors (Bowman, et al., 2010). Their location demonstrates the dependence on permanent water resources within an area that is characterized by climatic extremes, with droughts and fire alternating with wet and extreme flood events over the annual hydrological cycle. WMF communities provide habitat for species sensitive to limited water supply during the dry season, increase regional biodiversity, form natural fire breaks during annual low-intensity fire events (Russell-Smith, et al., 1992), and hence provide important ecological functions. It has been argued that WMF ecosystems are extremely sensitive to climate and environmental change, mainly because they are characterized by i) small patch sizes, ii) isolated
occurrence, iii) large patch margin to internal vegetation ratios, and iv) are sensitive to high intensity fires (Russell-Smith, et al., 1992). WMF are considered to be a relic of wetter past climates, and that they have fragmented into small patches due to increasing aridity of the Australian continent since the Pliocene (Greenwood, et al., 2005, Moss, 2008, Webb, et al., 1981). WMF have been found to occur on Holocene landforms and sediments, suggesting they may also be an ecosystem well adapted to Holocene conditions (Larsen, et al., 2016).

The current spatial extent and preservation condition of WMF has been suggested to be strongly controlled by climate and especially fire as main driver of destruction (Banfai, et al., 2006, Bowman, 2000), but their association with springs and rivers also suggests a strong dependence on the local hydro-geomorphic conditions. WMF is frequently found on sand-dominated deposits in the middle reaches of Northern Australian river systems (Williams, et al., 1999). These middle reaches are located between upstream bedrock channels on sandstone plateaus characterized by remarkably low rates of geomorphic change (Wasson 1992, Nott et al. 1996), and tidally influenced downstream reaches dominated by infilled estuaries with very little shoreline change since the mid-Holocene (Mulrennan, et al., 1998, Woodroffe, 1993) (Figure 1). In contrast, very little is known about the environmental dynamics and late Quaternary evolution within the ecologically significant middle reaches of river corridors in tropical northern Australia. At Magela Creek, a left-bank tributary of the East Alligator River, northwestern Arnhem Land, Northern Territory (Australia) the middle reach of the river corridor is characterized by a sand-dominated anabranching river pattern with channel form and function attributed to strong feedbacks between biotic and abiotic processes (Jansen, et al., 2010, Tooth, et al., 2008). Here, cyclic incision and filling has likely been controlled over glacial timescales (last 100 ka) by large sea-level changes (Nanson et al. 1993) while the more recent and nearly complete filling of the Magela Creek valley with sediments over the last ~8000 years has been attributed to a complex interaction between climate variability influencing sediment supply from the headwaters and the backwater effect of a large downstream billabong (Nanson, et al., 1993, Roberts, 1991). Located in a similar hydro-geomorphic setting to Magela Creek, studies on late Quaternary hydrological variability using the relative height of plunge pool deposits at Wangi Creek (Figure 2) point towards a climatically-driven decrease in flood magnitudes since the LGM (Nott, et al., 1999, Nott, et al., 1996), however the fluvial dynamics and especially the role of riverine ecosystems in the river corridor evolution over the same timescales remain elusive. In this context, a recent study at
Wangi Creek has demonstrated the importance of bio-hydro-geomorphic feedbacks in the modern evolution of river-floodplain dynamics (Larsen, et al., 2016). This study found an upstream migrating alluvial knickpoint caused channel incision and hydrological drainage of the previously waterlogged floodplain, leading to increased susceptibility to fire impacts and ultimately to the destruction of the riverine corridor vegetation (Larsen, et al., 2016). These processes and their observed responses suggest the hypothesis that Wangi Creek might also operate as a “cut-and-fill system” (Schumm, et al., 1984) over longer timescales. It therefore presents an important implication for the longer-term geomorphic dynamics of fluvial systems in tropical Australia, the evolution and survival of the associated WMF pockets located along these streams, and the resilience and management of these ecosystems. In this study, we present new data from a late Holocene palaeosol-sediment sequence exposed after recent passage of a knickpoint followed by WMF destruction along Wangi Creek (Larsen et al. 2016). This study aims to test whether the long-term timing of “cut-and-fill” processes are related to feedbacks between abiotic and biotic controls on river corridor dynamics. In order to do this, we (i) describe the sequences with regard to their sedimentary and pedogenic characteristics, (ii) present a chronology combining OSL and 14C, and (iii) reconstruct the taxonomic composition of past woodland and fire history from soil charcoal. This study has implications for understanding how abiotic and biotic feedbacks contribute to the longer-term fluvial and ecological dynamics in these tropical settings, as well as how the tropical context assists our overall knowledge on the mutual links and interdependencies between abiotic and biotic systems in earth surface processes.

**Study site**

Wangi Creek is a right-bank tributary of the Reynolds River in Litchfield National Park in the Northern Territory of Australia (Figure 2 a). Similar to most rivers in the area, Wangi Creek can be separated into three distinct morpho-dynamic sections (Figure 1): the upper reach constitutes the majority of the catchment, is located on the Litchfield plateau, which is mostly built from quartzites and Neoproterozoic sandstone (Ahmad, et al., 1993). Similar to other streams in the area, the weathered plateau sandstone forms the major source of the sand-dominated sediment load and deposition in the downstream reaches (Nanson, et al., 1993). On the plateau, Wangi Creek flows in a shallow...
bedrock channel with isolated pockets of alluvium. At the edge of the plateau Wangi Creek forms a 70 m high waterfall and an associated plunge pool at the foot of the escarpment. Downstream, in the middle reach, the creek flows in mostly multiple, anabranching channels within an incised valley across a slightly inclined pediment plain (~2.7 m km⁻¹) consisting mainly of older and deeply weathered alluvial deposits or fine-grained, sand-dominated sedimentary rocks (Ahmad, et al., 1993). This valley is partially filled up with sandy alluvium, is hitherto termed macro-channel (Figure 3), and further characterized in the section below. The downstream end of the middle reach, which is investigated in this study, is located at the confluence of Wangi Creek with several small tributaries just before Wangi Creek flows largely unchannelised across the infilled estuaries of the coastal floodplains (lower reach) and enters the Reynolds River (Figure 1, 2 b, c).

The vegetation of the studied reach is characterized by well-developed WMF, but this ecosystem is intact only in the upstream part, and degraded downstream (Figure 4). The WMF is the typical riparian forest within the Australian Monsoon Tropics (AMT) ecosystems, and occurs as small, distinct patches along rivers and springs, which are commonly not affected by fires (Bowman, 1992, Russell-Smith, 1991). WMF have a sharp boundary to the adjacent ecosystem the tropical mesic, eucalypt dominated savannah, here described as open woodland (OWL) (Griffiths, et al., 1997, Williams, et al., 2003), which burn annually or biannually, mostly by low-intensity anthropogenic fires. The climate of tropical Australia is characterized by about 2000 mm annual precipitation with 90 % falling within the six-month summer period between October and March. The closest climate station to the study area (Bachelor, NT, at ~32 km from the study area) records the strong seasonality and highly repetitive nature of high-intensity precipitation events annually for the area. As a consequence river hydrographs exhibit short-duration, high-magnitude, and high frequency flood events, and a large intra- and interannual variability (Moliere, et al., 2009). The hydrograph of Wangi Creek has been shown to also reflect this pattern with dry season low flow of ~2 m³s⁻¹ and maximum flow depths of 3-4 m during the wet season in 2013/2014 (Soper, 2014). This large seasonal variability in flow is geomorphologically expressed in a channel-in-channel-morphology (Figure 3). The macro-channel has a width between 140 and 320 m (Figure 3) and is inset into the surrounding gently westward dipping pediment surface. It is regularly inundated during the above described, tropical high magnitude, high frequency discharge events. The difference in elevation between the higher surface and the channel water level and inner floodplain is between ~5 m in the
upstream part of the reach and 1.5 m in the downstream kilometer of Wangi Creek (Figure 2 c). Dry season, anabranching channels are incised into the inner-floodplain to variable depths between a few centimeters to several meters. Enlarged channel sections (waterholes or billabongs) can be up to several meters deep with comparatively low flow velocities. Fresh sand deposits cover small patches of the inner-floodplain surface and confirm its regular inundation. The typical floodplain soil of the WMF is a Histosol, in which the A-horizon is a tropical peat of variable thickness, and the C-Horizon fluvial sands (Figure 4 b and d).

A single ~1.5 m high, abrupt and well defined knickpoint in channel bed elevation divides the study reach into an area with dense, intact WMF and thinned, disturbed and destructed WMF (Larsen, et al., 2016) (Figure 4). The knickpoint forms a natural divide with regard to the dry season channel morphology and hydrology, as well as the ecology and morphology of the inner-floodplain (Figure 4). Alluvial knickpoint migration is limited in extension through the existence of the escarpment at the upstream of the middle reach (Figure 2,3). Larsen, et al. (2016) report the initiation of the knickpoint at the downstream end of middle reach, which indicates that the process of knickpoint migration is limited to the middle reach.

Methods

Field observation

We mapped the geomorphology and vegetation of the study area during two field campaigns in October 2013 and May 2014. Mapping was done based on digital surface and canopy models (Fieber, et al., 2015) with a pixel size of 0.5 m based on an airborne LiDAR survey flown in June 2013, and aerial imagery (historical aerial photography (1941; www.nla.gov.au), CORONA satellite photographs (1966; USGS 2008), atmospherically corrected LANDSAT TM surface reflectance data (1987-2011; www.earthexplorer.com), and high-resolution satellite imagery provided by Bing (September 2012; m vexel.dev.openstreetmap.org/bing) and Google Earth (July 2013; maps.google.com). Mapping included: i) geomorphic characterization of channels and floodplain, ii) vegetation type and conditions, iii) marker soil horizons along existing exposures of floodplain sediment, iv) in-channel water level height, and v) measurement of shallow water table depth where possible. All field
findings were recorded with a hand-held global positioning system (GPS) with a typical horizontal accuracy of ~ 3 m in latitude and longitude. Where possible, a Trimble RTK differential GPS was used in combination with the online post-processing and correction service AUSPOS on the static base station. Catchment-wide spatial analysis such as watershed delineation were processed using the one arc-second SRTM derived Digital Elevation Model (DEM) (resolution 30 m) (Gallant, 2011).

Stratigraphy and sampling

Due to the channel incision caused by the recent knickpoint passage, floodplain soil-sedimentary sequences are exposed at several places along the river banks of lower Wangi Creek. We documented general stratigraphy at 2 sites, each including 2 vertical sections (site 1: WG-371 and WG-372; site 2: WG-553 and WG-548)) and sampled them for chronology. We surveyed the laterally extensive, homogeneous soil-sedimentary sequence for detailed analysis (WG-371). Here, several vertical sections were carefully cleaned and documented, in each exposure the basal cross-bedded sands were reached, ensuring that a complete floodplain sequence was analysed. Each layer was sampled i) in bulk (5 L) for grain size, total organic carbon, charcoal analysis, ii) every 5 cm within black and grey soil layers for organic carbon and pH, and iii) dating (optical stimulated luminescence, radiocarbon) depending on the stratigraphical context and charcoal abundance (radiocarbon), soil colour (humins, radiocarbon) and layering (OSL). In the laboratory, sediment of all main layers < 2 mm was treated with H₂O₂ and subsequently analysed in a Laser Particle Size Analyser (Mastersizer 2000, MALVERN instruments). Grain size results are given in table 3. Total organic carbon (TOC) was determined by Rock-Eval Pyrolysis (e.g. Carrie, et al. 2012), and are summarized in table 4. This technique is used to define the percentage of more labile organic matter (PC), and the percentage of residual carbon (RC), which is composed of strongly resistant and refractory compounds (Carrie, 2012), which can be related to black carbon (Po0t, et al., 2009). The major pyrolysate fraction of RC is the S2 fraction, given in mg HCg (Carrie, et al., 2012).

Chronology
We use a combination of optically stimulated luminescence (OSL) and radiocarbon dating on two different organic fractions (charcoal and humins) to establish a chronology for our sampled sites at Wangi Creek.

**Luminescence Dating**

**Sampling and pretreatment**

Six samples for optically stimulated luminescence (OSL) dating were collected by hammering a ~6 cm wide steel tube into the freshly exposed sediment and sealing it for light proof transport. Four samples come from our main soil-sediment sequence (WGM-A-371-25, WGM-A-371-150, WGM-B-371-50 and WGM-371-190). Sample WGN-372-25 comes from a slightly cemented sand deposit on the opposite river bank. Sample WG 553-123 comes from a freshly exposed sandy layer below approximately 100 cm of peat a few meters downstream of the knickpoint in 2014. All samples were opened in a red light laboratory, and material from both ends was used for dose rate determination. As the Wangi Creek catchment area exclusively contains quartzite, sandstone, and minor lateritic lithologies, we used a simplified preparation technique including sieving (180-212 µm), chemical pretreatment with \( \text{H}_2\text{O}_2 \) to eliminate organic matter, and hydrofluoric acid (HF) treatment (40 % for one hour, followed by 15 % HCl) to remove the alpha-irradiated rind of each grain and to destroy any remaining feldspar grains.

**Analyses and Equivalent Dose (De) determination**

We applied the Single Aliquot Regenerative Dose (SAR) protocol with parameters previously tested and specified for Wangi Falls (May, et al., 2015a) directly upstream of our study site within the same catchment and containing identical source rock lithologies. The suitability of these parameters was confirmed by dose recovery and preheat experiments (May et al 2015a). All samples were measured at the University of Bern, Switzerland except sample WGN-372-25 which was measured at the University of Sheffield (UK). For all samples, three hundred individual grains were measured by stimulation of each grain with green (532 nm) laser light for 2 s at 125 °C in Risø DA20 TL/OSL readers (Bøtter-Jensen, et al., 2003). Ultraviolet OSL emissions were measured using Electron Tubes Ltd 9635Q photomultiplier tubes fitted with a 7.5 mm Hoya U-340 filter. Laboratory irradiations were given using a calibrated 90Sr/90Y beta source attached to the readers.
**Dose rate determination**

The determination of environmental dose rate was carried out by two different methods. Firstly, relevant elemental concentrations (U, Th, K) were measured by ICP-MS and ICP-OES for four samples (WGM-A-371-25, WGM-A-371-150, WGM-B-371-50 and WGM-371-190). Dose rate for three further samples was calculated from high-resolution gamma spectrometry (HRGS) (Preusser, et al., 2001) and included a duplicate sample (WGM-371-190). For all calculations the conversion factors of Guérin, et al., 2011 were used. Due to HF treatment of the samples prior to measurement, alpha dose was considered negligible. Investigation for radioactive disequilibrium was undertaken by using the activity determined for different isotopes of the uranium decay chain (238U, 226Rn, 210Pb) (following Zander, et al., 2007). For all samples, field water content (~8–40%) was used as a guide to estimate sample water content in order to correct for the attenuation of beta, gamma dose rates, while the calculation of cosmic dose rate was done following Prescott, et al. (1994) using present day depth.

**Radiocarbon dating**

Different organic substances including charcoal, wood and soil humins were analysed using established AMS-techniques for radiocarbon dating. Radiocarbon dating was carried out by the Radiocarbon Dating Laboratory at Waikato University in Hamilton, New Zealand following standard
methods (Radiocarbon Dating Laboratory, 2017). The conventional age was calculated after Stuiver, et al. (1977), and calibration to calendar years was done using OxCal 4.2.4 (Bronk and Ramsey, 2013) using the IntCal13 atmospheric curve (Reimer PJ, 2013). Radiocarbon ages are given in cal BP (Table 1).

**Anthracology/Soil charcoal analysis**

In order to compare past fire activity in the layers within the sedimentary sequence, we extracted approximately between 10 to 20 L of bulk sediment sample from each sedimentary layer, and extracted all charcoal pieces > 2 mm. This was done by passing all sediment through sieves with 2 and 5 mm mesh size, and then extracting charcoal fragments with tweezers. The charcoal fragments and sediment were dried in an oven at 40 °C, and anthracomass was calculated by dividing the weight of the charcoal in grams by the weight of the sediment in kilograms. Where dried weight of sediments are not available (sample CH5 only), we assumed a water content of 15 % based on comparable samples in the sedimentary sequence, and calculated anthracomass accordingly. Following Hubau, et al., 2012, ~ 50 charcoal fragments or 100 % of the charcoal fragments per layer (if less than 50) were analysed. Individual pieces of charcoal were sectioned into the three anatomical planes of wood following Leney and Casteel (1975). These planes were then examined under a high-powered light microscope (Olympus BX 60) and typed based on their anatomical features following the criteria of the International Association of Wood Anatomists (IAWA, 1989; 2004). Each type specimen was identified with the aid of the University of Queensland wood reference collection for northern Australia. Identification was limited to the genus level. These identifications were then quantified by count and weight, and results are given in table 4.

**Results**

**Stratigraphy and Anthracology of site 1 (WG-371 and WG-372)**

The investigated reach of Wangi Creek exhibits a channel-in-channel morphology, typical for tropical streams with a high frequency, large magnitude of flood events (Figure 3). Site 1 (WG 371 and 372)
(location see Figure 4 f) was located where channel incision and valley widening had exposed floodplain sediments and intercalated soils along the stream banks, thus likely reflecting the longer-term sedimentary depositional history of Wangi Creek. The WG 371 sediment soil-sequence is the top ~4 m of the unconsolidated sedimentary fill within the macro-channel (Figure 5). The position of the investigated sediments within the macro-channel, their horizontal orientation, and sedimentary characteristics (cross-bedding, well sorted) provide evidence of their fluvial origin. All investigated sedimentary layers were consistently present along a 300 m long natural exposure at the left river bank, eroded by the incising micro-channel downstream of the headwards retreating knickpoint (see study site). The alluvial sediments are clearly distinct from the macro-channel banks at the opposite river bank where the river has exposed deeply weathered deposits of unknown age (Figure 4 g). Only a few, thin (< 1m) pockets of partly cemented alluvial sands (WG 372) overlay these weathered deposits, reflecting the effective removal of unconsolidated alluvial sediments of the macro-channel along the cut bank following incision and channel widening.

Within the younger, unconsolidated macro-channel fill (WG 371), black and grey horizons alternate with well sorted, light colored sands. All layers and horizons are sand-dominated, a result of the sandstone dominated catchment, and high transport capacities during annually occurring flood events. We identified 4 sedimentary units of sand deposition in which black or grey soils are developed (units 1-4, Figure 5). The base of all 4 units is formed by well sorted and white sand layers, which are topped by a darker/black soil. Unit 4 exhibits cross-bedded sands, which indicate the latest time period that the location experienced channel activity. Unit 1 has several grey horizons embedded, and a grey soil on top, which represents the present soil. Throughout the sedimentary profile, soil development is synchronous with ongoing deposition, indicated by the deposition of thin sand deposits within the black and grey soil horizons (Figure 5 a, b). From the sedimentological record, it seems that the sedimentary sequence is deposited over several thousand years with the exception of an erosional discordance indicating an erosional event at 180 cm, which truncated the upper black soil of unit 3. This discordance is covered by a coarse sand deposit, which confirms the likely scenario that the discordance was caused by an erosional flood event.

TOC values of all samples are low and range between 0.05 – 0.79 %, and consistently show higher values for black soil horizons than for white, well sorted layers and grey soil horizons (Figure 6 b,
Table 3). The same trend can be observed for the RC fraction of the OC (Figure 6c, Table 3). In the top of the profile where grey soils dominate (above 78 cm depth) (unit 1), greyish layers show TOC values of 0.24 - 0.39 %, only slightly raised in comparison to the adjacent white sands with 0.2 %. In the lower part of the profile (between 380 – 79 cm in depth), soil horizons are much darker in comparison to the top layers, and the difference in TOC content between the black soils (0.61 – 0.79 %) and adjacent white sand layers (0.05-0.31 %) are more pronounced. All layers a largely sand-dominated with a range of sand content between 77 – 98 %. Silt content make up for most of the remaining grain size fraction (0.5-18%), and clay content ranges between 0.6 and 5 %. Calculated sorting indices after Folk (1957) show values of all layers between 1.5 and 5.5 microns. Black soil horizons have coherently higher mud content (8, 13, 23, 29 %) than grey soil horizons including the top soil (3, 4, 5%), white sands which range between 1 and 7 % (Figure 6a), and coarser sand layers in the base of the profile and just above the discordance (1-5 %). This trend is also reflected in the sorting index with black soils yielding highest values between 2 up to 5.5, grey soils between 1.8 and 2.4, and white sands and coarse sands below 2 (Figure 6a). Most recent bank deposits near the present stream, collected for comparison, show very similar values to white and coarse sands within profile WG-371 (Figure 6a).

Anthracomass, or charcoal content, shows a trend generally similar to TOC, which implies a relationship between the two characteristics. High charcoal contents can be found in the black and grey soils that top the units 1, 2 and 4 (1878, 3226, 2385 mg/kg), and low charcoal content appears in sand layers (24, 27, 27, 19 mg/kg) and in grey soil layers (23, 27 mg/kg). However, the most dense and black soil at 180 – 206 cm depth (unit 3) has a very low charcoal content (44 mg/kg), but high TOC values (0.76 %). This unit was eroded, which is evident from the erosional discordance at 180 cm (see section above).

The charcoal record was composed of 13 wooded taxa, and was dominated by Eucalyptus sp. and Acacia sp. (n = 75, 63 respectively) (table 4). Other taxa identified in the record were Alphitonia sp. (1), Brachychiton sp. (7); Calliclris sp. (1), Ficus sp. (5), Flueggea sp. (12), Grewia sp. (42), Melaleuca sp. (2), Pandanus sp. (3), Terminalia sp. (19), Arecaceae (3), and Proteaceae (37). We summarized data in vegetation communities present in the area (after Griffiths, et al. (1997)) and found the majority of...
the charcoal originated from open woodland (OWL, or savannah) (138), followed by monsoon forest (WMF) (20), and fringe taxa (42). Fringe taxa grow at the boundary between WMF and OWL. Taxa that were common in all vegetation communities (shared taxa) counted 70 pieces, and can therefore have only limited interpretive power. OWL, WMF and fringe taxa are present to varying extents in all layers, including soil and sand layers (Figure 5 h-j). The record of shared taxa indicate no coherent trend with depth, but common taxa are more common in soil than in sand layers (Figure 5 j). Open woodland charcoal dominates the record and is present in all layers. In the lowest sand and soil unit (unit IV) open woodland charcoal accounts for 62 to 90 %, then drops to 4 % in the truncated soil that tops unit III, and increases coherently towards the top (84 %) (Figure 5 h). Charcoal belonging to WMF are only present in 6 of 11 samples. In addition, WMF charcoal exhibits a trend similar to the open woodland charcoal record, with relatively high values in the lowest layers (11-16 %), low values in the center of the profile (0-7 %), and higher values in the top layer (10 – 12 %) (Figure 5 i). Fringe taxa, here only represented by the taxa *Grewia*, grow dominantly in areas with no canopy cover. *Grewia* is present in 6 of 11 samples, with relatively low values in the bottom layers (2 – 3 %), a sudden increase to 50 to 79 % in the centre of the profile (truncated soil), and a decrease to 10 – 0 % within the top layers (Figure 5 j).

**Stratigraphy at site 2 (WG-550, WG-553 and WG-548)**

The investigated sediments in the vicinity of the knickpoint location (site 2) expose fluvial sands directly underlying a 1.1 m thick, structurally intact but drained tropical peat. The TOC analysis of the peat showed TOC values of 6 %, and grain size analysis of the mineral content was coherent with the samples of site 1, with 89 % sand, and a moderate mud-sand ratio of 7 %. The underlying sand was sampled for OSL dating (WG-553, Figure 4 d). In 25 m distance, the drained tropical peat was mostly burned and partly eroded, but islands of structurally intact peat patches were still present in association with the woody remains of tree trunks (WG-550, WG-548; Figure 4 e, f). This situation exhibits a complicated stratigraphy of plant remains within the peat layer, likely indicating several and repeated phases of erosion and growth of the peat layer at any one location. We sampled the bark of a tree stump (unknown species) (Figure 4 f) buried by younger peat and renewed tree growth (Pandanus) for radiocarbon dating (WG-548) (Figure 4 e). A second sample for radiocarbon dating (WG-550) was taken ~100 m further downstream along a minor, dry anabranching channel from a
woody root of a tree trunk (Figure 4 g). Here, a Pandanus tree growing on top of a tree trunk also reflects an extended period of peat and/or floodplain aggradation followed by the likely recent erosion and removal of the surrounding peat as the result of channel incision.

**Chronology**

**Radiocarbon data**

Radiocarbon dating of the sedimentary profile of site 1 (WG 371) indicates that the bottom, cross-beded channel deposition took place at about 3103 ± 21 cal BP (charcoal, WK-41280). The start of alluvial aggradation was dated in the same stratigraphic position to 3337 ± 20 cal BP (humins, WK-41272) and 3002 ± 23 cal BP (charcoal, WK-41278). In three cases, radiocarbon dates on humins seem to coherently yield ages 300 – 750 years older than radiocarbon ages on charcoal or wood remains sampled from the same layer depth (Table 1) (Figure 5 c). We interpret this to be the effect of fast decomposition and leaching of organic residuals from soils into the layers below, probably an effect of the low pH, extreme rainfall events and tropical temperatures. At site 2, both sampled trees yielded a calibrated age between 0 and 253 years ago (WK39272, WK39273) (Table 1).

**Luminescence dating**

**Dose rate measurements**

Elemental concentrations show considerable variability across all samples and range from ~0.37-2.9 ppm for U, ~1.6-8.3 ppm for Th, and ~0.07-0.17% for K (Table 1 and 2). Concentrations seems to be generally higher for HRGS measurements. The paired sample WGM-371-190 exhibits markedly lower U concentrations from ICP-MS measurements than for HRGS whereas Th and K concentrations overlap within error. A closer look into the activity ratios as determined by HRGS also reveals differences between 238U and 226Ra isotopes (Table 1). For all three samples, the parent 238U is significantly lower than the daughter nuclide 226Ra, providing strong evidence for the presence of varying degrees of isotopic disequilibria in all HRGS samples.
Despite the relatively homogeneous lithology of all samples sediments, total dose rates show considerable variation across all samples up to a factor of five (Table 3). More specifically, dose rates calculated from HRGS are generally higher (0.95-1.49 Gy/ka) than dose rates calculated from ICP-MS and ICP-OE measurements (0.43-0.79). This is also evident in the paired sample WGM-371-190 showing a ~30% higher dose rate for HRGS.

**Palaeodoses (De) and luminescence ages**

Overall, all luminescence samples show very good OSL characteristics with a dominant and bright fast component. Except in the very young samples WG553-123, >20 % of the single grains pass the applied rejecting criteria. Overdispersion values are range between ~14-33 %, with only WG553-123 having a higher overdispersion of 55%. The resulting De distributions are slightly asymmetrical (Supp Fig. 1), characterized by a few low De values and some high De values. For most samples, the differences between D_{w,s} derived with a Central Age Model (CAM, Galbraith, et al. 1999) are only 7-15 % higher than D_{w,s} based on a Minimum Age Model (Galbraith, et al., 1999, May, et al., 2015b). For samples WGM-371-A-25, WG 553-123 and WGN 372-25, however, this difference is between 40 and 67 %, possibly pointing to the presence of some partial bleaching in these samples. MAM based D_{w,s} are overall very low and range between 0.08 and 2.03 Gy (Table 4). The calculation of final depositional ages for our single grain samples yields follows the formula:

\[
\text{De (Gy)} / \text{Total Dose Rate (Gy/ka)}
\]

Resulting ages in our soil-sediment sequence range from 0.045±0.08 to 4.06±0.31 kal yrs (Table 4). Sample WGN 372-25 which is situated on the opposite river bank of the sequence at ~200 m depth generally agrees with this chronology, while sample WG 553-123 from further upstream yields the youngest age with 0.08±0.01 kyrs (Table 4).

**Discussion: Wangi Creek as a tropical cut-and-fill river-floodplain system?**

The discovery of an alluvial knickpoint migrating upstream within a trench-like valley suggests that Wangi Creek may operate as a cut-and-fill river system. Cut-and-fill river systems can have spatially distinct reaches of aggradation and erosion (Bull, 1997), or phases of aggradation and erosion that alternate in time (Cooke, et al., 1976). Most importantly, these rivers are controlled by internal
dynamics, and consequently care must be taken if external drives, such as palaeoclimate, sea-level rise, or anthropogenic impact are used to interpret their depositional record. Therefore, if cut-and-fill processes also dominate the geomorphic dynamics at Wangi Creek over longer timescales, these processes need to be considered when interpreting the evolution of the middle reaches of Northern Australian streams with similar geomorphic characteristics (e.g. Magela Creek).

After briefly discussing the uncertainties associated with establishing the chronological framework of this study, we explore the existence of a mid- to late Holocene cut-and-fill river system at Wangi Creek by considering the evidence for i) an aggradational and ii) erosional phase(s) (see below). We then discuss the findings with respect to published characteristics of other cut-and-fill river systems, and shed a particular focus on the importance of biogeomorphic feedbacks that may play a key role in the establishment of many cut-and-fill river systems.

**Establishing a chronological framework**

The age-depth relationship given by our radiocarbon and OSL ages provides a chronological structure for the deposition of sandy sediment and the formation of intercalated paleosols at site WG 371 between ~4000 yrs and <450 yrs ago. While these results present an overall coherent temporal framework, two observations require further discussion. Firstly, we observe a divergence between humin and charcoal based radiocarbon ages in the lower half of the profile. The difference between these two fractions is 400-760 years, e.g. 2003 ± 64 cal BP (humins, WK-41276) versus 1314 ± 89 cal BP (charcoal, WK-41281); 2341 ± 83 cal BP (humins, WK-41274) versus 1721 ± 99 cal BP (charcoal, WK-41279); and 3529 ± 67 (humins, WK-41272) versus 3120 ± 103 cal BP (charcoal, WK-41278). We speculate that this is the effect of fast decomposition, leaching and vertical mobility of organic residuals (i.e. humins) within the sedimentary profile, probably an effect of low pH (between 3.7 and 4.1). These processes are governed by extreme rainfall events, the seasonally rising and falling floodplain water table and tropical temperatures. Secondly, luminescence ages show considerable deviation from neighboring/adjacent radiocarbon ages, as well as age inversions within the OSL chronology. This is possibly related to variations in isotopic disequilibria observed in all HRGS data, disequilibrium cannot be determined by elemental concentrations as provided by ICP-MS.
measurements alone. The amount of disequilibrium in the environmental dose rate as expressed by \(^{226}\)Ra excess varies between the three measured samples, but is highest where the largest thickness of organic material is present in the profiles, and vice versa. Given the strong Uranium (U) absorption in organic matter (Porcelli, 2003), good solubility of U in groundwater and seasonally fluctuating groundwater tables, disequilibrium in these samples could be interpreted as the result of spatially variable uranium depletion by groundwater leaching through the sandy deposits, and uranium enrichment in the organic rich horizons of the floodplain deposits. This scenario would also explain the clear difference of 20 % in total dose rate as determined by HRGS and ICP-MS, respectively. Alternatively, \(^{226}\)Ra excess activity in relation to \(^{238}\)U may also result from uranium loss by weathering and leaching processes in hillslope deposits in the upper catchment previous to deposition in the floodplain. This type of disequilibrium has also been reported from alluvial deposits along the Alligator Rivers in Arnhem Land (Murray, et al., 1992), and should decrease over millennial timescales due to the relatively short \(^{226}\)Ra half-life. In fact, the youngest of our HRGS sample exhibits the largest disequilibrium (\(^{226}\)Ra/\(^{238}\)U is 0.3 in WG553-123). Overall, given the hydrologically similar setting and shared provenance of all sand samples from the small Wangi catchment both processes may contribute to the generation of disequilibria but clearly more data is required to test this hypothesis. In order to account for these issues, luminescence ages calculated with ICP-MS based dose rates should be viewed as maximum limiting depositional ages, whereas HRGS based dose rates can be interpreted as minimum limiting ages (Table 2).

Aggradational (fill) phases – the product of relative stability and soil development over most of the past ~4000 years

With the exception of one small discontinuity (discussed in the section below), sediment aggradation (site 1, Figure 5) is considered continuous during the past ~4000 years (until AD 1996, see Larsen, et al. (2016)), and characterized by the alternation of black or grey and white sands. All black sands have an elevated mud content (Figure 6 a) and OC values that are consistently higher than in the palaeosols (Figure 6 b). While it is surprising that the relatively low OC content (maximum of 0.8%) seems to have a strong effect on the black coloration of these palaeosols, in combination the data indicates that black layers are residuals of degraded palaeosols (Figure 6 b). In this context, we
hypothesize that the black palaeosols are likely the product of the degradation of and formerly well-developed soils analogous to the thick, peaty soils that characterize the modern floodplain surface further upstream, where Wangi Creek floodplain has not been affected by recent drainage and fire. Here, water-logged conditions and the presence of dense WMF vegetation result in the development of a ~1 m thick tropical floodplain peat, forming a Histosol (Figure 4 a,b) before its destruction by a combination of drainage, fire and erosion following the recent passage of a knickpoint (Larsen, et al., 2016).

More specifically, we argue that the formation of the black soils could be the product of peat degradation, and migration and enrichment of the residual OC in distinct layers in the soil column. Low pH, high temperatures, rainfall intensities and large pore sizes would support the vertical mobility of OC in the profile. In this scenario, OC accumulation could be regarded as a self-reinforcing mechanism that depends on three possible mechanisms: OC migration might be restricted to the zone of seasonal water table variability, in which it accumulates. Alternatively, OC typically associates with the higher silt and clay component of the black soils within units 2-4 (Kleber, et al., 2015, Six, et al., 2002), which are elevated in black soil layers 3 to 9 in comparison to the underlying sands (Figure 6 a, Table 3,4). Another explanation may be a relationship between black soils and fire. Black soils are often attributed to black carbon, a product of combustion. Therefore, fire might play a role in the evolution of the black soils because there is consistently higher RC content in black soils than in underlying sands of units 2-4 (Figure 6 c). However, anthracomass, which is an established indicator for fire frequency, shows that all soil horizons with high anthracomass values are dark, whereas not all dark layers have a high anthracomass. From these findings we suggest that fire is probably a component, but not a key factor controlling the development of the black palaeosols. Instead, we suggest that a set of conditions leads to the development of the black soils. These include the development, degradation and burial of a peaty A-Horizon, a high and seasonally fluctuating floodplain groundwater level, high porosity and small variations in grain size within the profile, and the frequent occurrence of fire in the catchment.

In addition to the black palaeosols, white sand layers add sediment mass to the sediment aggradation at site 1. These layers are spatially extensive, but have been found to be sometimes spatially discontinuous (part of unit 4, site 1). We interpret these white sands to be the product of
the sedimentation during high frequency, high magnitude flood events typical for tropical river settings. Earlier work in the research area has found that the presence of an intact wet monsoon forest and an peaty topsoil at Wangi Creek stabilize river banks and the floodplain surface almost completely (except within billabongs/enlarged channel sections) (Larsen, et al., 2016). These characteristics, in combination with a sand-dominated sediment load – means that surface erosion is largely absent, and deposition occurs as spatially extensive patches of sand deposited on top of the floodplain. Therefore, the white sands are interpreted as the product of the sedimentation during high frequency, high magnitude flood events typical for tropical river settings. The sedimentary characteristics of the extensive palaeo-white sands are very similar to the white sands (Figure 5, 6 a), suggesting that similar but possibly more extensive flooding processes were responsible for their deposition (Figure 7 d). In turn, this could be due to a higher sediment load and/or larger flood magnitude and/or frequency, or a combination of both. Due to the absence of soil development within these deposits it seems reasonable to presume a relatively rapid deposition, whereas the temporal resolution of our data does not allow distinguishing between deposition during a single flood or a phase of several consecutive flood events.

The analysis of historic aerial photographs and satellite imagery going back to 1941 showed that the wet monsoon forest at Wangi Creek was intact along the study reach before 1996 (Larsen, et al., 2016). Here, “intact” wet monsoon forest is generally associated with very dense and flood resistant vegetation, a water-logged subsurface and tropical peat overlying sands. The soil charcoal data from Wangi Creek shows the presence of all modern-day vegetation communities throughout the past 4000 years until 1996 AD (when WMF degradation started) (Larsen, et al. (2016)). In combination with the aggradational nature of the floodplain sediments generally suggests overall stable environmental conditions in this time period. The combination of all collected sedimentological, stratigraphic, chronological and charcoal data, however, does not exclude short-term variability, e.g. through changes in flood and fire magnitude and/or frequency (discussed above), but these changes have likely not affected the overall vegetation communities and eco-hydro-geomorphic feedbacks at Wangi Creek.

**Erosional (cut-) phases**
There are two types of erosional signatures within in the late Holocene sedimentary record of Wangi Creek. We suggest these originate in processes similar to those that we observe at present in the study area. One, minor erosional phase is represented in a small erosional discontinuity (black line within Figure 5 b at 1.8 m depth). Based on the stratigraphic and grain size analysis we interpret this discontinuity to be the result of a relatively small erosional event. This interpretation is based on the superimposed thin, horizontal deposition of non-bedded, coarser sands on top of the discontinuity, which indicates relatively low velocity and a minor erosional event. Also, calculated average aggradation rates above and below the discontinuity are relatively similar (~0.8 cm/year), (Figure 5 a) which supports the interpretation that only a small amount of sediment was eroded during this event, or consecutive events.

In contrast, a major phase of high-energy deposition at 2.7 m depth and an age of ~ 4000 years is very likely to be associated with major erosional activity and incision (Figure 4 g). In general, such a phase of fluvial activity could be caused by i) increased lateral channel migration, ii) avulsion or iii) channel incision. At Wangi Creek, lateral channel migration is restricted due to the macro-channel setting which has persisted longer than the Holocene. This is evident from the intense weathering of the macro-channel banks (Figure 4 c), a phenomenon also described for similar, mid-reach settings (Nanson, et al., 1993). Major avulsive processes which lead to a shift of the macro-channel are also unlikely as these would be visible from aerial imagery, which is not the case. Hence, it is probable that channel incision has caused a phase of increased fluvial activity and is the cause of the observed cross-bedded sands at 2.7 m depth. This incisional phase would have also likely removed previous sediments deposited in the macro-channel area (Figure 7 h). At present, the channel of Wangi Creek is also incised due to environmental and hydro-geomorphic feedbacks initiated by the headward retreat of an alluvial knickpoint (Larsen, et al., 2016). We hence interpret that both phases of major channel incision (~ 4000 years ago and at present) are characterised by similar processes. This assumption is also supported by the sedimentological similarity between channel deposits from ~ 4000 years ago and modern channel sands (Figure 7). We therefore propose that Wangi Creek has experienced two main phases of channel incision in the past ~4000 years likely triggered by the retreat and passage of an alluvial knickpoint (Larsen, et al., 2016). Alluvial knickpoints are indicative of a cut (erosional) phase in cut-and-fill river systems (Cooke, et al., 1976, Schumm, et al., 1984). In combination with the long preceding phase dominated by aggradation between ~4000 years ago and
AD 1996 (see section above), we therefore suggest that both past (~4000 yrs) and present alluvial knickpoint events serve as evidence that Wangi Creek can be considered a cut-and-fill system over mid- to late Holocene timescales (Figure 7 a-f).

Eco-hydro-geomorphic feedbacks cause the alternation of aggradational and erosional phases at Wangi Creek

In this study, we have described the first tropical cut-and-fill river system operating on a decadal-millennial time scale, which is characterized by a phase of aggradation and subsequent erosion. At Wangi Creek, the existence of this cut-and-fill river system is a product of i) a long-term aggradation (Figure 5 a, Figure 7 a – f) controlled by an extremely dense and resistant vegetation cover (wet monsoon forest, see Figure 4 a,b,d and Figure 5 i) which stabilizes river channels and the floodplain (Larsen, et al., 2016). The existence of this vegetation is related to the high river water level and floodplain water table, which are the product of the geomorphic setting and climate of the study area (see section above). The aggradation also depends on the sporadic deposition of fine-grained sediments on the floodplain, without which the floodplain surface would not rise (Figure 4 b, 5, 7 d-f, and sections above). ii) An alluvial knickpoint, through its headward retreat erosion, overcoming the stability created by the wet monsoon forest and the peaty Histosol (Figures 4 a,b,d, Figure 7 g) (Larsen, et al., 2016). iii) The incision and subsequent drainage of the waterlogged subsurface destabilising the wet monsoon forest to such an extent that channels can widen and most of the floodplain sediments can be eroded (Figure 4 f, Figure 7 h). This is of course also the effect of the sand-dominated deposition (Figure 5 d, Figure 6 a), which is easily erodible, in combination with the annually re-occurring large magnitude flood events in a tropical setting (Larsen, et al., 2016). Fire might accelerate the destruction of the peat, but only after drainage and hence influence the shorter-term variability within the aggradation phase (Figure 6 c), but we found no evidence that it plays a major role on a millennial scale.

Abiotic and biotic controls on geomorphology and sediment flux
The discovery of a tropical cut-and-fill system in the middle reach of Wangi Creek provides an alternative model for the evolution of the middle reaches of Northern Australian streams. Even though many questions remain open and should be addressed in future research in the area (e.g. what causes the initiation of a knickpoint?), the findings presented here point towards the importance of internal mechanisms and feedbacks within the eco-hydro-geomorphic system with environmental implications on multiple timescales. Firstly, downstream of mine sites, pollutants such as heavy metals or uranium are dominantly associated to fine-grained floodplain sediments (Noller, et al., 1993, Taylor, 2007). Even after decades of stability following site rehabilitation, excavation of these sediments through incision and bank erosion related to knickpoint passage may thus lead to the abrupt liberation and downstream transmission of contaminated sediment and water (Caitcheon, et al., 2012, East, et al., 1988, Taylor, 2007), demonstrating the need for more integrated biogeomorphological perspectives towards a more comprehensive understanding of pollution cycles in general (Mudd, et al., 2010). Secondly, the finding presented here of a tropical cut-and-fill river system has implications for the general interpretation of all cut-and-fill river systems, which have been described by Schumm’s benchmark paper “Arroyos and the semiarid cycle of erosion” (Schumm, et al., 1957). Schumm’s paper was followed by decades of research and discussion regarding the evolution of smaller, incised ephemeral river systems (well summarized in Cooke, et al. (1976)), with recent advances by Tucker, et al. (2006). Even though our study is set in a very different climatic setting, the prerequisites for the existence of a cut-and-fill system in the semi-arid setting are remarkably similar to those found at Wangi Creek, including i) (high) sediment delivery, ii) large magnitude flood events, and iii) a stable surface (summarized in Tucker, et al. (2006)). In addition, our study highlights three important factors to consider: firstly, the important role of the shallow floodplain water table through feedbacks with the stabilizing effects of vegetation, an effect also observed by Webb, et al. (2006) in semi-arid cut-and-fill systems. The fact that feedbacks between groundwater and riparian vegetation can control channel morphodynamics has also been found in other settings and river types (Bätz, et al., 2016), and might have been overlooked in the past. Secondly, the role of fire on short and longer-term sediment flux is heterogeneous. Frequent fire events may disturb the rainforest and lead to short pulses of sediment transport, but at Wangi Creek have not lead to a large instability of the eco-geo-hydrosphere of the river and floodplain system, and hence have not interrupted the trend of aggradation. This also means that the WMF is adapted
to burn and able to recover. Thirdly, infrequent knickpoints lead to the described eco-hydro-
geomorphic feedbacks which in turn causes rainforest destruction, incision and erosion (Figure 8). 
We hypothesize that the erosional phase following knickpoint migration, including channel incision, 
widening, and inset-floodplain stripping, could reduce the difference between in-channel water level 
and the shallow floodplain water table, which re-sets the hydro-geomorphic conditions for the WMF 
to re-establish (Figure 7 I, 7). The cyclicity of the system means that, instead of contrasting physical 
and biotic controls on geomorphology and sediment flux (e.g. Gurnell (2014), Tal, et al. (2010)), we 
rather have to consider the control of vegetation as part of a longer-term cycle, in which the 
dominance of biotic and abiotic processes not only switch, but depend on each other (Lane, et al., 
2016, Larsen, et al., 2018). This adds a new and contrasting perspective to earlier studies on the 
longer-term evolution along the middle reaches of Top End river systems that argued for a 
dominance of either climate or sea-level control on shifts between aggradational and degradational 
episodes over Holocene timescales (Nanson, et al., 1993, Roberts, 1991). If biota and abiotic 
processes have co-evolved over both longer and shorter timescales (Corenblit, et al., 2011), however, 
then the combination of process-based and Quaternary-scale studies is necessary to understand 
both, the present and past of river-floodplains.

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manuscript.

Conclusion
Wangi Creek represents a cut-and-fill river-floodplain system, for which this study finds the first concrete evidence. Fill phases are operating on a millennial scale (here ~4000 years) and are controlled by the vegetation and dense root system of the wet monsoon forest ecosystem. Fire is likely relatively frequent, and might disturb this ecosystem but not have longer-term effects, because the wet monsoon forest continues to exist throughout the 4000 years of aggradation. Hence, the wet monsoon forest ecosystem is likely to be able to recover after burning, if the right environmental conditions are established, e.g. a very shallow floodplain water table. In contrast, cut phases are most likely related to the hydro-geomorphic feedbacks initiated by a headwards retreating knickpoint, operating on a decadal scale. This process destabilizes and destroys the ecosystem by lowering the before very high floodplain water table, on which the wet monsoon rainforest depends. However, the erosional phase following knickpoint migration may reduce the difference between in-channel water level and shallow floodplain water table, which likely re-set the hydro-geomorphic conditions for the WMF to re-establish. In addition, this study highlights the important but often overlooked role of the shallow floodplain water table through feedbacks with the stabilizing effects of vegetation, which in this study controls channel morphodynamics. This study points towards a more holistic view of landscape evolution, in which we consider the control of vegetation as part of a longer-term cycle. Within this cycle, the dominance of biotic and abiotic processes do not only switch, but depend on each other.

**Figures**

**Figure 1**

Geologic, Geomorphologic and Ecological context of the upper, middle and lower reaches of tropical Northern Australian river corridors (adapted to Wangi Creek based on Williams (1991)).

**Figure 2**

Wangi Creek catchment and study reach within Australia (inset) (modified from Larsen et al., 2016). a) Wet monsoon rainforest vegetation is associated with rivers and groundwater wells along the base
of the sandstone escarpment; b) Location of the study reach in the long profile of Wangi Creek; c) Floodplain and channel surface in the study reach. The greater distance between floodplain and channel surface indicate incision downstream of an alluvial knickpoint.

Figure 3

Channel-in-channel morphology of Wangi Creek. High magnitude and frequency events during the wet season create macro-channels. During dry season low flow, water flows in small channels, and the macro-channel bed serves as floodplain. During high flow, macro-channels are inundated.

Figure 4

Environmental condition of the study reach. Base map: Canopy height model derived from green airborne LIDAR (reprinted from Larsen et al., 2016). A) intact wet monsoon forest; b) high floodplain water table with peat (black) and sand deposition on top (light colour); c) deeply weathered macro-channel banks; d) site 2, profile WG-553: recently drained subsurface showing a Histosol with peat development on fluvial sands. Arrow points to location of OSL sampling; e) site 2, profile WG-550 shows several levels of trees growing on top of each other; the peat matric between the plants is not yet completely removed; white arrow points to location of radiocarbon sampling; f) site 2, profile WG-448 shows almost complete erosion of top soil with three levels of trees growing on top of each other; arrow is pointing to the lowest tree, whose bark was sampled for radiocarbon sampling; g) spatial extension of site 1, profile WG-751; white arrow points towards black soil layers alternating with white sands; open woodland (OWL) growing on top of the exposure; h) site 1, profile WG-372; below dashed line: deeply weathered macro-channel boundary; above dashed line cemented and mottled sands.

Figure 5

Chrono-Stratigraphy of site 1 (WGM_371). Results of sedimentological investigations (a, b): a) photos of cleaned exposure; b) stratigraphic interpretation of (a), based on data displayed in (d), (e), (f), and (g). This results in the classification of sedimentary units I-IV. C) Age-depth model, including dates from OSL (box), radiocarbon of charcoal (triangles), and radiocarbon of humins (circles) including error ranges. The red line is the linear fit of all data points with R-Square of 0.75. D) is the mud/sand
ratio based on grain size analysis. Mud is considered to be clay and silt. E) sorting index in microns after Falk and Ward based on grain size analysis. F) Organic carbon content for bulk sediment samples (lines) and sub-samples taking in regular spacing every 7 cm (circles). g) Anthracomass is the weight percent of charcoal pieces larger than 2 mm per kg bulk sediment. H) Percentage of open woodland (OWL, savannah) tree species from the Anthracomass (g) record. I) Percentage of wet monsoon forest (WMF) tree species from the Anthracomass (g) record. J) Percentage of shared (blue circles) and fringe (purple diamonds) tree species. Dashed lines are indicative only.

**Figure 6**

Characterization of grain size and organic carbon. A) sorting (after Folk (1957)) and mud/sand ratio indicate a strong dominance of sand in the fluvial system. The scatter differentiates sands, present bank deposits, mineral fraction of peat, grey and top soils from black soils. Black soils are mostly less sorted and have a higher content of mud; b) S2a peak from Rock-Eval analysis clearly differentiates sediments without soil development and grey soils from top soil and black soils. Please note: the very low concentration of TOC might influence the calculation of the S2a peak; c) Larger percentage of residual carbon (RC) in black soils. RC is composed of strongly resistant and refractory compounds and is likely to originate in black carbon, which is a product of fire.

**Figure 7**

A conceptual model of the evolution of Wangi Creek cut and fill river-floodplain system. Fill, or aggradational phase are depicted in a-f; cut, or erosional phase in g-h. The dominance of erosion or aggradation is indicated by green upwards (aggradation) or downwards (erosion) green arrow on the right of each pictogram. Potential recovery of the system in i). a-b: year-long (cloud stands for wet season, sun for dry season) waterlogged surface condition in the inner-floodplain leads to peat aggradation. Drought and/or fire events (c) can cause subsidence of peat, but no complete destabilization of the system. D) Large magnitude, exceptional flood events (or a phase of consecutive large flood events) lead to spatially continuous sand deposition. The alternation of flood events and peat growth leads to an accumulation of the inner floodplain (e, f). The headward migration of an alluvial knickpoint leads to channel incision and destruction of the wet monsoon forest (g). Channel widening removes much of the sediment deposited during the past ~4000 years.
through mostly aggradational processes (a-f). We hypothesize that because of the erosion, the channel and floodplain water level, respectively shallow floodplain water table is again close to the surface (i), creates water-logged conditions and hence creates conditions to re-establish similar conditions than in a-f.

**Figure 8**

Process-Response-Model for the dynamics observed at Wangi Creek. Potential external drivers of the system are located in the top, striped box. Black arrows indicate their effects on the fluvial and vegetation dynamics at Wangi Creek. Green arrows indicate feedbacks which might lead to a recovery of the system and which would explain the potential cyclicity.

**Supplement Figure 1**

Single grain De distributions for OSL samples

**Bibliography**


Banfai DS, Bowman DMJS. 2006. Forty years of lowland monsoon rainforest expansion in Kakadu National Park, Northern Australia. *Biological Conservation* **131**: 553-565. DOI: [http://dx.doi.org/10.1016/j.biocon.2006.03.002](http://dx.doi.org/10.1016/j.biocon.2006.03.002)


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Caitcheon GG, Olley JM, Pantus F, Hancock G, Leslie C. 2012. The dominant erosion processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT), Mitchell (Qld) and Flinders (Qld) Rivers. Geomorphology 151-152: 188-195. DOI: https://doi.org/10.1016/j.geomorph.2012.02.001


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Wintle AG, Murray AS. 2006. A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols. Radiation Measurements 41: 369-391

Woodroffe CD. 1993. Late quaternary evolution of coastal and lowland riverine plains of Southeast Asia and northern Australia: an overview. Sedimentary Geology 83: 163-175. DOI: https://doi.org/10.1016/0037-0738(93)90010-3


Woodroffe CD. 1993. Late quaternary evolution of coastal and lowland riverine plains of Southeast Asia and northern Australia: an overview. *Sedimentary Geology* 83: 163-175. DOI: https://doi.org/10.1016/0037-0738(93)90010-3
Late Quaternary biotic and abiotic controls on long-term sediment flux in a northern Australian tropical river system

Annegret Larsen*; Jan-Hendrik May; Xavier Carah

• Wet monsoon rainforest can stabilize river systems for thousands of years
• Hydro-geomorphic feedbacks can destabilize monsoon rainforests and lead to its destruction, channel incision and floodplain erosion
• The control of vegetation on morphodynamics is part of a longer-term cycle, in which the dominance of biotic and abiotic processes do not only switch, but depend on each other.
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<td>charcoal</td>
<td>68.8 ± 0.2</td>
<td>3002 ± 23</td>
<td>3004</td>
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<tr>
<td>WGM-371 CH3</td>
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<td>68.0 ± 0.2</td>
<td>3103 ± 21</td>
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<td>150</td>
<td>39272</td>
<td>bark</td>
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<td>69 ± 25</td>
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<td>WG-550</td>
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<td>39273</td>
<td>wood</td>
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<td>126 ± 25</td>
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Table 2: Optical Stimulated Luminescence Results

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<th>De CAM [Gy]</th>
<th>Age CAM [ka]</th>
<th>De MAM [Gy]</th>
<th>Age MAM [ka]</th>
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<td>55/300</td>
<td>14.2</td>
<td>1.45 ± 0.03</td>
<td>1.44 ± 0.12</td>
<td>1.36 ± 0.07</td>
<td>1.35 ± 0.13</td>
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<tr>
<td>WGM 371-190**</td>
<td>55/300</td>
<td>14.2</td>
<td>1.45 ± 0.03</td>
<td>1.84 ± 0.12</td>
<td>1.36 ± 0.07</td>
<td>1.72 ± 0.14</td>
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<td>WGM 371-B-45</td>
<td>59/300</td>
<td>22.5</td>
<td>2.07 ± 0.07</td>
<td>4.35 ± 0.33</td>
<td>1.93 ± 0.07</td>
<td>4.06 ± 0.31</td>
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<tr>
<td>WGM 371-A-150</td>
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<td>16.8</td>
<td>0.92 ± 0.03</td>
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<td>0.80 ± 0.05</td>
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<tr>
<td>WGM 371-A-25</td>
<td>16/300</td>
<td>51.0</td>
<td>0.40 ± 0.05</td>
<td>0.75 ± 0.11</td>
<td>0.24 ± 0.04</td>
<td>0.45 ± 0.08</td>
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<tr>
<td>WG 553-123</td>
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<td>32.8</td>
<td>0.12 ± 0.01</td>
<td>0.13 ± 0.02</td>
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<td>1.92 ± 0.16</td>
<td>2.03 ± 0.16</td>
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Table 3: Results of grain size analysis

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<th>unit 4-soil</th>
<th>unit 4-soil</th>
<th>unit 3-sand</th>
<th>unit 3-sand</th>
<th>unit 3-soil</th>
<th>unit 3-soil</th>
<th>unit 2-sand</th>
<th>unit 2-soil</th>
<th>unit 2-soil</th>
<th>unit 1-soil</th>
<th>unit 1-soil</th>
<th>unit 1-soil</th>
<th>top soil</th>
<th>WG 450</th>
<th>WG-371HB*</th>
<th>**</th>
<th>WG-271LB**</th>
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<td>38.05</td>
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</table>

*calculated after Krumbein and Pettijohn (1938); **after Falk and Ward (1957); ***present high bar deposit; **** present low-bar deposit; non-unimodal grain size distribution in italic

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<table>
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<th>sample</th>
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<td>Unit 2-soil</td>
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<tr>
<td>Unit 2-sand</td>
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<td>Unit 2-sand</td>
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<tr>
<td>Unit 3-soil</td>
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Table 5: Anthracology results

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<th>unit 4-sand</th>
<th>unit 4-soil</th>
<th>unit 3-sand</th>
<th>unit 3-soil</th>
<th>unit 2-sand</th>
<th>unit 2-soil</th>
<th>unit 1-soil</th>
<th>unit 1-soil</th>
<th>unit 1-sand</th>
<th>top soil</th>
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<td>10.00</td>
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<td>37.93</td>
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</tr>
</tbody>
</table>
Sedimentary units

I

III

IV

Age (years before present)

Grain size (mud/sand)

Sorting (microns)

OC (%)

Anthracomass (g/kg)

OWL (%)

WMF (%)

Shared & fringe (%)

Depth (m)

grey soil

black soil

sand

course sand with small pebbles

sand, charcoal enriched

cross-bedded sand

OSL-dating

Radiocarbon-dating of charcoal

Radiocarbon-dating of organic matter

Sediments:

a) b) c) d) e) f) g) h) i) j)

shared taxa fringe taxa

Dating:

Charcoal:

wet monsoon forest

savannah

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between <~4000 - ~1800 yrs ago

between <~4000 - ~1800 yrs ago

between <~1800 - 20 yrs ago

between <~1800 - 20 yrs ago

>~4000 and since 20 yrs ago

>~4000 and since 20 yrs ago

>~4000 yrs ago, and in 20 yrs