Department of Science, Information Technology and Innovation

Bioavailable nutrients and organics in alluvial gully sediment

Chemistry Centre, Landscape Sciences

13/05/2016

Queensland Government

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Citation

Garzon-Garcia A, Burton J, Brooks AP. (2016). Bioavailable nutrients and organics in alluvial gully sediment. Department of Science, Information Technology and Innovation.

Acknowledgements

This document has been prepared by the Department of Science, Information Technology and Innovation. The project was funded by NESP as part of NESP Project 1.7, led by Griffith University and with in-kind contributions from the Chemistry Centre, Department of Science, Information Technology and Innovation (DSITI). Sample processing and analysis was conducted by the Chemistry Centre and Soil Processes (DSITI). In particular, we thank Rob De Hayr, Benjamin Hall, Kate Dolan, Siok Yo, Dan Yousaf and Angus Mcelnea. We also specially thank Dr. Phil Moody, Prof Jon Olley and Rob Dehayr for reviewing the manuscript.

May 2016

Executive summary

Gully erosion is a major source of fine sediment pollution to the Great Barrier Reef (GBR). This can be inferred from the knowledge that the large, dry, grazing-dominated catchments in the Tropics (e.g. Fitzroy, Burdekin) deliver the largest sediment loads to the GBR (Garzon-Garcia et al., 2015; Joo et al., 2012; Kroon et al., 2012) and from sediment source tracing studies that have indicated that subsurface soil is the predominant sediment source in these catchments, particularly in areas with active gully erosion (Hughes et al., 2009; Olley et al., 2013; Wilkinson et al., 2015). Alluvial gully erosion has been shown to be the dominant form of gully erosion in the Normanby Catchment (Brooks et al., 2013), and while data don't exist as to the relative contribution of the different gully forms for other catchments, it is likely that in catchments such as the Bowen River, alluvial gullies are a significant, if not the dominant source. Fine sediment and nutrient delivery to the GBR has detrimental chemical/biological effects on the reef (Bainbridge et al., 2012; Brodie et al., 2010; Brodie et al., 2012; Wolanski et al., 2008). Recent work undertaken in the Burdekin and Johnstone River catchments has demonstrated that there are significant quantities of bioavailable nutrients (nitrogen and phosphorus) associated with fine sediments derived from eroded soils (Burton et al., 2015). This work also indicated that sediments have the ability to produce dissolved inorganic nitrogen (DIN) from their organic N sources as they move through the waterways, thereby contributing to the DIN pool. Hence, given that we know alluvial gully erosion constitutes a significant component of the anthropogenically accelerated sediment load in the Normanby and Mitchell catchments where it has been studied in detail (Brooks et al., 2013; Shellberg et al., 2010; Shellberg et al., In review), by extension sediments are also contributing substantially to the anthropogenic DIN pool. Consequently, effective management practices should aim at reducing not only sediment yields from alluvial gullies, but also organic and nutrient yields. Research has been carried out in a number of key catchments within the GBR to identify the key sources of fine sediment (Bainbridge et al., 2016; Bainbridge et al., 2014; Hughes et al., 2009; Olley et al., 2013; Wilkinson et al., 2015), however very little is currently known about sources of organics and nutrients, particularly within the catchments of the dry tropics dominated by grazing. An understanding of the key sources of organics and nutrients and their bioavailability and quantity associated with alluvial gully erosion is fundamental to inform management decisions.

In this report, results are presented for various key indicators of bioavailable nutrients and organics (the term carbon is used interchangeably with organics in this report) and analysed for four gullies (three alluvial and one hillslope gully) in the Normanby River catchment. The key indicators were selected based on previous and ongoing research conducted by Burton et al. (2015). The nutrient fractions and organic pools associated with different particle size fractions (total soil, <63 um, and 10 um) were determined for different gully geomorphic units including terrace surface soil, bank surface soil, bank subsurface soil and gully floor deposits. The total sediment, organic and nutrient exports from the three alluvial gullies and their geomorphic units, were estimated using detailed annual sediment budgets coupled with nutrient and organic composition data from this study. A sensitivity analysis was also carried out to understand the effect of changes in gully depth, sediment yield and geomorphic unit on relative contributions to organics and nutrient export from alluvial gullies.

Note that this report presents nutrient export budget results and interpretation of data from a limited number of gullies. Considering the low level of replication, results are to be considered as an indication only of the nutrient and organic pools within different components of gully complexes and of the range of organic and nutrient yields from gullies in the Normanby catchment, and should not be extrapolated.

Main findings include the following:

- Alluvial gullies are important sources of organics and potentially bioavailable nutrients to the aquatic environment.
- The data indicate little difference between bioavailable nutrient indicators in sampled hillslope (n=1) and alluvial gullies (n=3) for all particle size fractions sampled.
- There are significant differences in C, N, and P content among soils/sediments in the geomorphological units measured with the general pattern being terrace > bank surface > gully floor > bank subsurface. This result indicates that accurate estimation of nutrient and organic losses from gullies must be based on sampling and measurement of the different units.
- The upper 10-20cm of alluvial terrace soil profiles appear to be an important long term store/source of bioavailable nutrients and organics, whilst gully floors may act as a temporary store depending on gully evolution stage.
- TOC soil content in the terrace surface soils was from 54 to 77 times larger (depending on particle size fraction) and TN from 5 to 10 times higher than in bank subsurface soil in alluvial gullies.
- Primary gully erosion into terrace alluvium is ubiquitous in catchments like the Normanby and Burdekin (Figure 1).
- Particle size significantly influences nutrient and organic content and would influence bioavailability - hence particle size fractionation should be a major consideration in future study designs.
- The <10um fraction is generally enriched in bioavailable nutrients compared to the <63um fraction (1.4 to 3.3 times on average for carbon and nitrogen fractions), which is generally enriched compared to whole soil irrespective of gully geomorphic unit (with some exceptions e.g., DRP) (1.4 to 9.5 times on average for carbon and nitrogen fractions). These results from gullies in the Normanby catchment are consistent with results from key soil types in the Burdekin and Johnstone catchments (Burton et al., 2015).
- Although terrace soil had the highest concentration of most nutrients and organics, bank subsoil was generally the main source of nutrients in these alluvial gullies, due to the sheer volume of sub-soil delivered from active gully erosion.
- The sources of organics and nutrient export from alluvial gullies will vary depending on the type of erosional process occurring in the alluvial gully (i.e. headscarp retreat versus secondary incision) and their stage of evolution (e.g., gully depth and sediment yields) – however these findings should be confirmed with larger sample replication.
- In general, terrace soil was found to be the main source of total organic carbon export when headscarp retreat contributes the majority of sediment.
- The contribution of terrace soil to nutrient export varied with the stage of gully evolution. In the initial stages of gully evolution [very shallow gullies (<1.0 m) growing fast into the terrace deposits], terrace soil is the main source of nutrient export. As a result it should be a priority to protect terrace deposits from fast headscarp retreat as these deposits contain large pools of carbon and nutrients that, when lost, would be very difficult to restore. These terrace soil organic and nutrient pools may also be the most bioavailable and have a larger relative impact once in the aquatic environment.
- As gully incision occurs, the main source of most nutrient fractions was clearly bank subsurface sediment. Although this sediment has lower nutrient concentration than terrace surface soil or gully floors, the sheer quantity of exported sediment from this source makes it the largest contributor to export. Therefore, despite the nutrient enrichment of the surface soils (which are

a component of both gully headscarp and sidewall retreat) gully subsoils would tend to be the main source of nutrients. Hence, there is no one component of a gully system that can be prioritised over another; the whole gully should be stabilised as all components are significant nutrient sources.

- When secondary incision erodes organic and nutrient rich sediment deposited on gully floors, this sediment may become a very important source of organics and nutrient export; even more so than bank subsurface soil. The retention of gully floor organics and nutrient deposits should be part of gully rehabilitation designs and should be prioritized when these deposits are rich in organics and nutrients.
- The majority of the nitrogen in alluvial gully soils/sediments is in organic form (more than 96% in all particle sizes and geomorphic units). The exported organic N from alluvial gullies is potentially bioavailable and thus may be mineralized into dissolved inorganic nitrogen during stream transport, once it gets to the estuarine or marine environment, or be used directly by algae in dissolved organic form.
- While it has long been recognised that gullies are an important source of fine sediment to the GBR, it is also apparent the gully sources are a much under-appreciated source of nutrients as well. When compared to typical values of anthropogenic nitrogen and phosphorus from other major land uses in GBR catchments, it is apparent that gullies could be even more significant sources than intensive agricultural land per unit area.

Gully/land use	sediment (t/ha/y)	TN (kg/ha/y)	TP (kg/ha/y)
Granite Normanby	114.0	54.0	23.7
Laura - Crocodile station	29.2	10.5	0.3
Laura - Crocodile Gap	28.8	12.6	1.6
Sugar cane	1.2	22.2	2.7
Banana	1.8	25.3	3.1
Nature conservation	0.2	3.6	0.3

(see table 7 in report)

One of the most important implications of our findings is that alluvial gully erosion cannot continue to be overlooked as an important source of nutrients and potentially bioavailable nutrients to the aquatic environment. It is fundamental to increase our understanding of the links between organics and nutrient sources, alluvial gully erosional processes and instream processing. For example, it is crucial to understand differences in the bioavailability of exported sediment from different geomorphic unit sources once in the aquatic environment. Although various indicators of the bioavailability of these sediments were quantified in this study, research is still necessary and on-going to define which of these indicators would be the best to predict the impact of organics and nutrients on primary production in the freshwater and marine environment (Burton et al., 2015) and what controls this bioavailability (Garzon-Garcia et al. in prep). The role of vegetation and litter has been proposed as crucial, not only to the rehabilitation of carbon and nitrogen pools in gullied landscapes, but to reduce the impacts of eroded sediment during its transport in the aquatic environment by promoting mineral nitrogen use by microbes during mineralization of vegetation litter carbon (Garzon-Garcia, 2014). Further research is necessary to better understand the role of vegetation in mediating these relationships.

This study gives some indication of management priorities to reduce organics and nutrient export from alluvial gullies and identifies the importance of (i) sampling and analysing key gully features separately, and (ii) understanding the stage of evolution of the gully / combination of erosion processes occurring (i.e. head scarp retreat versus secondary incision- Figure 2). The findings of this study should be further tested by: sampling a larger number of alluvial gullies (replicated by gully type), including sampling of exported sediment; examining the effects of changes in sediment particle size on nutrient bioavailability; determining the relative bioavailability of nutrient derived from different sources; and using sediment source tracing to determine the relative contribution of each geomorphic unit. It is recommended that sampling design targets main geomorphic units from gully categories based on erosional process (e.g., fast headscarp retreat, primary incision, secondary incision, widening, gully depth, etc.)

Figure 1 Example of primary gully erosion into an alluvial terrace on Springvale Station Normanby catchment

Figure 2 Example of secondary incision into a >50 yr old primary gully floor – Springvale Station – Normanby catchment

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Introduction

Gully erosion is a major source of fine sediment pollution to the Great Barrier Reef (GBR). This can be inferred from the knowledge that the large, dry, grazing-dominated catchments in the Tropics (e.g. Fitzroy, Burdekin) deliver the largest sediment loads to the GBR (Garzon-Garcia et al., 2015; Joo et al., 2012; Kroon et al., 2012) and from sediment source tracing studies that have indicated that subsurface soil is the predominant sediment source in these catchments, particularly in areas with active gully erosion (Hughes et al., 2009; Olley et al., 2013; Wilkinson et al., 2015). Alluvial gully erosion has been shown to be the dominant form of gully erosion in the Normanby Catchment (Brooks et al., 2013), and while data do not exist in any of the other catchments as to the relative contribution of the different gully forms, it is likely that in catchments such as the Bowen River, alluvial gullies are a significant, if not dominant, source. The effects of fine sediment delivery to the GBR go beyond physical impacts (i.e., increased turbidity, reduced light attenuation and smothering of seagrass meadows and corals) and include chemical and biological effects related to the nutrients and organics associated with sediment particles, which are key to the formation of marine snow and the generation of dissolved inorganic nitrogen (DIN), an important driver of crown of thorns starfish outbreaks (Bainbridge et al., 2012; Brodie et al., 2010; Brodie et al., 2012; Wolanski et al., 2008). Consequently, effective management practices should aim at reducing not only sediment yields from alluvial gullies, but also organic and nutrient yields. Understanding key sources of organics and nutrients associated with alluvial gully erosion and their bioavailability is fundamental to inform mitigation management.

In this report, results for various indicators of bioavailable nutrients and organics for three alluvial and one hillslope gully in the Normanby River catchment are presented and analysed. The key indicators were selected based on previous and on-going research conducted by Burton et al., (2015). The differences in various nutrient fractions and organic pools for different gully geomorphic units (e.g., gully bank subsurface soil, terrace soil) and different particle size fractions were examined. Using detailed annual sediment budgets for the three alluvial gullies, the organics and nutrient composition of their geomorphic units and potential contributions from each of these units to sediment export were used to estimate annual export of organics and nutrients from these alluvial gullies. A sensitivity analysis was also carried out to understand the effect of changes in gully depth, sediment yield and geomorphic unit on the relative contributions to organics and nutrient export from alluvial gullies.

Methods

Sample Collection

Samples were collected from the gullies and gully geomorphic units listed in Table 1 and shown in Figure 3.

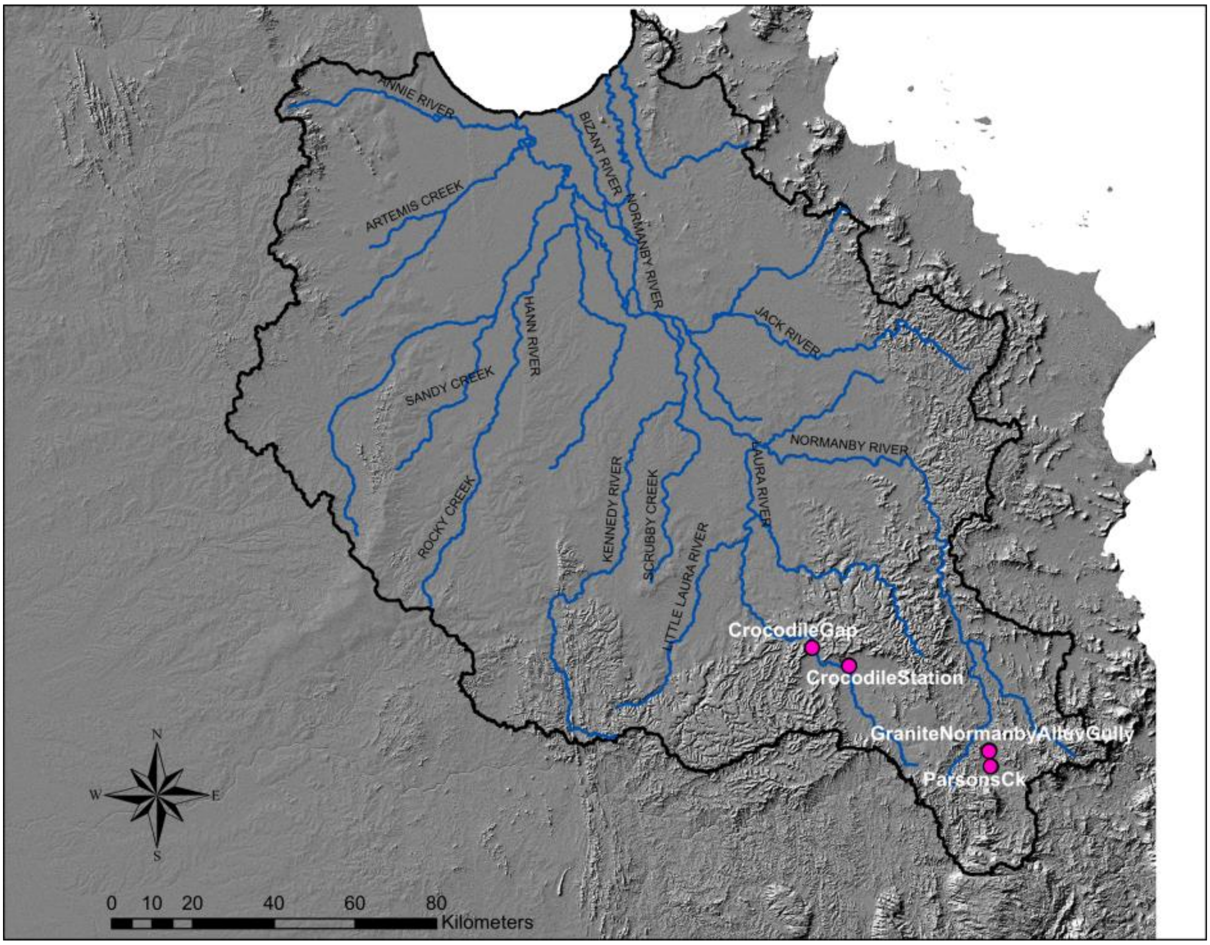


Figure 3 Map of the Normanby catchment showing the locations of the sampled gullies in the upper Laura and Normanby Rivers.

Table 1 List of sampled gullies and gully geomorphic units

Gully name	Gully type	Stream	Sampled Geomorphic Unit	Sampling date	Longitude	Latitude	Elevation (m)	Comments
Granite Normanby	Alluvial	Granite Normanby	Bank subsurface	20/07/2015	144.98599	-15.89717	184	Springvale Station.
			Bank surface	20/07/2015	144.98624	-15.89703	182	
			Terrace surface soil	20/07/2015	144.98527	-15.89859	189	
			Gully floor	20/07/2015	144.98658	-15.89730	177	
Parsons Ck	Hillslope	Parsons Creek	Bank subsurface	20/07/2015	144.98962	-15.93184	201	Gully on unnamed tributary of Parsons Creek; which is tributary of Granite Normanby; Springvale Station.
			Bank surface	20/07/2015	144.98964	-15.93198	203	
			Gully floor	20/07/2015	144.98972	-15.93180	202	
			Hillslope surface soil	20/07/2015	144.98903	-15.93226	208	
Laura Crocodile Station	Alluvial	Laura River	Bank subsurface	21/07/2015	144.67646	-15.70928	146	Alluvial gully on Laura River; Crocodile Station. Gully rehabilitation trial site.
			Bank surface	21/07/2015	144.67648	-15.70931	147	
			Terrace surface soil	21/07/2015	144.67619	-15.70949	149	
			Gully floor	21/07/2015	144.67643	-15.70923	146	
Laura Crocodile gap	Alluvial	Laura River	Bank subsurface	22/07/2015	144.59428	-15.66981	115	Alluvial gully on Laura River; Crocodile Gap area.
			Bank surface	22/07/2015	144.59409	-15.66965	114	
			Buried A horizon	22/07/2015	144.59428	-15.66985	115	
			Terrace surface soil	22/07/2015	144.59420	-15.66954	116	
			Gully Floor	22/07/2015	144.59445	-15.66995	116	

Figure 4 Bank subsurface geomorphic unit in the Granite Normanby alluvial gully and Laura Crocodile gap alluvial gully

Different gully geomorphic units and corresponding sampling methods are described as follows:

- Bank subsurface: Subsurface soil (excluding the organic A horizon), which was visually differentiated on exposed gully banks was sampled. First the gully wall was cleaned and then a sample was collected using a shovel or trowel.
- Bank (or gully wall) surface: The organic A horizon, which was visually differentiated on exposed gully banks was sampled. First the gully wall was cleaned and then a sample was collected from the gully bank surface (0-10 cm) using a trowel and spade.

Figure 5 Bank surface geomorphic unit in the Granite Normanby alluvial gully (clearly differentiated by colour from the bank subsurface unit)

- Buried A horizon: In the Crocodile Gap gully a distinct buried A horizon was sampled from the gully bank. First the sampling wall was cleaned and then a sample was collected from the buried A horizon using a trowel and spade.

Figure 6 Buried A horizon geomorphic unit in the Laura Crocodile gap alluvial gully

- Terrace: Alluvial gullies are developed by the erosion of previously deposited material in river terraces. Terrace surface soil samples were taken from deposits not affected by gully erosion by removing any vegetation from the surface of the soil and then collecting the surface soil (0-10 cm) using a trowel and spade. Material at these sites is assumed to represent bank surface material prior to any influence from gullying. Hence it is assumed bank/gully wall surface material will have similar characteristics as the terrace surface soil when an active gully scarp migrates through a terrace. The reason for sampling both is that the gully wall surface material is leached and altered due to its proximity to the gully incision, and so the terrace surface material is assumed to better represent the organic and nutrient status of these soils at the time the soil is first delivered to the gully.

Figure 7 Terrace surface soil geomorphic unit in the Granite Normanby and Laura Crocodile station alluvial gullies

- Hillslope: Hillslope gullies are distinct from alluvial gullies in that they are eroding into colluvial hillslope material. The hillslope sample was taken from intact hillslope material (not affected by gully erosion) by removing any vegetation and litter from the surface of the soil and then collecting the surface soil (0-10 cm) using a trowel and spade.

Figure 8 Hillslope geomorphic unit in the Parsons Creek hillslope gully

- Gully floor: Deposited sediment in the bottom of gullies was sampled by removing any vegetation from the surface of the soil and then collecting the surface soil (0-10 cm) using trowel and spade.

Figure 9 Gully floor geomorphic unit in the Granite Normanby alluvial gully

At all sites a composite sample of approximately 5-10kg was collected from various representative locations for each feature.

Sampling preparation

The following steps were taken to prepare the samples:

- Organic matter (including litter, roots and charcoal) was removed from whole soil samples. Soil lumps were broken down by hand to as small as possible and samples were then air dried at 40°C. Once air-dried, samples were checked a second time to remove any remaining organic matter and then mixed well.
- The sample was then processed through a jaw crusher set to 2 mm. Any organic matter found was removed. The sample was then mixed well.
- Once mixed, this sample was split into three sub-samples
- Sub-sample 1 was processed through a 2mm sieve and used for whole soil/sediment lab analysis in the Chemistry Centre DSITI and the analyses described in Table 2 were conducted.
- Sub-samples 2 and 3 were further processed to separate the <63 um and <10um fraction respectively, using the standard laboratory method for water-dispersible clay and the appropriate settling time based on Stoke’s Law. Following separation, the <63 um and <10um fractions were each dried at 40°C and then gently mixed and homogenised using a mortar and pestle. Following this, the samples were submitted to the DSITI Chemistry Centre and the analyses listed in Table 2 were conducted on each particle size fraction.

Sample analysis

Nitrogen (N) and phosphorus (P) analyses conducted in this project cover key pools and processes in the nitrogen and phosphorus cycles (Figure 10 and Figure 11). A selection of key carbon pools and processes and physical parameters were also measured (Figure 12). These parameters will be used to explain N and P pools and their bioavailability in the studied gullies and gully geomorphic units. The parameters analysed are summarised in Table 2 with full methods and references provided in Appendix 1. Equivalencies to water quality metrics are presented in Box 1.

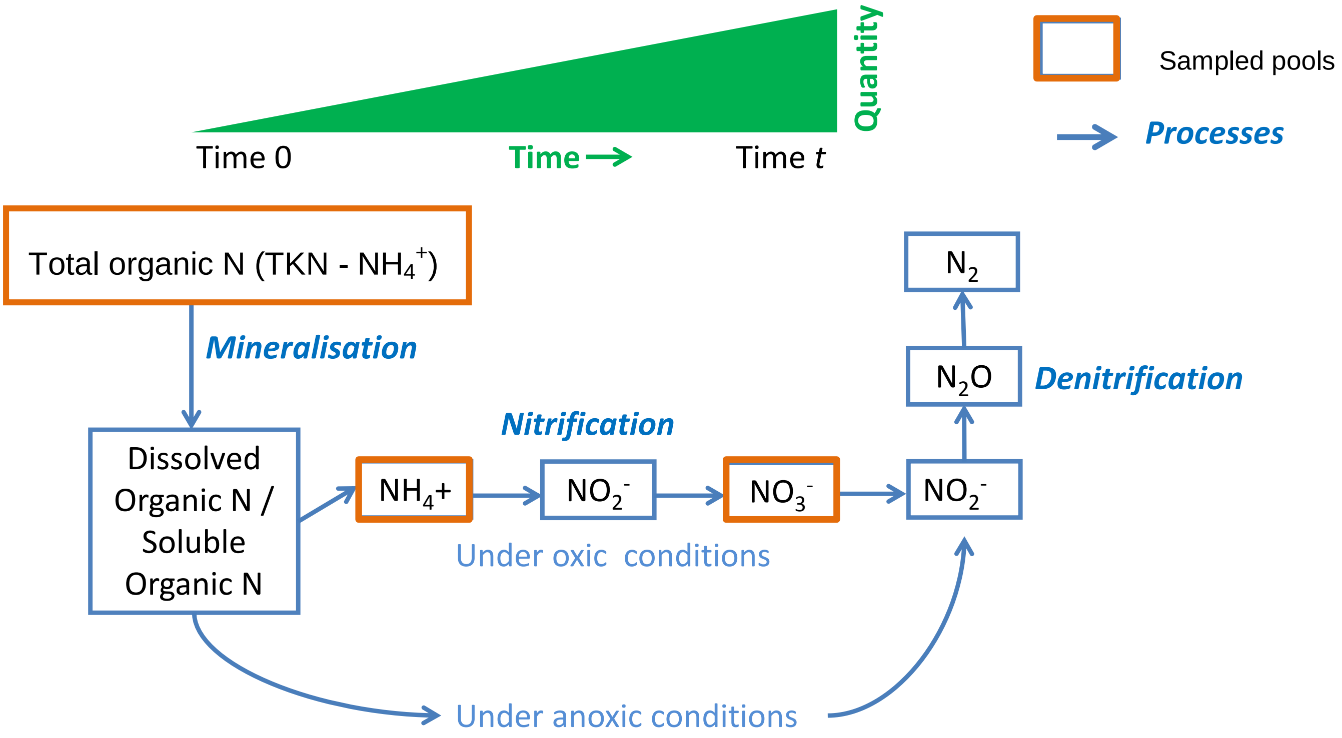


Figure 10 Key pools and processes of the nitrogen cycle. The trend of bioavailable nitrogen over time is indicated in the figure (Adapted from Burton et al. 2015)

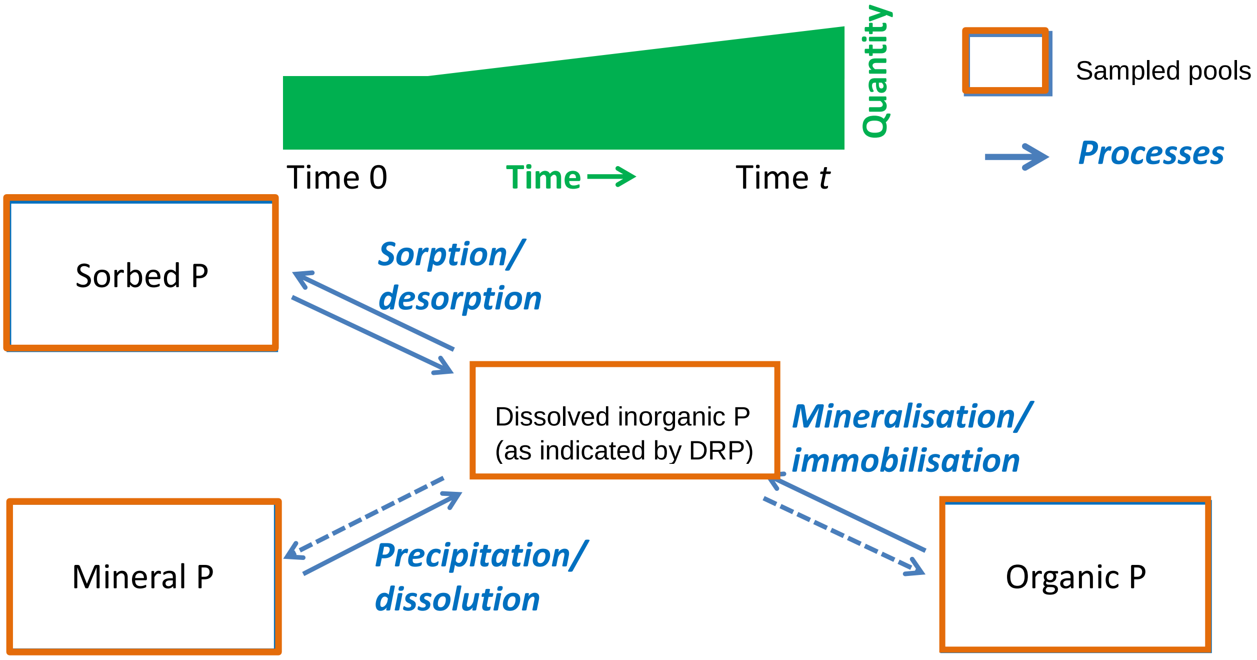


Figure 11 Key pools and processes of the phosphorus cycle. The trend of bioavailable phosphorus over time is indicated in the figure (Burton et al., 2015)

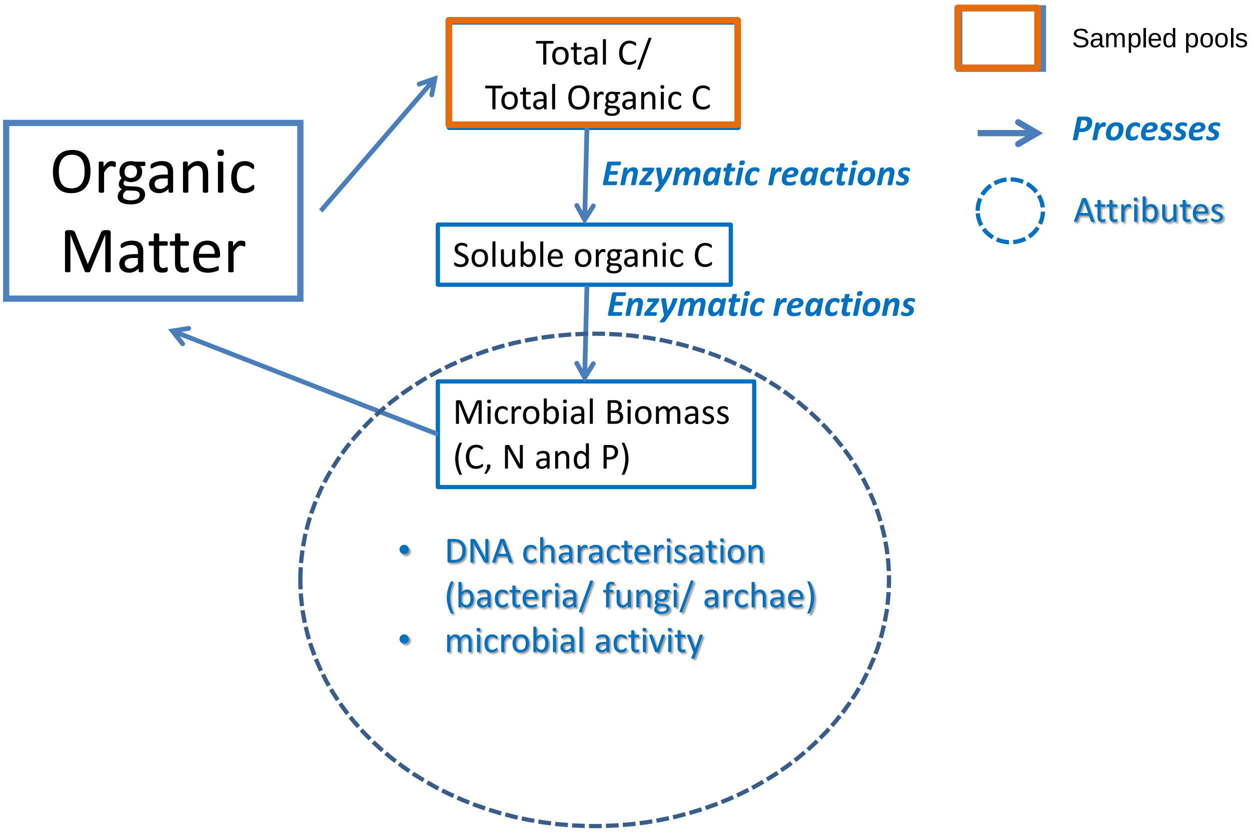


Figure 12 Key pools, processes and attributes of the carbon cycle (Burton et al., 2015)

Box 1. Approximate equivalencies between soil/sediment chemical parameters and water quality metrics

Soil/sediment parameter	**Water quality metric**
Total N (TN)	Total particulate nitrogen
Mineral N	No equivalency – Although it quantifies the same fractions as Dissolved inorganic N (DIN) (NO_3^-N + NH_4^+-N), mineral N is a KCl extraction of the soil/sediment, but does not equal the potential production of DIN as the sediment/soil mineralizes.
Total P (TP)	Total phosphorus
Sorbed P	No equivalency
Mineral P	No equivalency
DRP	No equivalency

Table 2 Nitrogen, phosphorus, carbon and other physical and chemical parameters measured in total soil/sediment, <63um and <10um soil/sediment fractions

Nitrogen (N)	Phosphorus (P)	Carbon (C)/ organics	Other possible explanatory measures
• Total N (TN) (refers to the total N pool) – Measured by the Dumas method • Mineral N (directly bioavailable pool) (refers to NH_4^+-N plus NO_3^--N) • NO_3^--N (directly bioavailable pool that is extracted by the KCl method) • NH_4^+-N (directly bioavailable pool – that is extracted by the KCl method)	• Total P (TP) (refers to the total P pool) – Measured by the total Kjeldahl P method • Sorbed P (refers to the P sorbed to the soil/sediment surface that is extracted by the Colwell-P method) • Mineral P (refers to P that is part of the soil/sediment mineral matrix. It is calculated as BSES-P minus Colwell-P) • Phosphorus Buffer Index (PBI) (an indicator of how tightly sorbed P is bound to the soil/sediment surface) • Dissolved reactive P calculated (DRP) (calculated as Colwell-P/PBI)	• Total C (includes both the organic and inorganic C) • Total organic carbon (TOC)	• Particle size (laser diffraction) • Oven dry moisture (105°C)

Results and Discussion

This report presents the results and interpretation of key carbon (C), nitrogen (N) and phosphorus (P) parameters measured in soils and sediments from a limited number of alluvial gullies (3) and one hillslope gully in the Normanby River catchment. Considering the low level of replication, results are to be considered only as an indication of the range of values that might comprise the nutrient and organic carbon pool in these gullies as well as the range of organics and nutrients exported from these types of gullies in the Normanby catchment. Consequently they should not be extrapolated.

To increase confidence in the range of bioavailable nutrient and organics present and exported from different gully types, further sampling would need to be undertaken to increase the number of replicates.

Bioavailable nutrients and organics in alluvial gullies

There were no large differences in most of the **total** nutrient and organic soil pools (TOC and TN) between gullies and gully types (alluvial versus hillslope). Most of the gullies had very low or undetectable TP. The statistics for all bioavailable nutrient and organics indicators by gully type (alluvial versus hillslope) are summarised in

Table **3**, Figure 13 and Figure 14. Data for all sampled gullies and geomorphic units are presented in Appendix 2.

Some of the differences found in **bioavailable** nutrient indicators between gullies follow:

- The alluvial Laura Crocodile station gully had larger bioavailable N fractions including NH_4^+-N (5-8 times larger), NO_3^--N (2-3 times larger) and mineral N (3-4 times larger) in the finer fractions than the other gullies. Factors known to affect bioavailable N in soils/sediment include biomass input, wet and dry cycles, vegetation type, and external inputs (e.g. manure, urine), among others (Austin et al., 2004; Evans et al., 2006; Garten and Ashwood, 2002; Gomez et al., 2012; Manzoni et al., 2010). Larger bioavailable N fractions in the Laura Crocodile station gully compared to other gullies could be driven by a larger contribution of organic material and nutrients from the surrounding terrace unit at this site compared to others (Appendix 2). The terrace unit in this gully had higher NH_4^+-N values than other gully terrace units. Further investigation of the factors listed above is required to improve our understanding of differences in bioavailable N among different gullies/gully types.
- The alluvial Granite Normanby gully had higher TP and sorbed P values in the <10 um fraction, and higher DRP values in all fractions compared to the other gullies (in all gully components). This was the only gully with Mineral P. Such differences could be caused by differences in the parent material of soils/sediments present in this gully. However, there are no differences in the underlying or headwater geology, and further investigation is required.

Key summary points of information:

- The data indicate little difference between bioavailable nutrient indicators in different hillslope and alluvial gullies for all studied size fractions– however it is reiterated that there was limited replication of alluvial gullies and no replication of hillslope gullies, therefore further investigation is necessary to confirm this result.

Table 3 Summary statistics for bioavailable nutrient and organics indicators by gully type and particle size fraction (ND: Non-detectable, NA: Not available)

		TOC (%)				TN(%)				NH4-N air.dry (mg/kg)				NO3-N air dry (mg/kg)				Mineral N (mg/kg)			
Gully type	Size Fraction	Mean	SD	Range		Mean	SD	Range		Mean	SD	Range		Mean	SD	Range		Mean	SD	Range	
Alluvial	<10 um	1.71	1.98	0.06	5.44	0.20	0.19	0.04	0.62	20.38	43.09	2.00	161.00	53.92	68.42	6.00	226.00	74.31	105.37	8.00	387.00
Alluvial	<63 um	0.94	1.13	0.04	3.24	0.11	0.10	0.03	0.31	18.78	31.47	3.00	100.00	19.80	20.39	2.00	69.00	36.40	43.52	5.00	139.00
Alluvial	Total	0.78	0.94	0.01	3.14	0.09	0.06	0.04	0.20	4.33	2.88	2.00	10.00	3.43	0.98	2.00	5.00	5.00	3.20	2.00	13.00
Hillslope	<10 um	1.69	1.64	0.14	3.82	0.16	0.12	0.04	0.32	11.33	10.41	3.00	23.00	17.00	9.49	8.00	29.00	27.33	21.73	11.00	52.00
Hillslope	<63 um	0.74	0.97	0.06	2.16	0.12	0.09	0.05	0.18	13.00	0.00	13.00	13.00	7.33	3.79	3.00	10.00	16.00	6.00	10.00	22.00
Hillslope	Total	0.44	0.50	0.04	1.15	0.05	0.03	0.03	0.07	ND	ND	ND	ND	12.00	NA	12.00	12.00	12.00	NA	12.00	12.00

		TKP (%)				Colwell P (mg/kg)				PBI col				DRP (mg/kg)			
Gully type	Size Fraction	Mean	SD	Range		Mean	SD	Range		Mean	SD	Range		Mean	SD	Range	
Alluvial	<10 um	0.04	0.02	0.02	0.09	12.38	15.14	2.00	57.00	137.62	75.96	46.00	291.00	0.12	0.14	0.01	0.41
Alluvial	<63 um	0.02	0.01	0.02	0.04	6.54	4.96	1.00	18.00	66.00	37.39	24.00	161.00	0.14	0.13	0.02	0.43
Alluvial	Total	0.02	0.01	0.02	0.04	5.46	6.05	1.00	24.00	31.15	19.55	8.00	83.00	0.24	0.17	0.04	0.63
Hillslope	<10 um	0.02	NA	0.02	0.02	3.00	1.41	1.00	4.00	96.00	27.24	56.00	117.00	0.05	0.02	0.03	0.07
Hillslope	<63 um	ND	ND	ND	ND	2.25	0.50	2.00	3.00	31.25	22.49	7.00	57.00	0.12	0.11	0.04	0.29
Hillslope	Total	ND	ND	ND	ND	1.50	1.00	1.00	3.00	16.00	11.60	5.00	31.00	0.16	NA	0.16	0.16

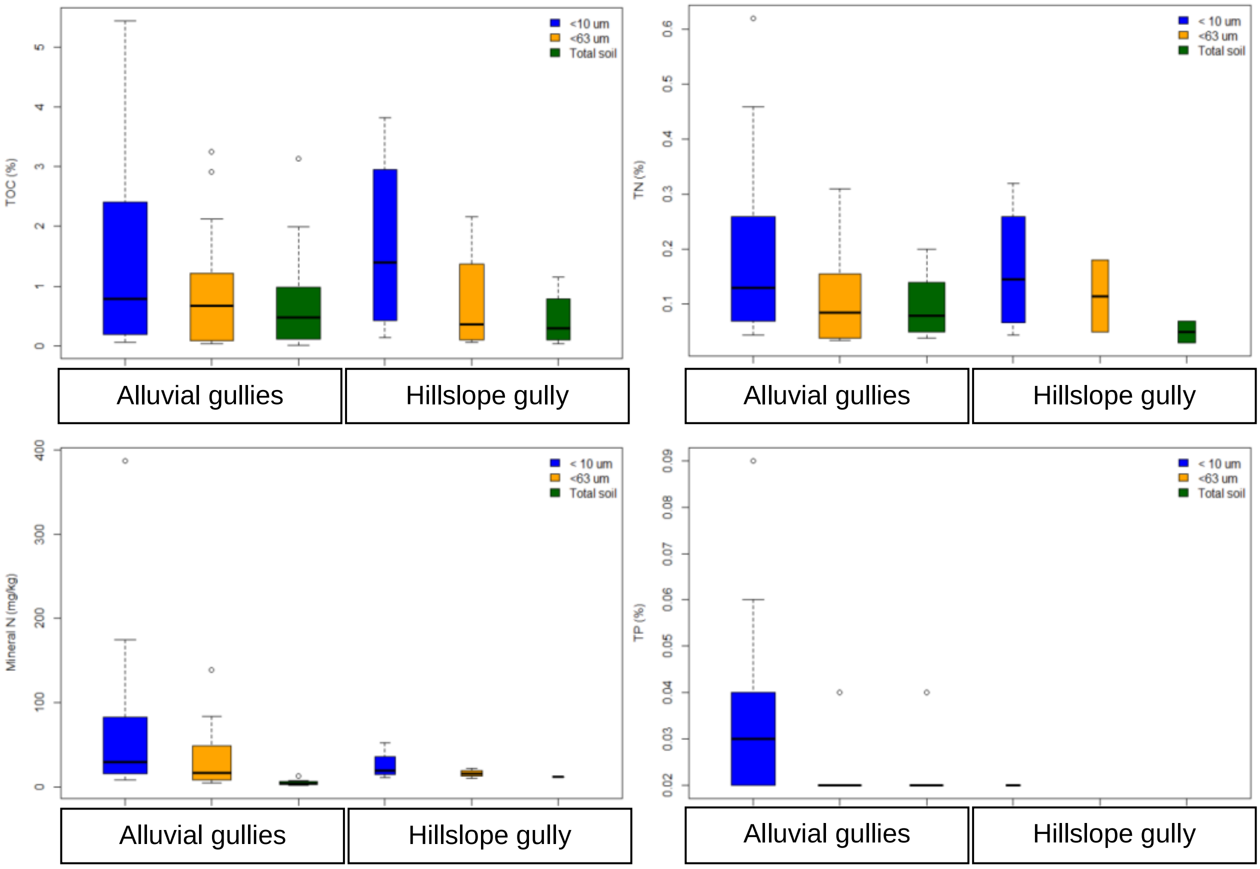


Figure 13 Percent total organic carbon (TOC), total nitrogen (TN), mineral N and total phosphorus (TP) in alluvial and hillslope gully soil/sediment for the total (green), <63 um (yellow) and <10 um (blue) particle size fractions. Boxes are intersected by median values and enclose data between the first and third quartiles, with lines extending to maximum and minimum values excluding outliers (values above and below 1.5 times the inner quartile range from the first and third quartiles, respectively). Box width is proportional to the square root of n for each group. Absence values indicate the parameter was non-detectable in any of the samples.

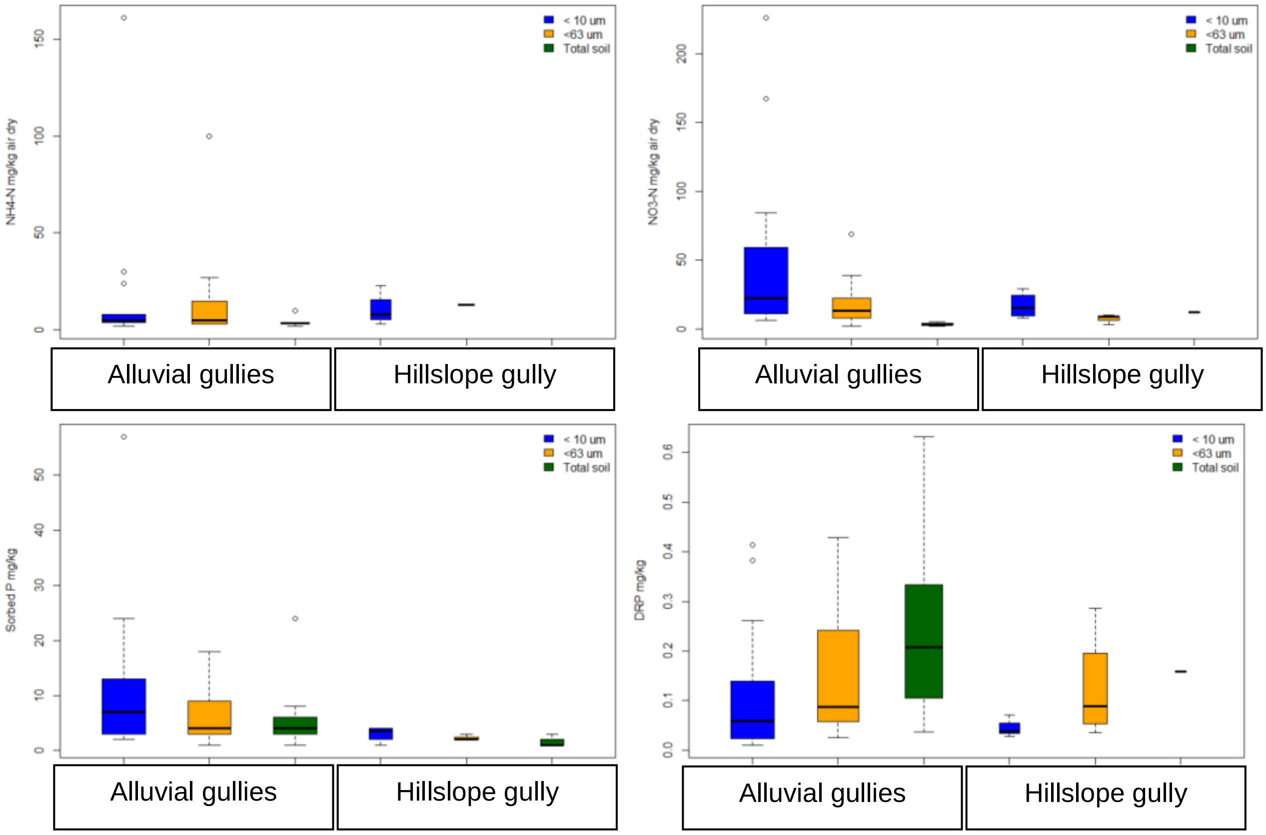


Figure 14 Ammonium (NH_4-N), nitrate (NO_3^--N), sorbed phosphorus (P) and dissolved reactive phosphorus (DRP) in alluvial and hillslope gully soil/sediment for the total (green), <63 um (yellow) and <10 um (blue) particle size fractions. Boxes are intersected by median values and enclose data between the first and third quartiles, with lines extending to maximum and minimum values excluding outliers (values above and below 1.5 times the inner quartile range from the first and third quartiles, respectively). Box width is proportional to the square root of n for each group. Absence values indicate the parameter was non-detectable in any of the samples.

Bioavailable nutrients and organics in geomorphological units of alluvial gullies

There are clearer differences between different gully components than between gully types (alluvial versus hillslope) for most parameters (TOC, TN, TOC:TN ratios, mineral N, DRP and TN:TP ratios) (Figure 15 and Figure 16 versus Figure 13 and Figure 14). Summary statistics for bioavailable nutrients and organics indicators by geomorphic unit and particle size fraction are presented in Appendix 3.

Irrespective of particle size, the terrace geomorphic unit had significantly higher TOC and TN values followed by hillslope and bank surface geomorphic units (Figure 15). TOC soil content in the terrace unit was from 54 to 77 times larger (depending on particle size fraction) and TN from 5 to 10 times larger than in bank subsurface soil in alluvial gullies (Figure 17a). The presence of trees in terraces and the hillslope, which would contribute organic matter inputs to the soil, and the fact that there is a thin A soil horizon layer that has not been completely eroded in these units, would explain the larger presence of C and N pools in this unit as compared to the others. Interestingly, TN values in the terrace soils were similar to average TN values found in fertilized cane and banana soils in the Wet Tropics (Burton et al., 2015). Mineral N values, though 1.7 to 2.0 times lower in the total soil fraction, were 1.5 times higher in the <10um fraction in the terrace soils compared to cane and banana soils in the Wet Tropics (Burton et al., 2015).

The gully floor and bank subsurface had the lowest values for most parameters (TOC, TN, TP and TOC:TN values), which was expected (Figure 15). Previous research indicates that organic C in subsurface soil, the main likely source of gully floor sediment, is highly stabilized with most labile carbon already processed by microorganisms (Fontaine and Barot, 2005; Fontaine et al., 2007). It is likely that the very low presence of fresh organic matter in subsoils is driving the low TOC:TN ratio in the subsoils compared with surface or terrace soils. The gully floor sediment tended to be enriched in TOC compared to the bank subsurface (from 2 to 6 times higher content depending on particle size fraction in alluvial gullies) (Figure 17b), and to have higher TOC:TN ratios. It is likely this is caused by the enrichment of gully floor sediment with vegetation litter while it sits in the gully floor (Garzon-Garcia et al., 2014). Gully floor sediment also had higher DRP (Figure 16, Figure 17b). A larger proportion of fine sediment in the gully floor does not seem to be the main factor controlling these higher values, as the proportion of fine fraction was only slightly higher for the <10 um fraction in the alluvial Granite Normanby gully. All other gullies have lower amounts of fines than the bank subsurface (See fine content for different geomorphic units and gullies sampled in Appendix 4). The higher TOC and DRP values are likely to be the result of accumulation of organics and their associated nutrients that have moved from the landscape and accumulated in the gully floor. Similar results have been found in hillslope gullies of subtropical Queensland (Garzon-Garcia et al., 2014).

The buried A horizon in the alluvial Laura Crocodile gap gully and the bank surfaces in all gullies were very similar in all parameters, except for PBI, extractable nitrate and ammonium, which were higher in the former, and DRP, which was lower (Figure 16). This gully feature is different in bioavailable nutrient content most likely because of more frequent contact with water. These results indicate that when present, the buried A horizon should be considered as a separate geomorphic unit for sampling of bioavailable nutrients until there is enough replication to verify these findings.

The concentrations of the most available forms of nitrogen (NO_3^--N and NH_4^+-N – i.e. mineral N) were higher in the finer fractions of the terrace geomorphic unit compared to other unit fine fractions (Figure 16). The lowest extractable nitrate concentrations from the finer fractions occurred for the bank subsurface and the lowest extractable ammonium concentrations for the gully floor and bank subsurface units. Nitrate in the terrace fine soil was on average 5 to 17 times higher and ammonium was 24 times higher in the <10 um fraction, when compared with bank subsurface soil fine fractions in alluvial gullies (Figure 17a). These findings indicate that the terrace geomorphic unit in the sampled alluvial gullies is an important store of bioavailable forms of nitrogen in its fine soil fractions.

The fine sediment fractions of the gully floor were slightly more enriched with extractable NO_3^--N (from 2 to 4 times higher content depending on particle size fraction), sorbed P (2 times higher) and DRP (2 times higher) compared to the bank subsoil fine fractions. The <10 um fraction of the gully floor was more enriched with TN (1.3 times higher) and had higher PBI values and TN:TP ratios compared to the bank subsurface soil <10 um fraction (Figure 17b).

Sorbed P and DRP concentrations were higher in the terrace geomorphic unit followed by the gully floor (Figure 16). The TP was more enriched in the finer fraction of the terrace geomorphic unit compared to the other units (Figure 15). These findings indicate that the terrace is also an important store of phosphorus in the sampled alluvial gullies, which have low contents of this element overall.

It is important to note here that the parameters that are being measured, though considered indicators of nutrient bioavailability, are not direct measurements of the quantities of bioavailable nutrients from different sources that would be contributed in the aquatic environment (Burton et al. 2015). For example, as can be inferred from mass balances (subtraction of the inorganic nitrogen fraction from the total nitrogen fraction), the majority of the nitrogen in these soils/sediments is in organic form (more than 96% for all geomorphic units and particle sizes). The relative bioavailability of this organic fraction from different geomorphic unit sources and particle size fractions, combined with their selectivity for erosion and transport, would determine the relative geomorphic unit source impact in the streams receiving this sediment and ultimately, their relative impact in the Great Barrier Reef.

The role of particle size

Most bioavailable nutrients and organics indicators including TOC, TN, NH_4^+-N, NO_3^--N, mineral N, sorbed P and PBI generally increased their concentration as the particle size reduced. Average enrichment ratios (nutrient parameter in the fine fraction / nutrient parameter in the total soil) for all gullies sampled, between the total soil and the <63 um and <10um particle size fractions and for all nutrient and organics bioavailability indicators are presented in Figure 18. Values greater than 1 indicate enrichment.

A larger enrichment in nitrogen with fraction size reduction compared to carbon or phosphorus was found, evident in a lower TOC:TN ratio in both fine fractions and a larger TN:TP ratio in the <10 um fraction (Figure 18).

The largest enrichments with particle size reduction occurred for the most bioavailable fractions of nitrogen, with enrichments of 10 to 24 times on average for NO_3^--N and 6 to 7 times on average for NH_4^+-N (Figure 18). Average mineral N enrichment in the <10 um fraction in these soils/sediments was larger than the enrichment found in some banana, cane and dairy soils for the same fraction in the Wet Tropics (2.0 to 2.6 times larger enrichment ratios) (Burton et al., 2015).

Although sorbed P increased in the <10 um fraction by 2 times on average, the PBI, which is an indicator of how tightly P is bound to the sediment surface, increased by 7 times. This is the reason why the DRP is the only measure of bioavailable nutrients that reduced for smaller particle sizes (Figure 18).

Key summary points of information:

- There are significant differences in C, N, and P content between the geomorphic units measured with the general pattern being terrace>surface>gully floor>subsurface. This result indicates that accurate estimation of nutrient and organic losses from gullies will rely on sampling and analysing all the different units.
- Terraces appear to be an important long term store of bioavailable nutrients and organics, whilst gully floors may act as a temporary store depending on gully evolution.
- Particle size also significantly influences nutrient and organic content and would influence bioavailability; it must therefore be included in design and analysis of future studies.
- The <10um fraction is generally enriched in bioavailable nutrients compared to the <63um fraction, which is generally enriched compared to whole soil irrespective of gully geomorphic unit (with some exceptions e.g., DRP). These results from gullies in the Normanby catchment are consistent with results from key soil types in the Burdekin and Johnstone catchments (Burton et al., 2015).

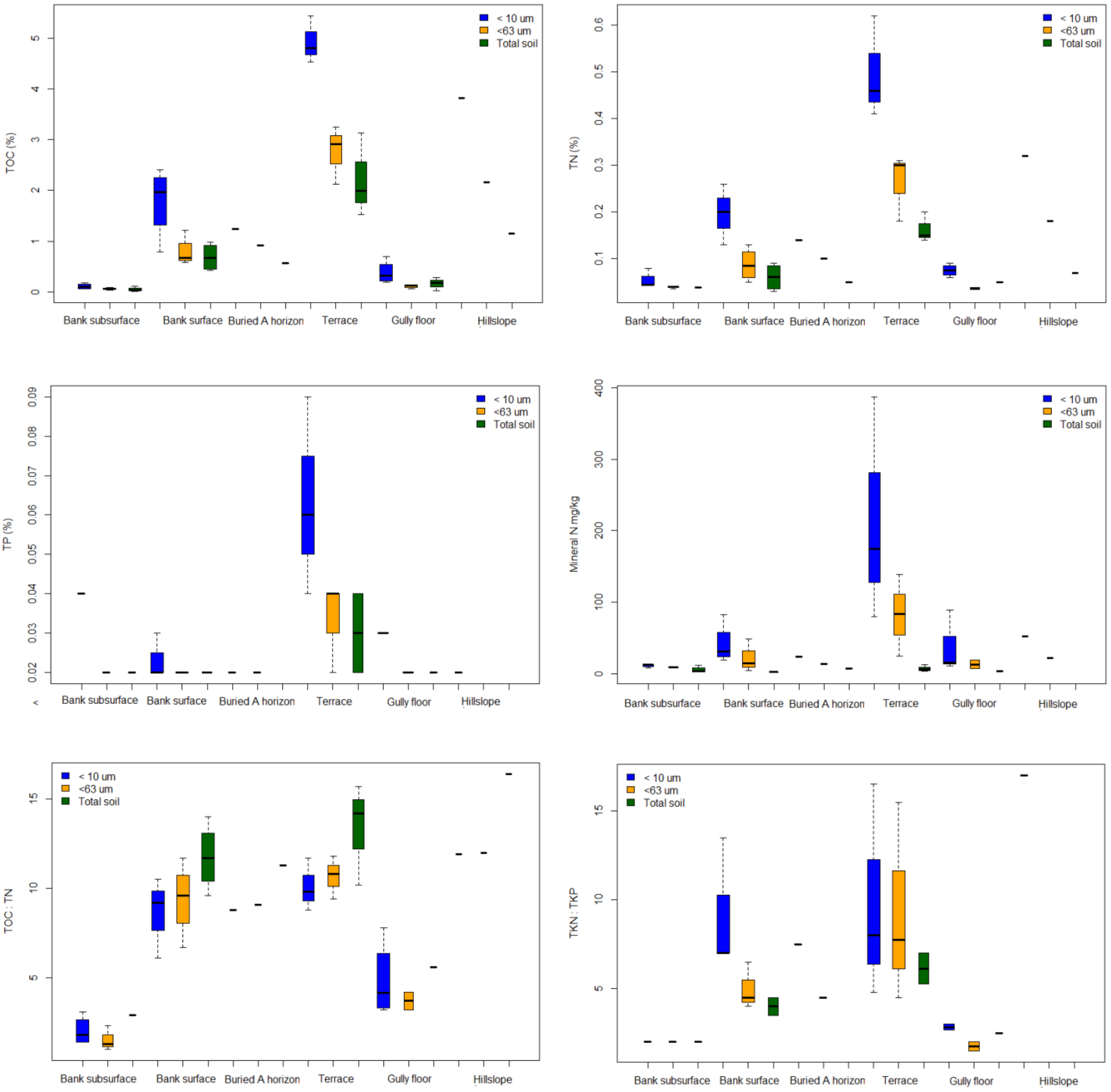


Figure 15 Percent total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), mineral N (mg/kg),TOC:TN ratio and TN:TP ratio by gully geomorphology component for the total (green), <63 um (yellow) and <10 um (blue) particle size fractions. Boxes are intersected by median values and enclose data between the first and third quartiles, with lines extending to maximum and minimum values excluding outliers (values above and below 1.5 times the inner quartile range from the first and third quartiles, respectively). Box width is proportional to the square root of n for each group. Absence values indicate the parameter was non-detectable in any of the samples.

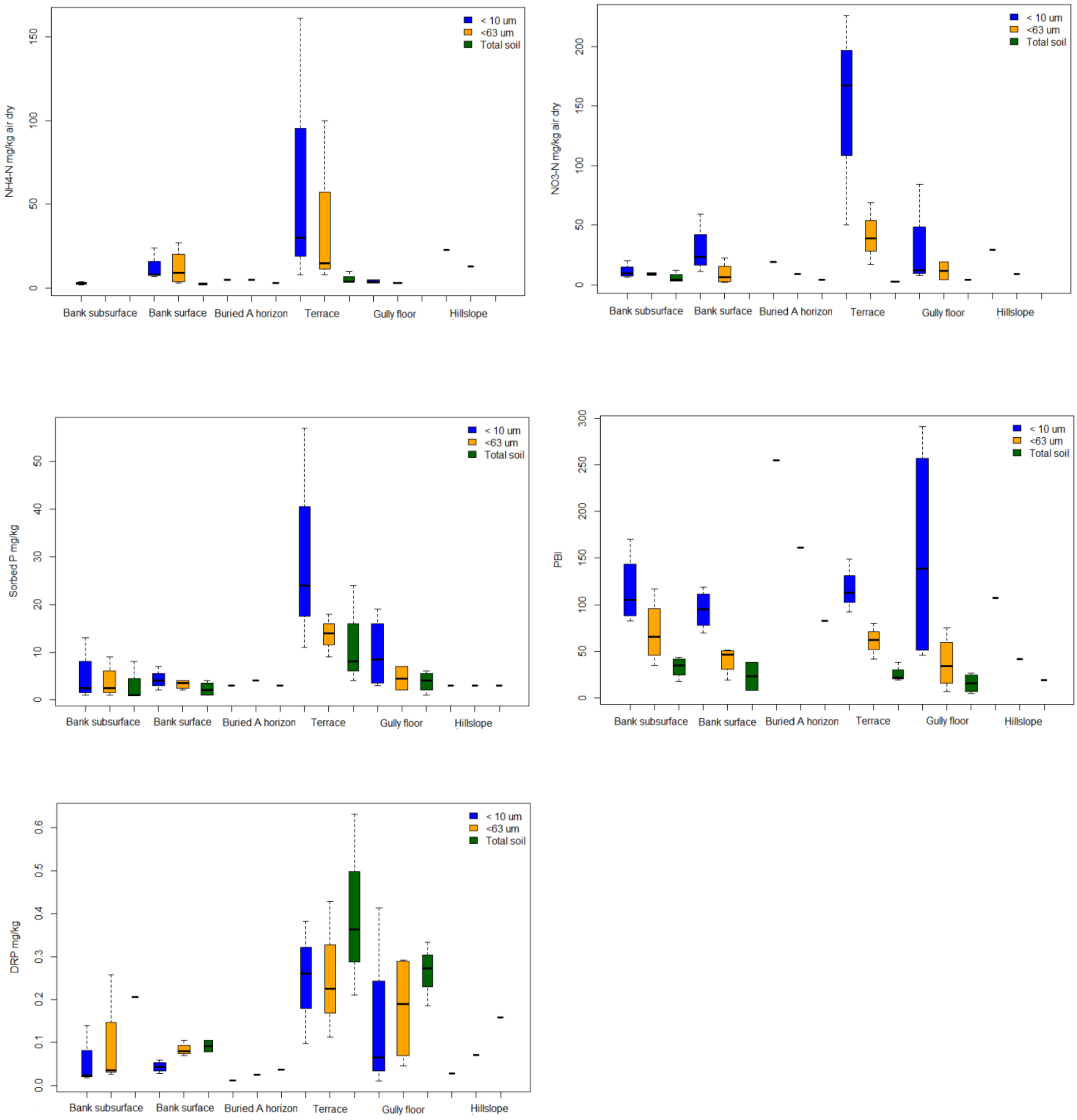
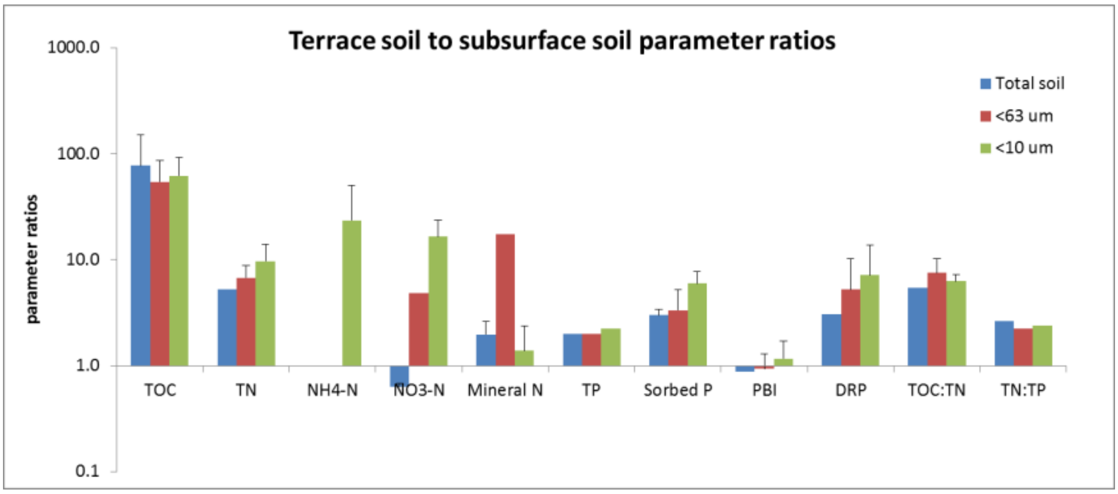


Figure 16 Ammonium (NH4-N), nitrate (NO3-N), sorbed P, phosphorus buffer index (PBI) and dissolved reactive P (DRP) by gully geomorphology component for the total (green), <63 um (yellow) and <10 um (blue) particle size fractions. Boxes are intersected by median values and enclose data between the first and third quartiles, with lines extending to maximum and minimum values excluding outliers (values above and below 1.5 times the inner quartile range from the first and third quartiles, respectively). Box width is proportional to the square root of n for each group. Absence values indicate the parameter was non-detectable in any of the samples.



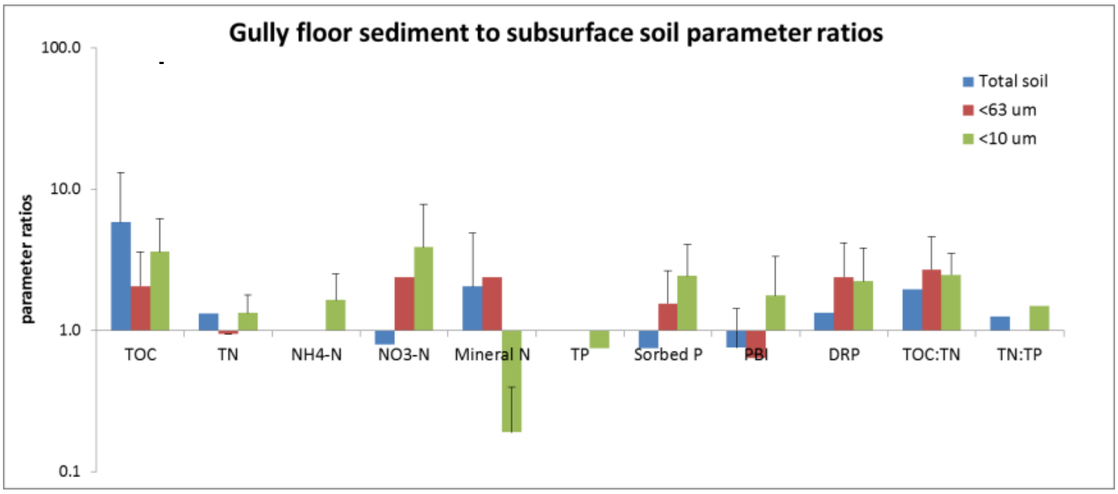


Figure 17 Enrichment ratios between (a) terrace surface soil and bank subsurface soil and (b) gully floor sediment and bank subsurface soil, for various nutrient and organics parameters in the total soil, and fine fractions (<63 um and <10 um) of alluvial gullies sampled in the Normanby catchment

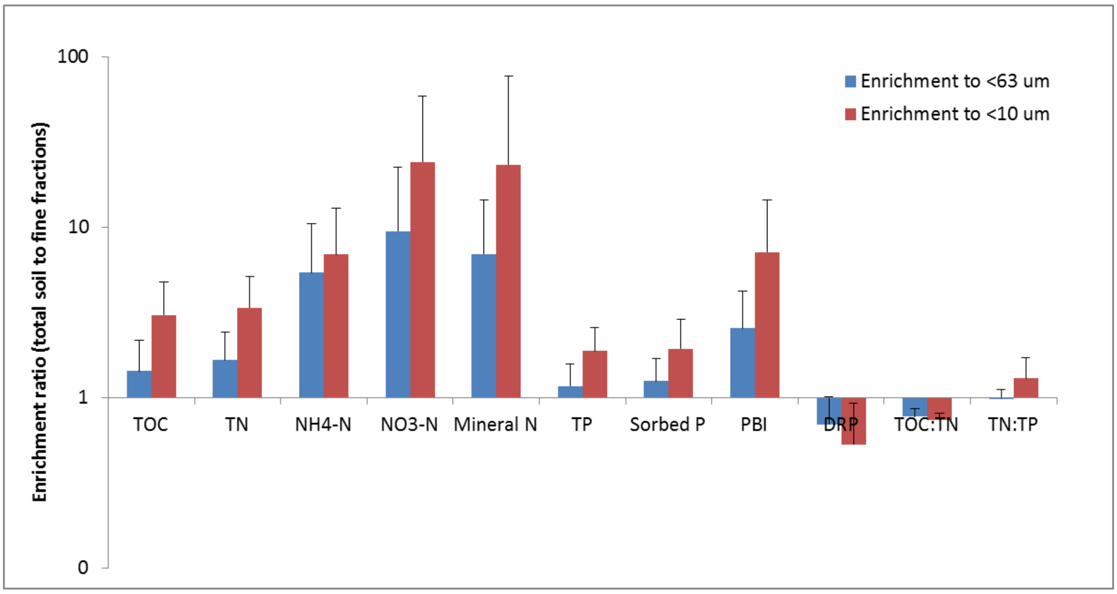


Figure 18 Enrichment ratio of various nutrient and organics bioavailability indicators in the fine fractions (<63 um and <10 um) of gullies sampled in the Normanby catchment.

Bioavailable nutrients and organics export from alluvial gullies

The key sources of organics and nutrients exported from alluvial gullies at any point in time would depend on geomorphic unit contents at source and their relative contributions to exported sediment. To understand how the key sources may change between different alluvial gullies we have developed mass balances of organics and nutrient export using detailed knowledge of sediment yields and hypothetical source contributions based on experience, for the three alluvial gullies sampled in this study.

To understand how the key sources may change during different stages of gully evolution, we have also developed a sensitivity analysis to source contribution for a hypothetical alluvial gully using the average of geomorphic unit contents for the three sampled alluvial gullies (Table 3).

Considering that there is not enough information at this time on particle size fraction export from these gullies, it was assumed that there was no selectivity in particle size fraction transport and thus the total soil organics and nutrient fraction values were used for the budgets. Considering finer sediment fractions were found to be enriched in organics and nutrients, results presented here are likely an underestimation of export from these gullies.

Case study 1: Granite Normanby alluvial gully

Here we present annual sediment yields for the Granite Normanby alluvial gully as well as hypothetical breakdown of key source contributions to sediment export. In this gully, a secondary incision has eroded the rich gully floor material of the primary gully incision. This type material,   considered to be similar to the bank surface soil, was not sampled as part of the gully floor geomorphic unit. Only the secondary incision floor was sampled. Considering this, for the organics and nutrient export budgets it was assumed that the primary incision gully floor had similar characteristics to the bank surface geomorphic unit.

Table 4 Observed erosion rate from gully 2011-2015 and estimated contributions from each source component

	m^3	t	t/yr	gully area (ha)	sediment yield (t/ha/yr)
Headscarp retreat	255.5	408.8	102.2		
Gully Floor Incision	69.3	110.9	27.7		
Total	324.8	519.7	129.9	1.14	114.0

	typical depth (m)
headscarp	3.5
2ndry incision	2

Estimated breakdown of component contribution	Headscarp retreat	2ndry Incision
terrace surface	0.05	0
bank surface	0.05	0
sub-surface	0.85	0.9
gully floor (secondary)	0.05	0
gully floor (primary)	0	0.1

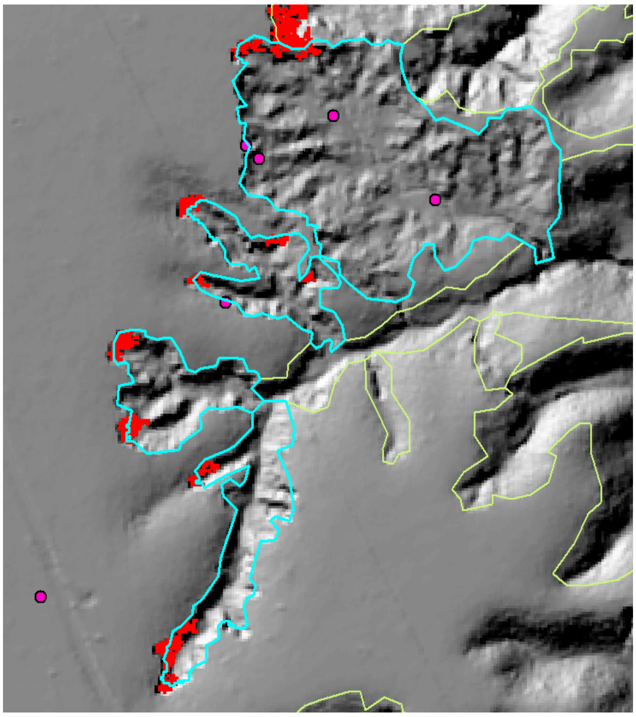


Figure 19 Granite Normanby Gully showing the headscarp erosion in red between 2011 & 2015. Also shown (purple dots) are the sample locations for the gully. Note that the erosion detected by the aerial LiDAR in this gully is an absolute minimum amount of erosion due to the conservative limit of detection applied (0.5m change)

Estimated annual mass contributions to sediment, organics and nutrient export from different geomorphic units in the Granite Normanby alluvial gully are presented in Figure 20. Percent contributions of exported fractions from geomorphic units are summarized in Figure 21.

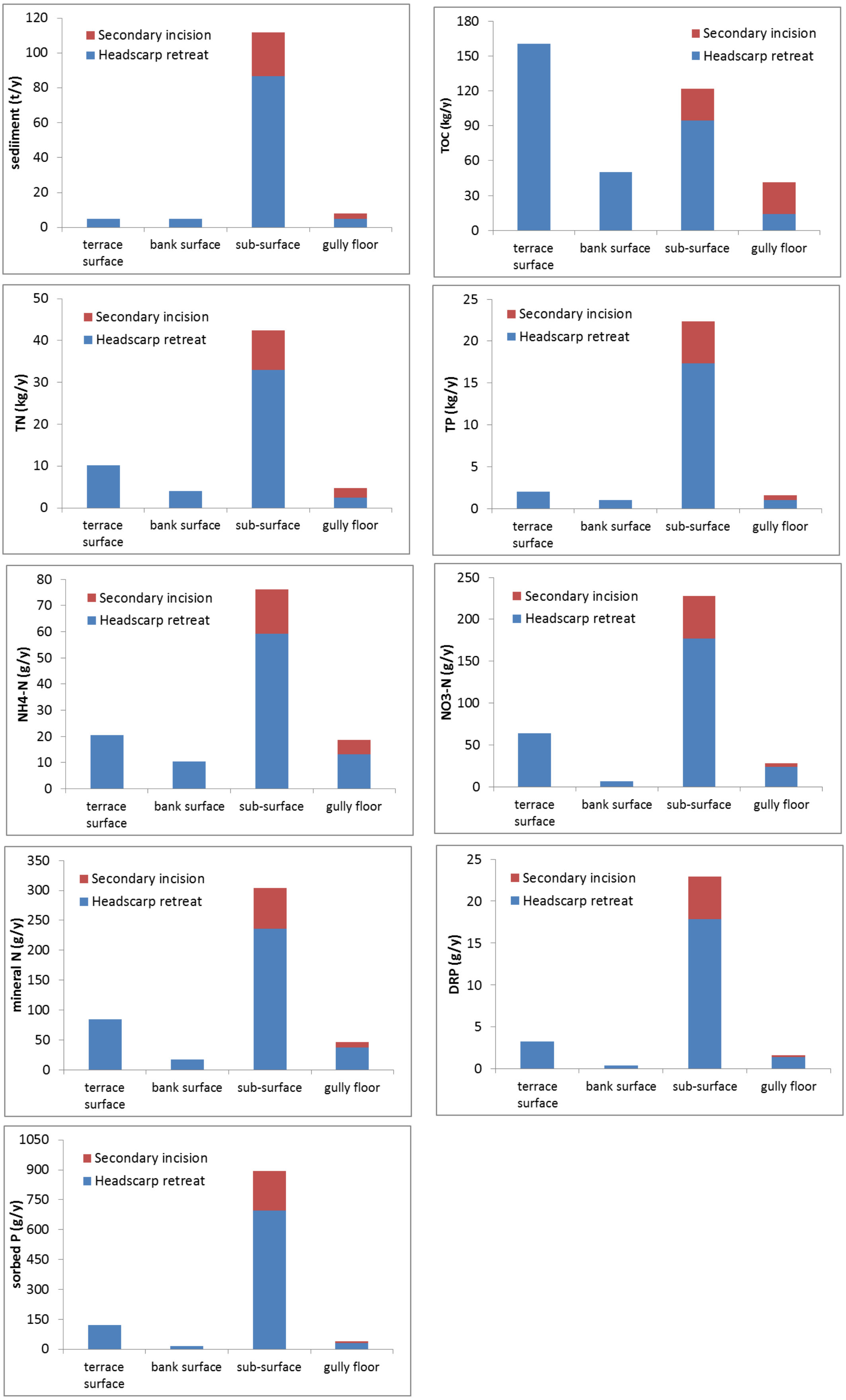


Figure 20 Estimated annual mass contributions of sediment, organics and nutrient export from different geomorphic units in the Granite Normanby alluvial gully

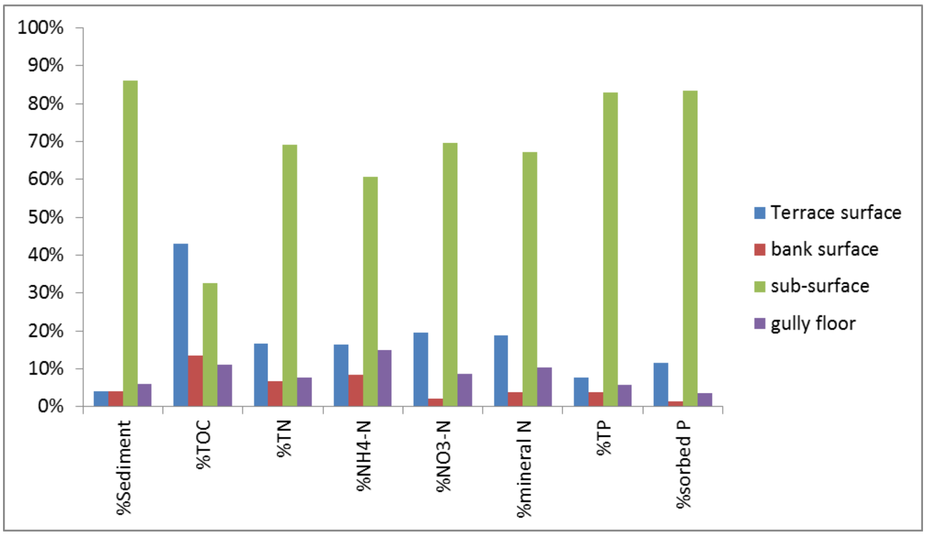


Figure 21 Percent contributions of exported organics and nutrient fractions from different gully geomorphic units in the Granite Normanby alluvial gully

Key conclusions from Granite Normanby alluvial gully budgets:

- Headscarp retreat would be contributing most of the export of organics and nutrient pools; this is driven by headscarp retreat contributing 79% of the sediment export in this gully (surface plus subsurface sediment contributions from Figure 20).
- The relative contribution to export from different geomorphic units is not homogenous between organics and nutrient fractions.
- Subsurface soil was the main source of export for all nutrient fractions, contributing from 61% to 84% of the NH_4^+-N and sorbed P exported, respectively. This is caused by the large contribution of subsurface soil to sediment export in this gully (86%).
- Terrace surface soil was the main source of TOC export contributing 43% of the exported TOC, followed by subsurface soil which contributed 33%.
- Although terrace surface soil is richer in all organics and nutrient fractions than subsurface bank soil, the larger amount of sediment sourced from subsurface soil in this gully compared to the amount sourced from terrace soil (86% versus 4%) makes subsurface bank soil the main source of all nutrients. However, terrace soil is the main source of TOC due to the terrace soil in this gully having 29 times more TOC than bank subsurface soil, and the latter source only contributing 22 times more sediment than the former.
- Given that more than 96% of the TN for all geomorphic units is organic N, the relative bioavailability of the exported organic nutrient fraction would determine which source would cause a larger impact in the aquatic environment (both freshwater and marine).

Case study 2: Laura Crocodile Station alluvial gully

Here we present annual sediment yields for the Laura Crocodile Station alluvial gully as well as hypothetical breakdown of key source contributions to sediment export.

Table 5 Observed erosion rate from gully 2011-2015 and estimated contributions from each source component

	m^3	t	t/yr	gully area (ha)	sediment yield (t/ha/yr)
Headscarp retreat	71.2	114.0	28.5		
Gully Floor Incision	11.9	19.0	4.8		
Total	83.1	133.0	33.2	1.14	29.2

	typical depth (m)
headscarp	4
2ndry incision	1

Estimated breakdown of components	Headscarp retreat	2ndry Incision
floodplain surface	0.05	0
bank surface	0.05	0
sub-surface	0.85	0.9
gully floor (secondary)	0.05	0.1

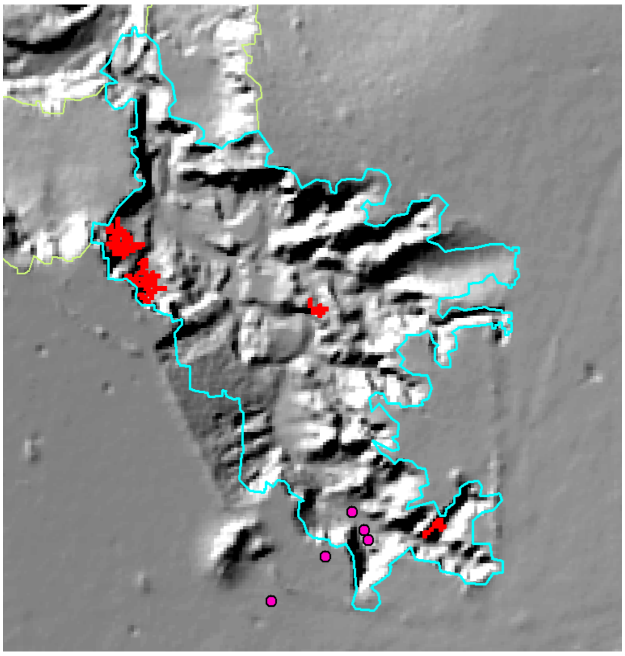


Figure 22 Crocodile Station gully showing the headscarp erosion in red between 2011 & 2015. Also shown (purple dots) are the sample locations. Note that the erosion detected by the aerial LiDAR in this gully is an absolute minimum amount of erosion due to the conservative limit of detection applied (0.5m change)

Estimated annual mass contributions to sediment, organics and nutrient export from different geomorphic units in the Laura Crocodile Station alluvial gully are presented in Figure 23. Percent contributions of exported fractions from geomorphic units are summarized in Figure 24.

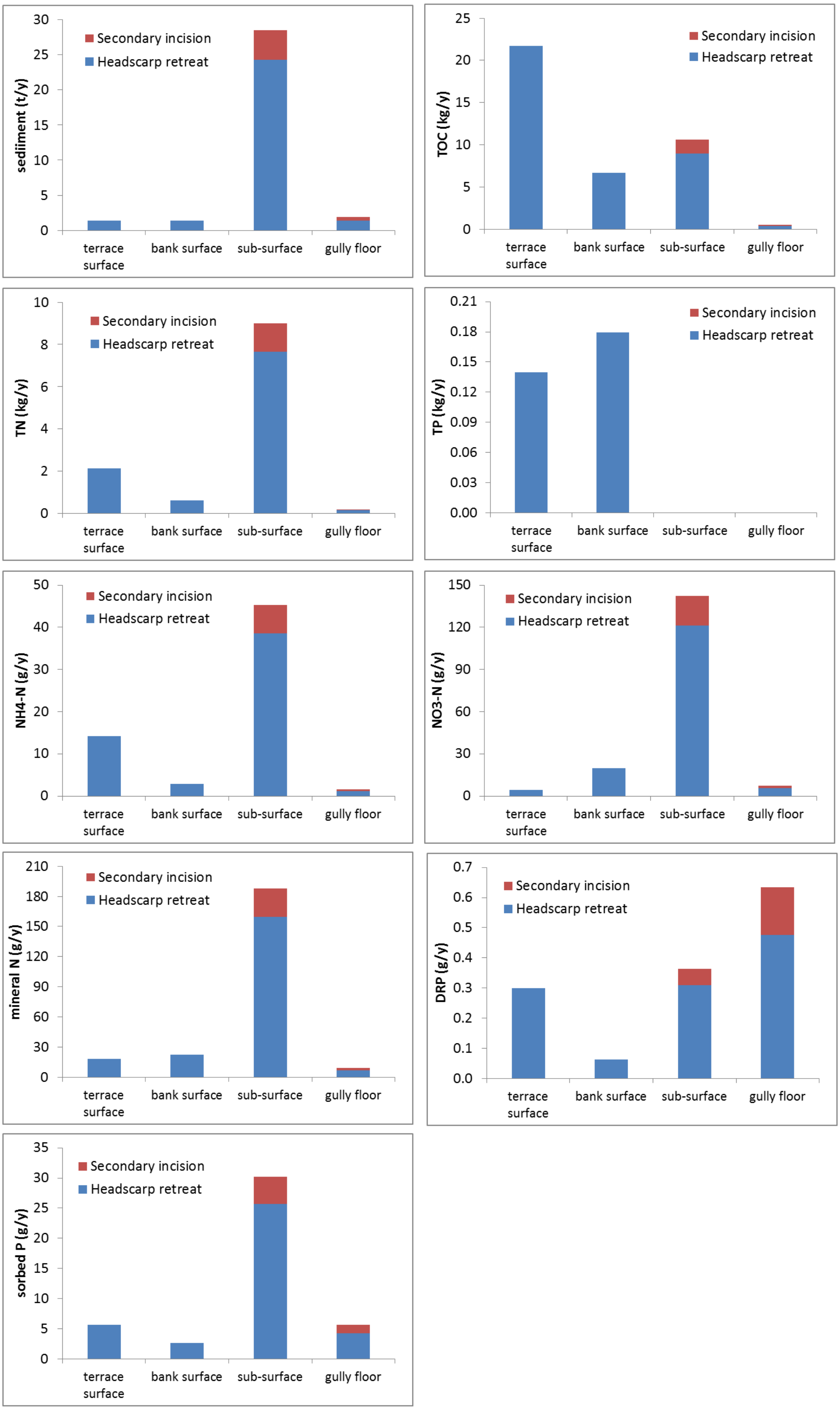


Figure 23 Estimated annual mass contributions of sediment, organics and nutrient export from different geomorphic units in the Laura Crocodile Station alluvial gully

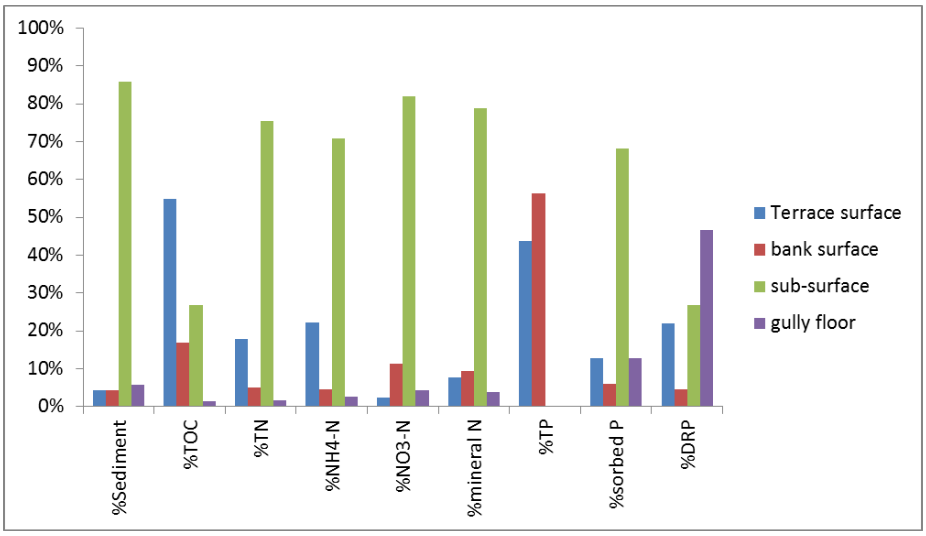


Figure 24 Percent contributions of exported organics and nutrient fractions from different gully geomorphic units in the Laura Crocodile Station alluvial gully

Key conclusions from Laura Crocodile Station alluvial gully budgets:

- This gully had very similar results to the Normanby Granite alluvial gully in terms of geomorphic unit contributions to pollutant export. This was expected considering headscarp retreat is also the main sediment source in this gully and relative contributions from geomorphic units were assumed to be the same, except for gully floor contributions from the secondary incision, which were assumed to come from the secondary incision gully floor in this gully. The annual sediment yield was 4 times lower in this gully.
- Lower sediment yields in this gully compared to the Normanby Granite alluvial gully caused from 2 (NH_4^+-N) to 85 (TP) times higher yields of organics and nutrients from the Normanby Granite alluvial gully.
- Headscarp retreat would be contributing most of the export of organics and nutrient pools; this is driven by headscarp retreat contributing 86% of the sediment export in this gully.
- The relative contribution to export from different geomorphic units is not homogenous between organics and nutrient fractions
- Subsurface soil was the main source of nutrient export for most fractions, contributing from 71% to 82% of the exported nitrogen fractions. This is due to the large contribution from subsurface soil (86%) to sediment export. Exceptions to subsurface soil being the main nutrient source included TP, which was undetectable in gully bank subsoil; and DRP, which was higher in the gully floor sediment in this gully compared to other sources.
- Terrace surface soil was the main source of TOC export contributing 55% of the exported TOC, followed by subsurface soil which contributed 27%.
- Although terrace surface soil is richer in all organics and nutrient fractions than subsurface bank soil, the larger amount of sediment sourced from subsurface soil in this gully compared to the amount sourced from terrace soil (86% versus 4%) makes subsurface bank soil the main source of most nutrients. However, terrace soil is the main source of TOC due to its higher concentration. Terrace soil in this gully had 41 times more TOC than bank subsurface soil, and the latter source is only contributing 22 more times sediment than the former.

- Given that more than 96% of the TN for all geomorphic units is organic N, the relative bioavailability of the exported organic nutrient fraction would determine which source will cause the larger impact in the aquatic environment (both freshwater and marine).

Case study 3: Laura Crocodile Gap alluvial gully

Here we present annual sediment yields for Laura Crocodile Gap alluvial gully as well as a hypothetical breakdown of key source contributions to sediment export. In this gully, a secondary incision has eroded the rich gully floor material of the primary gully incision. This type material, considered to be similar to the bank surface soil, was not sampled as part of the gully floor geomorphic unit. Only the secondary incision floor was sampled. Considering this, for the organics and nutrient export budgets it was assumed that the primary incision gully floor had similar characteristics to the bank surface geomorphic unit.

Table 6 Observed erosion rate from gully 2011-2015 and estimated contributions from each source component

	m^3	t	t/yr	gully area (ha)	sediment yield (t/ha/yr)
Headscarp retreat	64.3	103.0	25.7		
Gully Floor Incision	1071.7	1714.8	428.7		
	1136.1	1817.7	454.4	15.8	28.8

	typical depth (m)
Headscarp	1.8
2ndry incision	2.4

Estimated breakdown of components	Headscarp retreat	2ndry Incision
floodplain surface	0.2	0
bank surface	0	0
sub-surface	0.8	0.7
gully floor (secondary)	0	0.1
gully floor (primary)		0.2

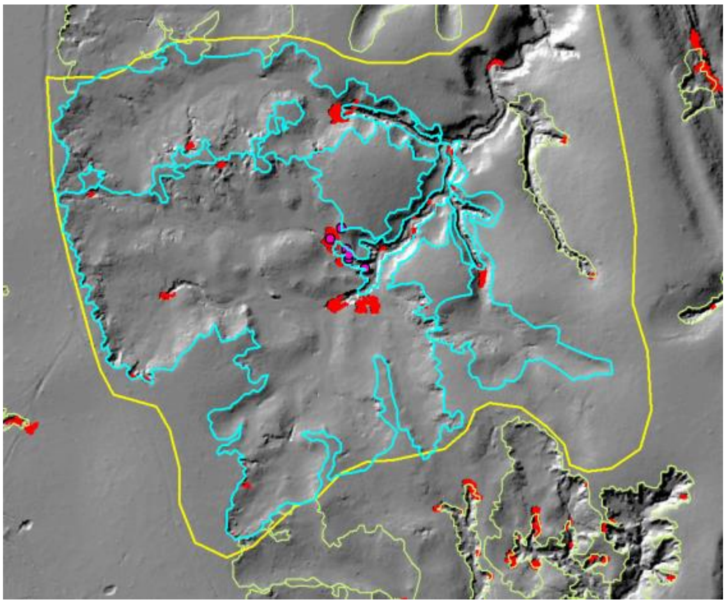


Figure 25 Laura Crocodile Gap alluvial gully complex showing the headscarp & secondary incision erosion in red between 2011 & 2015. Also shown (purple dots) are the sample locations. Note that the erosion detected by the aerial LiDAR in this gully is an absolute minimum amount of erosion due to the conservative limit of detection applied (0.5m change)

Estimated annual mass contributions of sediment, organics and nutrient export from different geomorphic units in the Laura Crocodile Gap alluvial gully are presented in Figure 26. Percent contributions from geomorphic units for exported fractions are summarized in Figure 27.

Key conclusions from Laura Crocodile Gap alluvial gully budgets:

- This gully had very different results to the Normanby Granite and Laura Crocodile Station alluvial gullies in terms of geomorphic unit contributions to export. This was expected considering the gully floor secondary incision is the main sediment source in this gully and not headscarp retreat. The secondary incision mainly sourced sediment from the gully bank subsurface and from the primary gully floor and secondary gully floor incisions; the former was assumed to be much richer in organics and nutrient content than the latter and similar to the surface bank soil. The annual sediment yield was 3.5 to 14 times higher in this gully.
- The secondary gully floor incision is mostly contributing to the export of organics and nutrients; this is driven by the secondary incision contributing 94% of the sediment export in this gully.
- The relative contribution to export from different geomorphic units is not homogenous between organics and nutrient fractions
- Subsurface soil was the main source of nutrient export for most fractions, contributing from 52% to 66% of the exported nitrogen fractions. This is caused by the large contribution of the subsurface soil to sediment export in this gully (71%). Exceptions to subsurface soil being the main nutrient source included TP, which was undetectable in gully bank subsoil; and DRP, which was higher in the gully floor sediment in this gully compared to other sources. In these two cases, the gully floor was the main source to export.

- Gully floor sediment can be the main source of TOC and some nutrient fractions when gully incision and not headscarp retreat, dominates sediment export. This was the case in this gully where it was the main source of TOC export, contributing 85% of the exported TOC, followed by terrace soil which contributed 11%.
- Although terrace surface soil is richer in all organics and nutrient fractions than all other sources, the larger amount of sediment sourced from subsurface soil in this gully compared to the amount sourced from terrace soil (71% versus 1%) makes subsurface bank soil the main source of most nutrients.

Given that more than 96% of the TN for all geomorphic units is organic N, the relative bioavailability of the exported organic nutrient fraction would determine which source would cause the larger impact in the aquatic environment (both freshwater and marine).

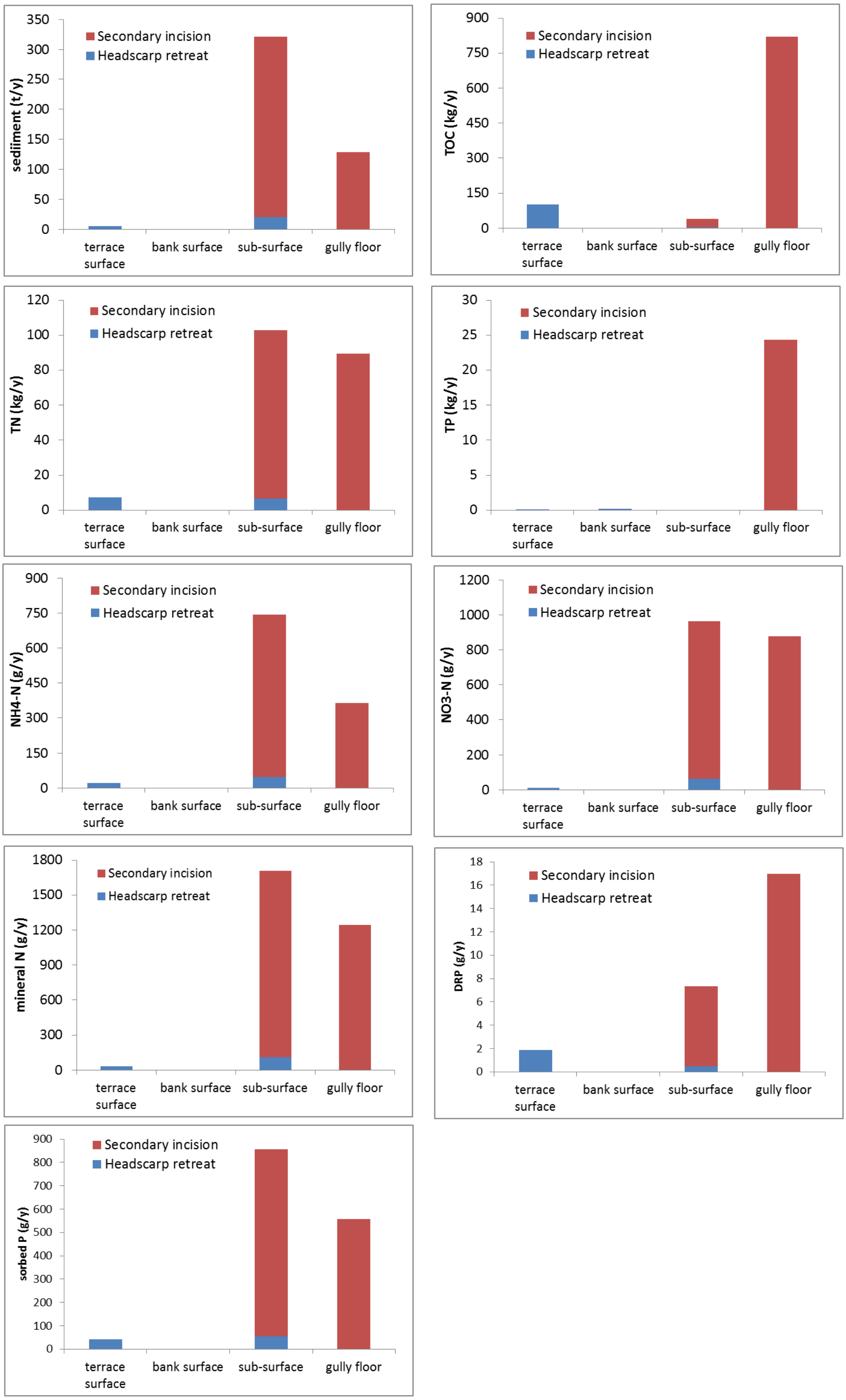


Figure 26 Estimated annual mass contributions of sediment, organics and nutrient export from different geomorphic units in the Laura Crocodile Gap alluvial gully

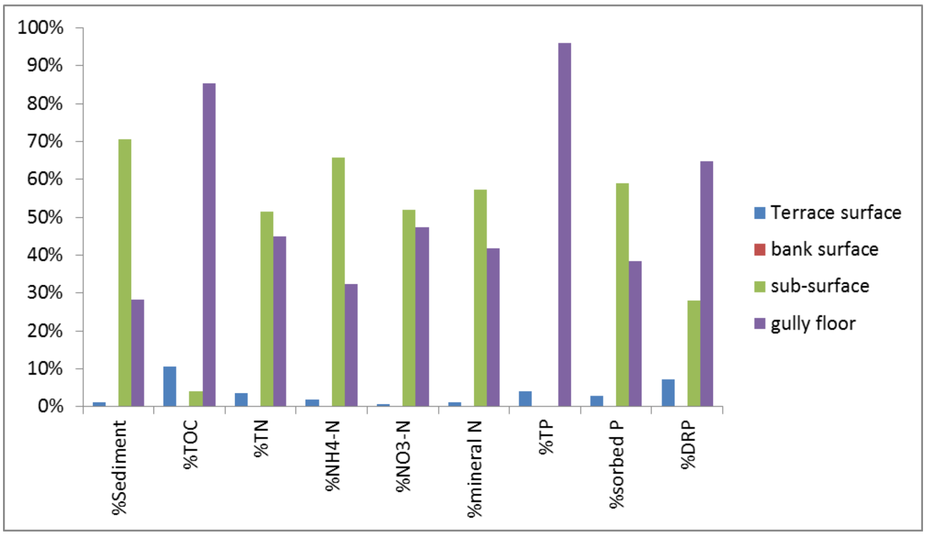


Figure 27 Percent contributions of exported organics and nutrient fractions from different gully geomorphic units in the Laura Crocodile gap alluvial gully

Sensitivity analysis

Here we present a sensitivity analysis for source contribution on organics and nutrient export outcomes when there are changes in sediment yields and relative source contributions to sediment export. This analysis has been carried out for a hypothetical alluvial gully that is retreating and deepening. We explore how sediment source contributes to sediment, organics and nutrient export as the gully develops for 5 gully stages as follows:

	m^3	t	t/yr	gully area (ha)	sediment yield (t/ha/yr)
Headscarp retreat Obs	267.1	427.4	106.8		51.6
Headscarp retreat Obs +0.5m	487.6	780.2	195.0		94.2
Headscarp retreat Obs + 1.0m	708.1	1133.0	283.2		136.8
Headscarp retreat Obs + 1.5m	928.6	1485.8	371.4		179.4
Headscarp retreat Obs + 2.0m	1149.1	1838.6	459.6		222.0

	typical depth (m)
main gully	1.5

Estimated breakdown of components	Headscarp retreat (obs)	obs + 0.5m	obs + 1.0m	obs + 1.5m	obs + 2.0m
floodplain surface	0.1	0.055	0.038	0.029	0.023
bank surface	0.05	0.050	0.050	0.050	0.050
sub-surface	0.8	0.845	0.862	0.871	0.877
gully floor	0.05	0.05	0.05	0.05	0.05

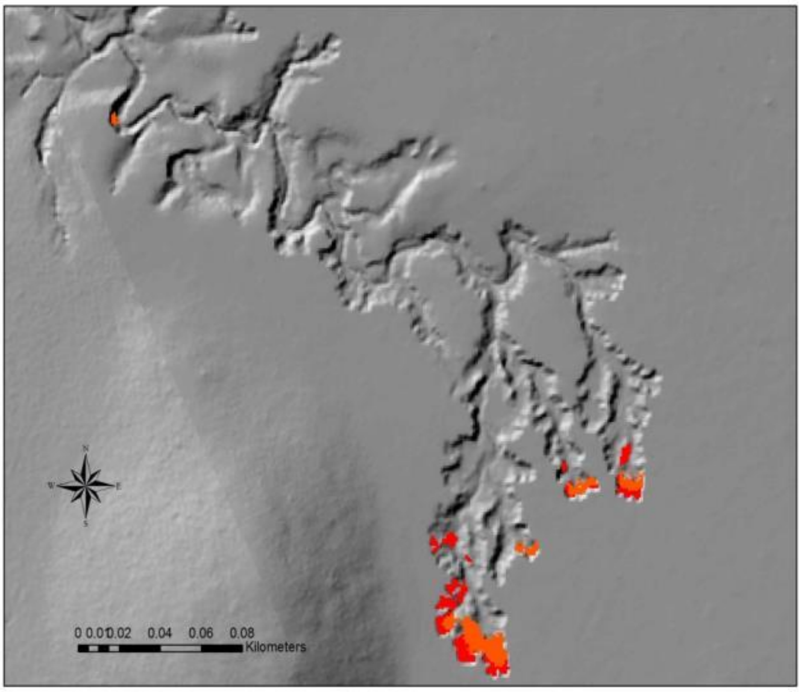


Figure 28 Observed erosion in Granite Normanby distal gully over the period 2009-11 in orange and 2011-15 in red. Modelled scenarios have then be derived to show relative nutrient contributions with gully deepening.

Estimated annual mass contributions of sediment, organics and nutrient export from different geomorphic units in the hypothetical developing alluvial gully are presented in **Figure 29**.

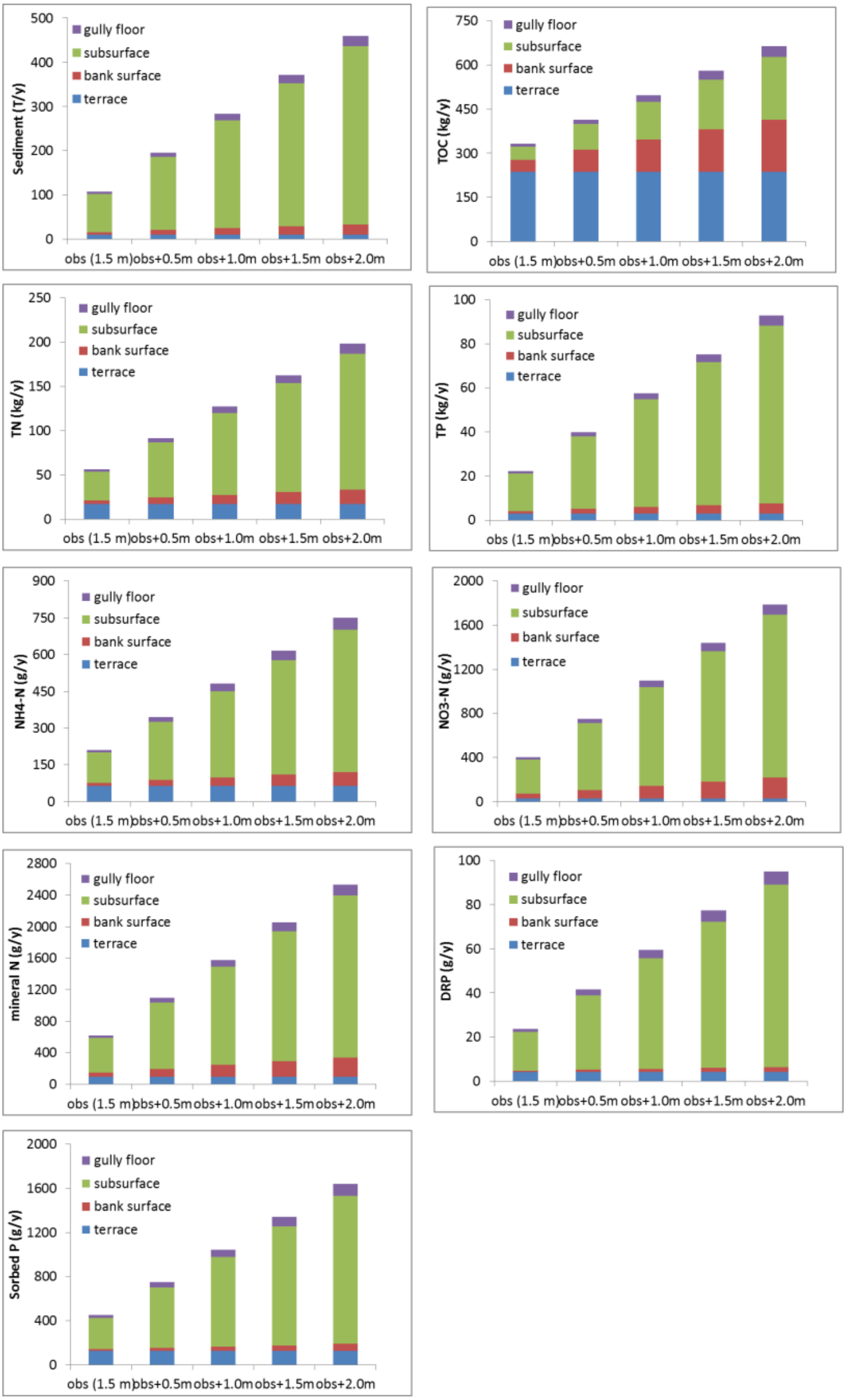


Figure 29 Estimated annual mass contributions of sediment, organics and nutrient export from different geomorphic units in a hypothetical developing alluvial gully

Key conclusions from the empirical modelling of gully sediment and nutrient budgets:

- Sediment, organics and nutrient yields increase as the gully grows. In this case, it was assumed sediment loads increased linearly as for organics and nutrient fraction export.
- The relative contribution to export from different geomorphic units is not homogenous as the gully develops.
- As the gully develops, the contribution of subsurface bank soil to sediment and nutrient export increases more rapidly than the contribution of other geomorphic units, making it the more dominant source as the gully becomes larger.
- Subsurface bank soil was the main source of nutrient export for all gully stages, contributing from 58% of TN export in the first stage to 87% of DRP export in the last stage. This is caused by the large contribution of subsurface soil to sediment export for all stages (from 80% to 88%).
- Terrace surface soil was the main source of TOC export for all gully stages, contributing from 71% of the exported TOC in the first stage to 36% of the exported TOC in the last stage. The secondary source of TOC export was subsurface bank soil which contributed from 14% of the exported TOC in the first stage to 32% of the exported TOC in the last stage.
- Although terrace surface soil is richer in organics and nutrient fractions than subsurface bank soil, the larger amount of sediment sourced from subsurface soil in this hypothetical gully compared to the amount sourced from terrace soil (from 8 times more in the first stage to 38 times more in the last stage) makes subsurface bank soil the main source of nutrients. Nonetheless, terrace soil is the main source of TOC due to the much higher concentrations of this parameter compared to the other sources (see **Figure 17**a). Terrace soil has on average 77 times more TOC than bank subsurface soil.
- For even earlier stages of gully evolution (gullies <1.5 m deep), terrace surface contributions to nutrient export would be larger and may be the main source. In **Figure 30**, simulated contributions for a hypothetical 0.5 m deep gully with a 0.2 m deep A horizon can be seen. For this case, it is assumed that subsurface soil would contribute 60% of the sediment yield and terrace surface soil 40%. It is shown that terrace surface soil may be the main source to organics and nutrient fraction export in early stages of gully evolution.
- The relative bioavailability of the exported organic nutrient fraction (e.g. more than 96% of the TN for all geomorphic units) will determine which source would cause the larger impact in the aquatic environment (both freshwater and marine).

To be able to frame these results, they were compared with modelled annual average exports per unit area for different landuses in the Wet Tropic catchments (Hateley et al., 2014) (see Table 7). It can be seen that annual TN and TP export per unit area from alluvial gullies can be larger than that from sugarcane and banana crops. On average 46% of sugarcane and 59% of banana crops TN would be exported as dissolved inorganic N (mineral N) in the Wet Tropics (Hateley et al., 2014), compared with only 2% for alluvial gullies (measured as KCl extractable mineral N). However, the exported organic N from alluvial gullies (98% of TN) is potentially bioavailable and thus may be mineralized into dissolved inorganic N during stream transport, once it gets to the estuarine or marine environment, or be used directly by algae in dissolved organic form. As a consequence, mineral N yields estimated here from alluvial gully soil/sediments, do not reflect the contribution of alluvial gullies to dissolved inorganic N downstream. This result shows the importance of understanding not only sources of organics and nutrients from alluvial gullies, but also their in-stream processing.

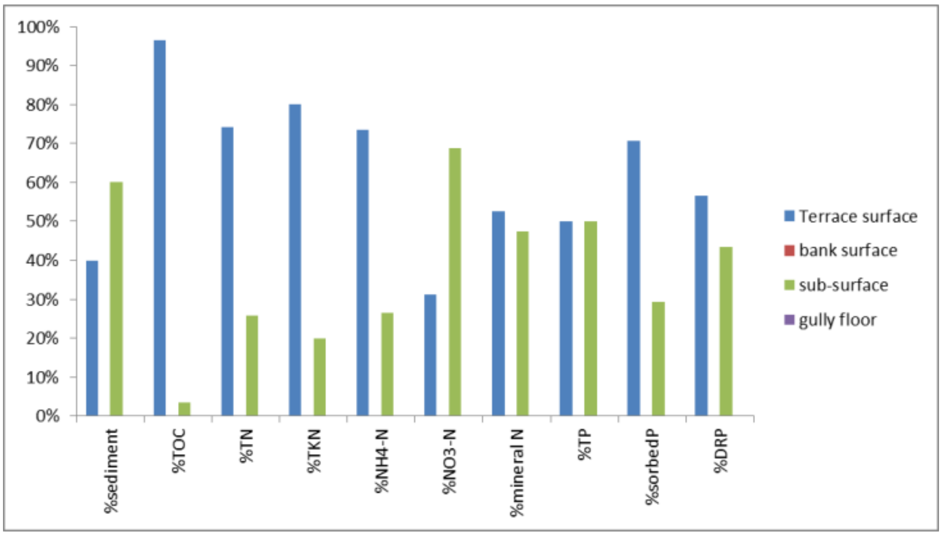


Figure 30 Percent contributions of all exported organics and nutrient fractions from different gully geomorphic units in a 0.5 m deep hypothetical gully (60% subsurface soil contribution to sediment yield and 40% terrace surface soil contribution to sediment yield)

Table 7 Annual exports per unit area of sediment, nitrogen (TN) and phosphorus (TP) from alluvial gullies (this study) and various modelled land uses in the Wet Tropics*

Gully/land use	sediment (t/ha/y)	TN (kg/ha/y)	TP (kg/ha/y)
Granite Normanby	114.0	54.0	23.7
Laura - Crocodile station	29.2	10.5	0.3
Laura - Crocodile Gap	28.8	12.6	1.6
Sugar cane	1.2	22.2	2.7
Banana	1.8	25.3	3.1
Nature conservation	0.2	3.6	0.3

*Modelled values from Hateley et al. (2014)

Main conclusions and Implications for management

In summary, research findings indicate that nutrient and organics soil/sediment pools are not distributed equally in alluvial or hillslope gullied landscapes or across their soil/sediment particle sizes. Although there were not very large differences between the sampled gullies overall, there were differences between the gully geomorphic units. The most eroded areas in a gully complex tend to have the least amount of nutrients and organics, and in their least readily bioavailable forms. This is likely caused by the sediment present in eroded areas being predominantly sourced from the subsurface soil horizons, which tend to be particularly poor in organics and nutrients when compared with bank surface soils or terrace soils (Garzon-Garcia et al., 2014). The finer fractions of soil/sediment also tended to be richer in nutrients and organics and in their most bioavailable forms (Burton et al., 2015), and in the richer geomorphic units like terrace soils and surface gully bank soils also have larger nutrient enrichment ratios.

Although terrace soil had the largest pools of most nutrients and organics, bank subsoil was generally the main source of sediment in these alluvial gullies and has been shown to be the main source of sediment in the wet tropics and dry tropics catchments of the GBR (Bainbridge et al., 2016; Bainbridge et al., 2014; Hughes et al., 2009; Olley et al., 2013; Wilkinson et al., 2015). In this study it is shown that the sources of organics and nutrient export from alluvial gullies would vary depending on the type of erosional process occurring in the alluvial gully (i.e. headscarp retreat versus secondary incision) and their stage of evolution (gully depth and sediment yields). These aspects will ultimately determine the relative contribution of different geomorphic units to sediment yields and consequently to organics and nutrient export. These findings should be confirmed with larger sampling replication.

In general, terrace soil was found to be the main source to TOC export when headscarp retreat contributes the majority of sediment. The contribution of terrace soil to nutrient fraction export varied with the stage of gully evolution. In the initial stages of gully evolution [very shallow gullies (<1.0 m) growing fast into the terrace deposits], terrace soil would be the main source of nutrient export. This implies that it should be a priority to protect terrace deposits from fast headscarp retreat as these deposits contain large pools of carbon and nutrients that, when lost, would be very difficult to restore. As gully incision occurs, the main source of most nutrient fractions export clearly becomes bank subsurface sediment. Although bank subsurface sediment has much smaller nutrient pools than terrace surface soil, the sheer quantity of exported bank subsurface sediment over compensates for its lower nutrient content making it the main source. In the longer term, gully bank subsoils would tend to be the main source of nutrients. As a consequence, the long term aim should be the stabilization of gully banks and reduction of incision, which would have a larger effect on reducing nutrient export due to gully erosion.

When secondary incision occurs and there is organic and nutrient rich sediment deposited on the gully floor, this sediment may become a very important source of organics and nutrient export, even more so than bank subsurface soil. The deeper and older the deposits, the more important this source would be. The protection of gully floor organics and nutrient deposits should be part of gully rehabilitation designs and should be prioritized when these deposits are of importance.

These findings point to the importance of increasing our understanding of the links between organics and nutrient sources, alluvial gully erosional processes and instream processing. For example, it is crucial to understand differences in the bioavailability of exported sediment from different geomorphic unit sources once in the aquatic environment. Although various indicators of the bioavailability of these sediments were quantified in this study, research is still necessary to define which of these indicators would be the best to predict the impact of organics and nutrients to primary production in the freshwater and marine environment (Burton et al., 2015) and what controls this bioavailability (Garzon-Garcia et al. in prep). The role of vegetation and litter has been proposed as fundamental, not only to the rehabilitation of carbon and nitrogen stores in gullied landscapes, but to reduce the impacts of the mineralization of eroded sediment in the aquatic environment by promoting nitrogen retention (Garzon-Garcia, 2014). Further research is necessary to better understand the role of vegetation in mediating these relationships.

This study gives some indication of how to establish management priorities to reduce organics and nutrient export, which would depend on key alluvial gully erosional processes. Findings should be validated by sampling a larger number of alluvial gullies, including sediment export sampling, the role of particle size in export, relative bioavailability of different sources, and ideally source tracing. It is recommended that sampling design targets key geomorphic units from gully categories based on the erosional process (e.g. fast headscarp retreat, primary incision, secondary incision, widening, gully depth, etc).

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Appendix 1 Sample analyses

Methods used by the DSITI Chemistry Centre generally follow the Australian Laboratory Handbook Method codes as per Rayment, G.E. and Lyons, D.J. (2011). “Soil Chemical Methods – Australasia”. This is the principal reference manual for soil analytical methods in Australia/New Zealand. Where methods follow the procedures specified in Rayment and Lyons (2011), they are referred to by manual’s method code in parentheses. Additional (original) references are provided for further information, or where the analytical method is not described in Rayment and Lyons (2011).

Air Dry moisture (2A1)

The Air Dried Moisture Content (ADMC) was determined gravimetrically. This determination (ADMC) expresses moisture content of air dried soils (dried at 40°C) as a percentage on an oven-dried basis, i.e. soils which have been further dried to 105°C for at least 16 h. It is necessary to determine ADMC where it is required to correct soil chemical results performed on air-dry samples to an oven-dry basis for consistency.

Total Kjeldahl Nitrogen (7A2) and Phosphorus (9A3a)

Total Kjeldahl Nitrogen (TKN) and Total Kjeldahl Phosphorus (TKP) were determined on soil samples subjected to Kjeldahl digestion with sodium sulfate and selenium as catalyst. Following dilution with water, ammonium-nitrogen was determined by an automated segmented-flow colorimetric procedure based principally on the indophenol reaction with salicylate and sodium hypochlorite. Similarly, after conversion of all, or almost all, P to orthophosphate, orthophosphate was determined colorimetrically, based on the reaction of ammonium molybdate and potassium antimony tartrate. This method covers procedures for the quantitative determination of total nitrogen, (excluding nitrates) and of phosphorus as orthophosphate in soils.

Mineral Nitrogen (7C2a)

Samples were extracted with 2 M KCl (1:10 soil to solution ratio for 1 h at 25°C) to determine their mineral-nitrogen concentrations automated colorimetric procedures to determine ammonium-nitrogen (NH_4-N) and nitrate-nitrogen (NO_3-N).

Bicarbonate Extractable (Colwell) P (9B2) and Organic P

Colwell P (Colwell 1963) (referred to in this report as Sorbed P) was determined by extracting air dried sample with 0.5M $NaHCO_3$ buffered to pH 8.5 with NaOH at a 1:100 soil/solution ratio for 16 h at 25°C. The sample extract phosphorus concentration is determined by an automated modification of the Murphy and Riley (1962) colorimetric method.

Acid Extractable (BSES)-P (9G2)

Air dried samples were extracted at the rate 1:200, with 0.005M H_2SO_4 on an end over end tumbler for 16 h. The orthophosphate level determined by an automated colorimetric by segmented flow analysis. This method is based on the extraction method developed by Kerr and von Stieglitz (1938) and Murphy and Riley (1962).

Adjusted Phosphorus Buffer Index (PBI) (9I2b)

Sample is equilibrated in an end-over-end shaker for 16 h in a 0.01M $CaCl_2.2H_2O$ solution containing 100 mgP/L with a soil/solution ratio of 1:10.

PBI is derived from the Freundlich equation for describing the relationship between total P sorbed and final solution P concentration (i.e. the P sorption curve). The total amount of P sorbed by the soil is calculated as the amount of previously sorbed P, plus the amount of freshly sorbed P. The previously sorbed P is estimated as the Colwell–P (Colwell 1963) status of the soil. Therefore, the 'total P sorbed' for use in calculating PBI is the addition of Colwell P to the amount of freshly sorbed P. The amount of freshly sorbed P in the soil (mg P/kg) is calculated as the difference between the initial amount of P added (=1000 mg P/kg at the specified soil/solution ratio of 1:10) and the amount of P left in the equilibrating solution, expressed as mg P/kg air dry soil. Sample solution freshly sorbed P concentration is quantified by ICP-OES.

$$PBIadj = \frac{total\ P\ sorbed\ (mg/kg)}{residual\ P\ (mg/L)^{0.41}}$$

$$total\ sorbed\ P = Colwell\ P\ (mg/kg) + P\ added\ (mg/kg) - (residual\ P\ mg/L \times 10)$$

To simulate marine conditions, PBI was also carried out using the above procedure but with 0.5M NaCl replacing 0.01M $CaCl_2.2H_2O$ as the background solution.

Total Organic Carbon (6B3)

Following acid pre-treatment to remove carbonates, samples (<0.5mm) are analysed by Dumas high temperature combustion and infrared/thermal conductivity detection on a C-N Analyzer.

Particle size –

By laser diffraction

Samples were re-suspended in water without chemical dispersant into the Malvern Mastersizer 2000 and the particle size distribution determined after mechanical dispersion following AS 4863.1-2000 (ISO 13320-1:1999).

Appendix 2 Bioavailable nutrient and organics indicators for all sampled gullies, geomorphic units and particle size fractions (ND: Non-detectable, NA:Not available)

Gully name	Gully type	Gemorphology Unit	Fraction	TOC (%)	TN(%)	TOC:TN ratio	NH4-N air dry (mg/kg)	NO3-N air dry (mg/kg)	Mineral N (mg/kg)	TP (%)	Sorbed P (mg/kg)	PBI	DRP (mg/kg)	Mineral P (mg/kg)
Granite Normanby	Alluvial	Gully floor	total	0.28	0.05	5.6	<2	<2	ND	0.02	6	22	0.27	65
		Bank surface	total	0.98	0.08	12.2	<2	<2	ND	0.02	3	38	0.08	ND
		Bank subsurface	total	0.11	0.04	2.9	<2	3	3	0.02	8	39	0.21	ND
		Terrace	total	3.14	0.2	15.7	4	<2	4	0.04	24	38	0.63	ND
Parsons Creek	Hillslope	Bank surface	total	0.42	0.03	14.0	<2	<2	ND	<0.01	<2	9	ND	ND
		Bank subsurface	total	0.04	<0.03	NA	<2	12	12	<0.01	<2	31	ND	ND
		Gully floor	total	0.17	<0.03	NA	<2	<2	ND	<0.01	<2	5	ND	ND
		Hillslope	total	1.15	0.07	16.4	<2	<2	ND	<0.01	3	19	0.16	ND
Laura Croc Station	Alluvial	Gully floor	total	0.03	<0.03	NA	<2	4	4	<0.01	3	9	0.33	ND
		Bank subsurface	total	0.04	<0.03	NA	<2	5	5	<0.01	<2	44	ND	ND
		Bank surface	total	0.47	0.04	11.2	2	<2	2	<0.01	<2	8	ND	ND
		Terrace	total	1.52	0.15	10.2	10	3	13	<0.01	4	19	0.21	ND
Laura Croc gap	Alluvial	Terrace	total	1.99	0.14	14.2	4	2	6	0.02	8	22	0.36	ND
		Bank surface	total	0.87	0.09	9.6	3	<2	3	0.02	4	38	0.11	ND
		Buried A	total	0.57	0.05	11.3	3	4	7	<0.01	3	83	0.04	ND
		Bank subsurface	total	0.01	<0.03	NA	<2	3	3	<0.01	<2	18	ND	ND
		Gully floor	total	0.17	<0.03	NA	<2	<2	ND	<0.01	5	27	0.19	ND

Gully name	Gully type	Gemorphology Unit	Fraction	TOC (%)	TN(%)	TOC:TN ratio	NH4-N air dry (mg/kg)	NO3-N air dry (mg/kg)	Mineral N (mg/kg)	TP (%)	Sorbed P (mg/kg)	PBI	DRP (mg/kg)	Mineral P (mg/kg)
Granite Normanby	Alluvial	Gully floor	<10 um	0.24	0.07	3.4	5	11	16	0.03	19	46	0.41	91
		Bank surface	<10 um	1.84	0.2	9.2	8	25	33	0.03	7	119	0.06	ND
		Bank subsurface	<10 um	0.18	0.08	2.2	2	6	8	0.04	13	93	0.14	47
		Terrace	<10 um	4.81	0.41	11.7	30	50	80	0.09	57	149	0.38	ND
Parsons Creek	Hillslope	Bank surface	<10 um	2.09	0.2	10.5	8	11	19	<0.01	4	104	0.04	ND
		Bank subsurface	<10 um	0.14	0.04	3.1	<2	20	20	<0.01	<2	117	ND	ND
		Gully floor	<10 um	0.70	0.09	7.8	3	8	11	<0.01	4	56	0.07	ND
		Hillslope	<10 um	3.82	0.32	11.9	23	29	52	0.02	3	107	0.03	ND
Laura Croc Station	Alluvial	Gully floor	<10 um	0.19	0.06	3.2	5	84	89	<0.01	3	291	0.01	ND
		Bank subsurface	<10 um	0.06	0.05	1.4	3	10	13	<0.01	2	83	0.02	ND
		Bank surface	<10 um	2.40	0.26	9.2	24	59	83	0.02	4	86	0.05	ND
		Terrace	<10 um	5.44	0.62	8.8	161	226	387	0.04	11	113	0.10	ND
Laura Croc gap	Alluvial	Terrace	<10 um	4.53	0.46	9.8	8	167	175	0.06	24	92	0.26	ND
		Bank surface	<10 um	0.79	0.13	6.1	7	22	29	0.02	2	70	0.03	ND
		Buried A	<10 um	1.24	0.14	8.8	5	19	24	0.02	3	255	0.01	ND
		Bank subsurface	<10 um	0.06	0.05	1.4	4	9	13	<0.01	3	170	0.02	ND
		Gully floor	<10 um	0.39	0.08	4.9	3	13	16	0.03	13	222	0.06	ND

Gully name	Gully type	Gemorphology Unit	Fraction	TOC (%)	TN(%)	TOC:TN ratio	NH4-N air dry (mg/kg)	NO3-N air dry (mg/kg)	Mineral N (mg/kg)	TP (%)	Sorbed P (mg/kg)	PBI	DRP (mg/kg)	Mineral P (mg/kg)
Granite Normanby	Alluvial	Gully floor	<63 um	0.12	0.04	3.2	3	<2	3	0.02	7	24	0.29	70
		Bank surface	<63 um	0.69	0.07	9.8	3	2	5	0.02	4	51	0.08	ND
		Bank subsurface	<63 um	0.09	0.04	2.3	<2	<2	ND	0.02	9	35	0.26	ND
		Terrace	<63 um	2.13	0.18	11.8	8	17	25	0.04	18	42	0.43	ND
Parsons Creek	Hillslope	Bank surface	<63 um	0.58	0.05	11.7	13	3	16	<0.01	2	19	0.11	ND
		Bank subsurface	<63 um	0.06	<0.03	NA	<2	10	10	<0.01	2	57	0.04	ND
		Gully floor	<63 um	0.14	<0.03	NA	<2	<2	ND	<0.01	2	7	0.29	ND
		Hillslope	<63 um	2.16	0.18	12.0	13	9	22	<0.01	3	42	0.07	ND
Laura Croc Station	Alluvial	Gully floor	<63 um	0.06	<0.03	NA	<2	19	19	<0.01	2	44	0.05	ND
		Bank subsurface	<63 um	0.05	0.04	1.3	<2	8	8	<0.01	<2	74	ND	ND
		Bank surface	<63 um	1.22	0.13	9.4	27	22	49	0.02	3	43	0.07	ND
		Terrace	<63 um	2.91	0.31	9.4	100	39	139	0.02	9	80	0.11	ND
Laura Croc gap	Alluvial	Terrace	<63 um	3.24	0.3	10.8	15	69	84	0.04	14	62	0.23	ND
		Bank surface	<63 um	0.67	0.10	6.7	5	9	14	0.02	4	50	0.08	ND
		Buried A	<63 um	0.91	0.10	9.1	5	9	14	0.02	4	161	0.02	ND
		Bank subsurface	<63 um	0.04	0.04	1.0	<2	<2	ND	<0.01	3	117	0.03	ND
		Gully floor	<63 um	0.14	0.03	4.2	3	4	7	0.02	7	75	0.09	ND

Appendix 3 Summary statistics for bioavailable nutrient and organics indicators by gully geomorphic unit and particle size fraction (ND: Non-detectable, NA:Not available)

		TOC (%)					TN(%)					TOC:TN ratio					NH4-N air dry (mg/kg)					NO3-N air dry (mg/kg)				
Geomorphology Unit	**Fraction**	**Mean**	**Median**	**SD**	**Range**		**Mean**	**Median**	**SD**	**Range**		**Mean**	**Median**	**SD**	**Range**		**Mean**	**Median**	**SD**	**Range**		**Mean**	**Median**	**SD**	**Range**	
Bank subsurface	<10	0.11	0.10	0.06	0.06	0.18	0.05	0.04	0.02	0.04	0.08	2.0	1.8	0.8	1.4	3.1	3.0	3.0	1.0	2.0	4.0	11.3	9.5	6.1	6.0	20.0
Bank subsurface	<63	0.06	0.06	0.02	0.04	0.09	0.04	0.04	0.00	0.04	0.04	1.5	1.3	0.7	1.0	2.3	ND	ND	ND	ND	ND	9.0	9.0	1.4	8.0	10.0
Bank subsurface	Total	0.05	0.04	0.04	0.01	0.11	0.04	0.04	NA	0.04	0.04	2.9	2.9	NA	2.9	2.9	ND	ND	ND	ND	ND	5.8	4.0	4.3	3.0	12.0
Bank surface	<10	1.78	1.97	0.70	0.79	2.40	0.20	0.20	0.05	0.13	0.26	8.8	9.2	1.9	6.1	10.5	11.8	8.0	8.2	7.0	24.0	29.3	23.5	20.7	11.0	59.0
Bank surface	<63	0.79	0.68	0.29	0.58	1.22	0.09	0.09	0.04	0.05	0.13	9.4	9.6	2.1	6.7	11.7	12.0	9.0	10.9	3.0	27.0	9.0	6.0	9.2	2.0	22.0
Bank surface	Total	0.69	0.67	0.28	0.42	0.98	0.06	0.06	0.03	0.03	0.09	11.8	11.7	1.8	9.6	14.0	2.5	2.5	0.7	2.0	3.0	ND	ND	ND	ND	ND
Buried A	<10	1.24	1.24	NA	1.24	1.24	0.14	0.14	NA	0.14	0.14	8.8	8.8	NA	8.8	8.8	5.0	5.0	NA	5.0	5.0	19.0	19.0	NA	19.0	19.0
Buried A	<63	0.91	0.91	NA	0.91	0.91	0.10	0.10	NA	0.10	0.10	9.1	9.1	NA	9.1	9.1	5.0	5.0	NA	5.0	5.0	9.0	9.0	NA	9.0	9.0
Buried A	Total	0.57	0.57	NA	0.57	0.57	0.05	0.05	NA	0.05	0.05	11.3	11.3	NA	11.3	11.3	3.0	3.0	NA	3.0	3.0	4.0	4.0	NA	4.0	4.0
Terrace	<10	4.93	4.81	0.47	4.53	5.44	0.50	0.46	0.11	0.41	0.62	10.1	9.8	1.5	8.8	11.7	66.3	30.0	82.7	8.0	161.0	147.7	167.0	89.6	50.0	226.0
Terrace	<63	2.76	2.91	0.57	2.13	3.24	0.26	0.30	0.07	0.18	0.31	10.7	10.8	1.2	9.4	11.8	41.0	15.0	51.2	8.0	100.0	41.7	39.0	26.1	17.0	69.0
Terrace	Total	2.22	1.99	0.83	1.52	3.14	0.16	0.15	0.03	0.14	0.20	13.4	14.2	2.8	10.2	15.7	6.0	4.0	3.5	4.0	10.0	2.5	2.5	0.7	2.0	3.0
Gully floor	<10	0.38	0.32	0.23	0.19	0.70	0.08	0.08	0.01	0.06	0.09	4.8	4.2	2.1	3.2	7.8	4.0	4.0	1.2	3.0	5.0	29.0	12.0	36.7	8.0	84.0
Gully floor	<63	0.12	0.13	0.04	0.06	0.14	0.04	0.04	0.00	0.03	0.04	3.7	3.7	0.7	3.2	4.2	3.0	3.0	0.0	3.0	3.0	11.5	11.5	10.6	4.0	19.0
Gully floor	Total	0.16	0.17	0.10	0.03	0.28	0.05	0.05	NA	0.05	0.05	5.6	5.6	NA	5.6	5.6	ND	ND	ND	ND	ND	4.0	4.0	NA	4.0	4.0
Hillslope	<10	3.82	3.82	NA	3.82	3.82	0.32	0.32	NA	0.32	0.32	11.9	11.9	NA	11.9	11.9	23.0	23.0	NA	23.0	23.0	29.0	29.0	NA	29.0	29.0
Hillslope	<63	2.16	2.16	NA	2.16	2.16	0.18	0.18	NA	0.18	0.18	12.0	12.0	NA	12.0	12.0	13.0	13.0	NA	13.0	13.0	9.0	9.0	NA	9.0	9.0
Hillslope	Total	1.15	1.15	NA	1.15	1.15	0.07	0.07	NA	0.07	0.07	16.4	16.4	NA	16.4	16.4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

		Mineral N (mg/kg)					TP (%)					Sorbed P (mg/kg)					PBI					DRP (mg/kg)				
Geomorphology Unit	**Fraction**	**Mean**	**Median**	**SD**	**Range**		**Mean**	**Median**	**SD**	**Range**		**Mean**	**Median**	**SD**	**Range**		**Mean**	**Median**	**SD**	**Range**		**Mean**	**Median**	**SD**	**Range**	
Bank subsurface	<10	11.3	13.0	2.9	8.0	13.0	0.04	0.04	NA	0.04	0.04	4.8	2.5	5.6	1.0	13.0	115.8	105.0	38.9	83.0	170.0	0.06	0.02	0.07	0.02	0.14
Bank subsurface	<63	9.0	9.0	1.4	8.0	10.0	0.02	0.02	NA	0.02	0.02	3.8	2.5	3.6	1.0	9.0	70.8	65.5	34.7	35.0	117.0	0.11	0.04	0.13	0.03	0.26
Bank subsurface	Total	5.8	4.0	4.3	3.0	12.0	0.02	0.02	NA	0.02	0.02	2.8	1.0	3.5	1.0	8.0	33.0	35.0	11.3	18.0	44.0	0.21	0.21	NA	0.21	0.21
Bank surface	<10	41.0	31.0	28.6	19.0	83.0	0.02	0.02	0.01	0.02	0.03	4.3	4.0	2.1	2.0	7.0	94.8	95.0	21.3	70.0	119.0	0.04	0.04	0.01	0.03	0.06
Bank surface	<63	21.0	15.0	19.3	5.0	49.0	0.02	0.02	0.00	0.02	0.02	3.3	3.5	1.0	2.0	4.0	40.8	46.5	14.9	19.0	51.0	0.08	0.08	0.02	0.07	0.11
Bank surface	Total	2.5	2.5	0.7	2.0	3.0	0.02	0.02	0.00	0.02	0.02	2.3	2.0	1.5	1.0	4.0	23.3	23.5	17.0	8.0	38.0	0.09	0.09	0.02	0.08	0.11
Buried A	<10	24.0	24.0	NA	24.0	24.0	0.02	0.02	NA	0.02	0.02	3.0	3.0	NA	3.0	3.0	255.0	255.0	NA	255.0	255.0	0.01	0.01	NA	0.01	0.01
Buried A	<63	14.0	14.0	NA	14.0	14.0	0.02	0.02	NA	0.02	0.02	4.0	4.0	NA	4.0	4.0	161.0	161.0	NA	161.0	161.0	0.02	0.02	NA	0.02	0.02
Buried A	Total	7.0	7.0	NA	7.0	7.0	ND	ND	ND	ND	ND	3.0	3.0	NA	3.0	3.0	83.0	83.0	NA	83.0	83.0	0.04	0.04	NA	0.04	0.04
Terrace	<10	214.0	175.0	157.2	80.0	387.0	0.06	0.06	0.03	0.04	0.09	30.7	24.0	23.7	11.0	57.0	118.0	113.0	28.8	92.0	149.0	0.25	0.26	0.14	0.10	0.38
Terrace	<63	82.7	84.0	57.0	25.0	139.0	0.03	0.04	0.01	0.02	0.04	13.7	14.0	4.5	9.0	18.0	61.3	62.0	19.0	42.0	80.0	0.26	0.23	0.16	0.11	0.43
Terrace	Total	7.7	6.0	4.7	4.0	13.0	0.03	0.03	0.01	0.02	0.04	12.0	8.0	10.6	4.0	24.0	26.3	22.0	10.2	19.0	38.0	0.40	0.36	0.21	0.21	0.63
Gully floor	<10	33.0	16.0	37.4	11.0	89.0	0.03	0.03	0.00	0.03	0.03	9.8	8.5	7.6	3.0	19.0	153.8	139.0	122.0	46.0	291.0	0.14	0.06	0.19	0.01	0.41
Gully floor	<63	13.0	13.0	8.5	7.0	19.0	0.02	0.02	0.00	0.02	0.02	4.5	4.5	2.9	2.0	7.0	37.5	34.0	29.2	7.0	75.0	0.18	0.19	0.13	0.05	0.29
Gully floor	Total	4.0	4.0	NA	4.0	4.0	0.02	0.02	NA	0.02	0.02	3.8	4.0	2.2	1.0	6.0	15.8	15.5	10.4	5.0	27.0	0.26	0.27	0.07	0.19	0.33
Hillslope	<10	52.0	52.0	NA	52.0	52.0	0.02	0.02	NA	0.02	0.02	3.0	3.0	NA	3.0	3.0	107.0	107.0	NA	107.0	107.0	0.03	0.03	NA	0.03	0.03
Hillslope	<63	22.0	22.0	NA	22.0	22.0	ND	ND	ND	ND	ND	3.0	3.0	NA	3.0	3.0	42.0	42.0	NA	42.0	42.0	0.07	0.07	NA	0.07	0.07
Hillslope	Total	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3.0	3.0	NA	3.0	3.0	19.0	19.0	NA	19.0	19.0	0.16	0.16	NA	0.16	0.16

Appendix 4 Fine sediment content (<63 um, <10 um) for all sampled gullies by geomorphic unit