Understanding nutrient export from remediated gully systems

Final report

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Executive Summary

Gully erosion is a major sediment source to the Great Barrier Reef (GBR). Nutrients are exported in association with sediment erosion in various forms (e.g., dissolved and particulate). Some of these nutrient forms are or become bioavailable (e.g., dissolved inorganic nitrogen (DIN)) as they are transported, along with suspended sediment, through catchments and eventually into marine fine sediment plumes (Garzon-Garcia et al., 2021, 2018, in prep). An increase of bioavailable nutrients and sediment delivered to the coastal environments of the GBR since the arrival of Europeans has been associated with a range of damaging effects to the GBR.

Gully and streambank soil/sediment erosion are the main source of exported bioavailable nutrients in predominantly eroding grazing catchments (Garzon-Garcia et al., 2018, in prep) and in the marine sediment plumes they generate in the receiving waters of the GBR lagoon (Garzon-Garcia et al., 2021b). Thus, in theory, addressing sediment erosion through gully remediation would reduce the export of fine sediment associated nutrients and their bioavailable forms.

Trials of gully rehabilitation at various sites throughout the GBR have now clearly shown that sediment yields from gullies can be reduced by >80% within the space of one to two years (Brooks et al., 2021, Bartley et al., 2021, Doriean et al., 2021). However, sample data from different gully remediation sites (including Strathalbyn and Crocodile Stations) suggest gully remediation can both decrease and increase bioavailable nitrogen (BAN) forms (i.e., DIN, adsorbed ammonium-nitrogen, and mineralisable nitrogen). This disagreement in BAN data between remediated gully sites suggested more information is needed to fully understand the effect of gully remediation on certain BAN forms (i.e., DIN and other bioavailable particulate nutrients).

The gully remediation works at Strathalbyn Station, in the Bonnie Doon Creek subcatchment of the Lower Burdekin, has resulted in an increase in the concentration of dissolved nutrient forms in discharge from the remediated gullies compared to an untreated condition. The remediation works at Strathalbyn Station included the use of organic soil amendments, such as hay and bagasse as mulch and imported topsoil, and this project was designed to investigate the role the organic amendments may have played in the increased concentration of dissolved nutrients. Understanding the links between sediment and associated BAN reductions, via gully remediation, will allow us to enhance the prioritisation of gully remediation practices, account for nutrient reductions in catchment models and possibly develop a financial water quality investment system, such as a Reef Credit method, for DIN sourced from gullies in GBR catchments.

Project Objectives

The main objective of this project is to better understand the role of different soil amendments used as part of gully remediation on the export of bioavailable nitrogen (BAN) and other bioavailable nutrients (e.g., carbon and phosphorus) and to make recommendations towards gully remediation in the future.

Specific objectives to achieve this included:

- Characterise the total and soluble nutrients present in different amendment treatments introduced to gullies as part of remediation works (including hay mulch, bagasse, rock aggregate and topsoil).
- Understand changes in nutrient characteristics of amendment treatments with time.
- Understand the potential generation of dissolved inorganic nitrogen (DIN) from different amendment treatments that can be exported in runoff
- Explore the potential of using carbon and nitrogen isotopes to trace the origin of DIN exported from gully systems
- Refine and validate gully baseline nutrient loads (Garzon-Garcia et al., 2021a), and thereby determine whether there has been a net reduction in potential DIN yield from the gullies post-remediation that takes into account the short-term yield of DIN from organic soil amendments as part of the remediation process, coupled with previously documented particulate nitrogen (PN) reductions.

Other project objectives include:

- Continue to monitor water quality of gully outflow during high-flow events in the wet season 2021-2022 and integrate with data from previous monitored wet seasons (2018-2021) to understand the effect of gully remediation on nutrient export from gully systems.
- Assess the potential to develop a Reef Credit method to account for DIN reductions from gully remediation.

Nutrient export from gully systems after remediation

After four wet seasons (2018-2022) of monitoring nutrients in runoff from actively eroding and remediated gullies at Strathalbyn Station, we have compiled an important body of work and dataset, significantly advancing our understanding of the export of nutrients from these systems.

The main conclusions from the four wet seasons of monitoring nutrients in runoff from gullies at Strathalbyn are:

- Gully remediation has contributed to a significant reduction in the export of TSS [10x lower Event mean concentration (EMC), 98.9% reduction on average] and particulate nutrients (PN and PP) (>10x lower EMC, 92-95% reduction on average) from gully outlets
- Gully remediation has caused a net increase in the EMC of soluble organic nutrients (DOC, DON and DOP) and DIN (2-10 times greater than the highest DIN of an untreated gully) from gullies and there is no evidence of these going down up to 4 years after remediation.
- The majority of carbon, nitrogen and phosphorus export was in particulate fractions before gullies were remediated*.* Whereas the majority then shifted to dissolved fractions after the gullies were remediated.
- Most of the dissolved nitrogen consists of DON before remediation and in first years after*,* then DIN becomes as large or larger.
- The majority of DIN is oxidised N (NOx-N).
- Adsorbed NH_4-N can be an important bioavailable nitrogen fraction *(*can be larger than water soluble ammonium) before and after gullies are remediated. This implies that it is important to monitor adsorbed NH_4-N before and after remediation to understand reductions and impact as it is a fraction that would become bioavailable when the sediment enters the estuaries (Garzon-Garcia et al., 2021b).
- Although Total Nitrogen discharge from gullies massively decreases following gully remediation, due to the reduction of particulate fractions, the bioavailable nitrogen (BAN) discharge increases, due to an increase in the concentration of DIN.

The role of soil amendments in generating bioavailable N from remediated gullies

Initial findings of an increase in soluble nutrients, particularly DIN, after gully remediation prompted this project to explore if the increase was caused by soil amendments used as part of gully remediation. After carrying out a long-term incubation experiment, using APSIM to model the mineralisation of N in different amendments and a fourth monitoring season as part of this project, we have concluded the following:

- Soil amendments are the main cause of the increase in soluble organic nutrients and DIN from remediated gullies.
- The decomposition of organic amendments (soil and hay) can either consume DIN (high C:N ratio) or produce DIN (low C:N ratio). Rhodes grass (*Chloris gayana*) (T1 and T4) and the imported soil (control and gully 13) produce DIN whereas the Rhodes grass, sorghum and bagasse (Control and Gully 13) consume DIN. The balance between DIN producers and consumers determines whether there is a net production or consumption of DIN from the amendments.
- DIN generation potential is not the only important characteristic in selecting an amendment for gully remediation, although it should be considered. Ideally, the amendment should have a high C:N ratio so that DIN production is delayed until vegetation is established in the gully which can act as a sink for DIN produced.
- At Crocodile Station in the Normanby catchment of Cape York, the use of rock surface capping without organic amendments in gully remediation produced a net reduction in total, particulate and dissolved forms of N and P.

Accounting for nutrient export from gullies

Baseline methodology to estimate export from active gully systems

A baseline methodology to estimate nutrient and bioavailable nutrient pool yield from eroding gullies was developed by Garzon-Garcia et al. (2021) and applied to the Northern gullies and gully 13 at Strathalbyn. In this report we refined and validated this baseline method as follows:

- The sediment baseline used towards estimating the nutrient baseline at Strathalbyn was refined using recent research findings by Daley et al (in press) indicating that the earlier used estimates are underestimates. This is due to the fact that as much as 90% of the contemporary sediment yield is sourced from the gully internal surfaces which was unaccounted for. Considering this, the surface soil contribution to sediment export is also significantly lower than initially thought.
- The implications of these new insights is that it is critical to utilise the appropriate conceptual model of gully evolution for the gully in question, which accounts for the changing relative proportion of surface to sub-surface soil and associated nutrients through the gully's evolutionary history.
- Geochemistry of sediment sources explored in this report, has failed to provide conclusive results and is unlikely to be appropriate in most gullies at this scale to trace surface and subsurface sources of sediment. Consequently, it was not possible to refine the nutrient baseline for Strathalbyn gullies in terms of soil type contribution to export for the Northern gullies.
- Changes in the surface soil contribution to the baseline sediment export did not cause significant changes in the nutrient and bioavailable nutrient baseline yields estimated by Garzon-Garcia et al (2021). None-the-less, the contribution from surface soil to baseline nutrient yields reduced significantly, with subsoil now clearly being the main nutrient and bioavailable nutrient source associated with contemporary sediment export from alluvial gullies at Strathalbyn.
- Nutrient loads calculated as part of this report, were used to further validate the nutrient baseline methodology.

Monitoring of nutrients towards assessment of the effects of gully remediation in runoff water quality

After four wet seasons of monitoring nutrients in runoff from active and remediated gullies at Strathalbyn Station, we have several learnings about the best practice to monitor nutrients and calculating loads for these systems:

- There are good linear correlations between PN and TSS concentrations in untreated control gullies. This implies that for gullies of similar characteristics (geomorphology and soil type) it is possible to monitor TSS and PN with sufficient resolution (e.g., autosampler samples covering the hydrograph evenly for at least 3 events for each of 2-3 wet seasons) to establish the relationship. After this either the Reef credit method or monitoring TSS could be used to establish the TSS baseline for export and then estimate the baseline for PN export from the TN versus TSS relationship.
- There are good linear correlations between PN and TSS in treated gullies, though those relationships vary with the type of remediation (amendments used as part of the remediation) and gully type (geomorphology and soil type). Monitoring TSS and PN with high resolution (autosampler samples covering the hydrograph evenly for at least 3 events for each of 2-3 wet seasons) would be enough to determine the relationship and then estimate PN reductions from TSS reductions (Reef Credit method).
- There were no clear relationships evident between soluble nitrogen or DIN and TSS for controls nor treatments. To get an understanding of the export of these fractions from controls and treatments it would be necessary to monitor them directly (autosampler samples covering the hydrograph evenly for at least 3 events for each of 2-3 wet seasons). For controls the baseline methodology could be used instead.
- Event mean concentrations (EMCs) are the best method to directly compare nutrient yield between gullies (controls and treatments). EMCs are designed to normalise nutrient loads by runoff volume which standardises the load to catchment area and the intensity of the rainfall event.
- We acknowledge the difficulty of monitoring nutrients in gullies as these systems are generally remote and there is the need to use refrigerated autosamplers and recover the samples for filtering in less than 48 hours. None-the-less, it is necessary to monitor remediated gullies for at least 2-3 wet seasons to get an initial understanding of relationships and effects on particulate and dissolved nutrients.
- To be able to estimate nutrient EMCs for gully runoff we recommend to: install flumes at the outlets of gullies to better quantify discharge and to better sample the low water levels typical of these systems; use refrigerated autosamplers at gully outlets; have a good coverage of each event sampled (at least 5 samples) with samples at the rise, peak and drawdown stages; install pressure transducers to be able to validate runoff models.

Accounting for nutrient export

This project provides a better understanding of the effect of gully remediation on the export of bioavailable nutrients from gully systems in which soil amendments are used as part of remediation. Main findings are:

- The increase in DIN associated with gully remediation is expected to be high at least for a few years as the hay mulch fully decomposes as indicated by the APSIM modelling.
- The bioavailable nutrients reduced in association with PN reductions after gully remediation (of 11-33 mg/L in EMCs, 95% CI) did not compensate for the DIN increase caused by the use of soil amendments (on average 5x higher EMCs). This is because only 0.5-2.2% of the PN of source soils at Strathalbyn station is bioavailable (1–7-day bioavailability timeframe).
- When a new stable equilibrium is achieved in the rehabilitated gullies, DIN in runoff may still be higher when compared to controls (eroding gullies). For example, DIN in catchment runoff samples (0.024 – 0.23 mg/L) tended to be higher than in control outlet samples (EMC average = 0.07 mg/L, SD=0.06 mg/L). It is expected that hydrologic and biogeochemical conditions in rehabilitated gullies would be different than that of their catchments, and the influence this may have on DIN processing and generation is difficult to predict.

These findings imply that where soil amendments, such as low C:N ratio hay mulch is used in gully remediation works, there is no immediate benefit to water quality in terms of bioavailable nitrogen export from remediated gullies, compared to a degraded gully. There is no data we are aware of with nutrient export from stabilised or rehabilitated gully systems that have already achieved a new dynamic stable state condition. Understanding this condition for rehabilitated gullies would give more insight into the accounting of bioavailable nutrients for these systems. The reduction in PN and its bioavailable component from gully remediation (potential DIN generation downstream in transport measured up to 7 days) is overshadowed by the increase in DIN from amendments, but those reductions may still be beneficial further downstream in the Reef lagoon where sediments continue to generate bioavailable nutrients in plumes and after settling and resuspending with wind and currents (Garzon-Garcia et al., 2021b). Additionally, DIN from these recently remediated systems seem to have a larger DIN export than runoff entering the gullies from their catchments (2x average EMCs). It would be expected that as they reach a new stable equilibrium DIN export in runoff may be reduced.

Proposed future works to inform gully remediation and co-benefits – Recommendations

- We recommend that remediated gullies are monitored for particulate and dissolved nutrient fractions (C,N and P) including adsorbed ammonium for at least 3 years after remediation to develop relationships between TSS and particulate nutrients, and understand gully specific effects on the export of dissolved nutrients.
- Follow up monitoring should be undertaken again after ~ 3 years at the sites which used hay-based soil amendments to confirm whether the predicted trends towards a net reduction in DIN production to levels below baseline have been achieved.

Implications for ongoing gully remediation

- Ongoing gully remediation should avoid the use of low C/N ratio surface amendments, such as Rhodes grass (*Chloris gayana*) or sorghum hay, and instead rely on high C/N ratio amendments such as bagasse and/or rock capping.
- Locally sourced cracking clay soils (imported Vertosol) as an amendment can be used, however the maintenance of high ground cover, and the reduction of grazing pressure is critical to prevent mobilisation of the imported soil and associated nutrients during runoff events.
- This research has suggested it is likely that a stacked reef credit for PN/DIN reduction (i.e. on top of sediment reductions) is possible for gully remediation sites using rock capping and/or high C/N ratio amendments. However, the evidence from this project does not support the production of credits for sites using low C/N ratio amendments. The viability of PN/DIN reduction credits will be determined based on the trading price of credits and the number generated from a gully remediation project, versus the cost of measuring/modelling and accrediting the credits.
- Monitoring of un-incised (non-gullied) drainage swales should be undertaken as proxies for the pre-incision landforms to establish the range of DIN and DON loads that might be expected under baseline conditions under fully grassed drainage swales (i.e. gully prior land surfaces).

Background

Gully erosion is a major sediment source to the Great Barrier Reef (GBR). Nutrients are exported in association with sediment erosion in various forms (e.g., dissolved and particulate). Some of these nutrient forms are or become bioavailable (e.g., dissolved inorganic nitrogen (DIN)) as they are transported, along with suspended sediment, through catchments and eventually into marine fine sediment plumes (Garzon-Garcia et al., 2021, 2018, in prep). An increase of bioavailable nutrients and sediment delivered to the coastal environments of the GBR since the arrival of Europeans has been associated with a range of damaging effects including an increase in the frequency of Crown-of-Thorns starfish outbreaks (Brodie et al., 2005; Fabricius et al., 2010; but see Pratchett et al., 2017); reduced photic depth (Fabricius et al., 2016, 2014); reduction in seagrass meadow area (Lambert et al., 2021); an increased susceptibility to coral bleaching (Wooldridge, 2009); reef degradation and reduced coral biodiversity (DeVantier et al., 2006; Fabricius, 2005); an increase in macroalgae and consequent competition with coral (De'ath and Fabricius, 2010); and possible links to coral disease (Haapkyla et al., 2011). Gully and streambank soil/sediment erosion are the main source of exported bioavailable nutrients in predominantly eroding grazing catchments (Garzon-Garcia et al., 2018, in prep) and in the marine sediment plumes they generate in the receiving waters of the GBR lagoon (Garzon-Garcia et al., 2021b). Thus, in theory, addressing sediment erosion through gully remediation would reduce the export of fine sediment associated nutrients and their bioavailable forms.

Trials of gully rehabilitation at various sites throughout the GBR have now clearly shown that sediment yields from gullies can be reduced by >80% within the space of one to two years (Brooks et al., 2021, Bartley et al., 2021, Doriean et al., 2021). Initial assumptions were made that there should be a commensurate reduction in nutrient yields from the same rehabilitated gullies, but results to date (after up to 4 years of monitoring) suggest this is not necessarily the case (Garzon-Garcia et al., 2021a). Water quality monitoring data collected to date, from various gully remediation sites, suggest particulate nitrogen (PN) and particulate phosphorus (PP) are significantly reduced (60-90%), compared to a control, as a result of intensive landscape scale gully remediation (Brooks et al., 2020; Garzon-Garcia et al., 2021a, 2019). Fine sediment is also reduced to a similar degree (Doriean et al., 2021). However, sample data from different gully remediation sites (including Strathalbyn and Crocodile Stations) suggest gully remediation can both decrease and increase bioavailable nitrogen (BAN) forms (i.e., DIN, adsorbed ammonium-nitrogen, and mineralisable nitrogen). This disagreement in BAN data between remediated gully sites suggests more information is needed to fully understand the effect of gully remediation on certain BAN forms (i.e., DIN and other bioavailable particulate nutrients). The nutrient yield status associated with gully remediation is a major knowledge and policy gap at present and will remain so until sufficient data is collected to resolve the science.

The gully remediation works at Strathalbyn Station, in the Bonnie Doon Creek subcatchment of the Lower Burdekin, has resulted in an increase in the concentration of dissolved nutrient forms in discharge from the remediated gullies compared to an untreated condition. The remediation works at Strathalbyn Station included the use of organic soil amendments, such as hay and bagasse as mulch and imported topsoil, and this project was designed to investigate the role the organic amendments may have played in the increased concentration of dissolved nutrients. Understanding the links between sediment and associated BAN reductions, via gully remediation, will allow us to enhance the prioritisation of gully remediation practices, account for nutrient reductions in catchment models and possibly develop a financial water quality investment system, such as a Reef Credit method, for DIN sourced from gullies in GBR catchments.

Objectives

The main objective of this project is to better understand the role of different soil amendments used as part of gully remediation on the export of bioavailable nitrogen (BAN) and other bioavailable nutrients (e.g., carbon and phosphorus) and to make recommendations towards gully remediation in the future.

Specific objectives to achieve this included:

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- Understand changes in nutrient characteristics of amendment treatments with time.
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- Explore the potential of using carbon and nitrogen isotopes to trace the origin of DIN exported from gully systems.
- Refine and validate gully baseline nutrient loads (Garzon-Garcia et al., 2021a), and thereby determine whether there has been a net reduction in potential DIN yield from the gullies post-remediation that takes into account the short-term yield of DIN from organic soil amendments as part of the remediation process, coupled with previously documented particulate nitrogen (PN) reductions.

Other project objectives include:

- Continue to monitor water quality of gully outflow during high-flow events in the wet season 2021-2022 and integrate with data from previous monitored wet seasons (2018-2021) to understand the effect of gully remediation on nutrient export from gully systems.
- Assess the potential to develop a Reef Credit method to account for DIN reductions from gully remediation.

Part 1 – Gully remediation works and amendments

Description of works and amendment treatments used for gully remediation

In this project, we assessed four gullies that were remediated at Strathalbyn Station (Bonnie Doon Creek subcatchment - lower Burdekin) between 2017 and 2020. Treatments 1 (T1) and 4 (T4) gullies were remediated in October to December 2017 and May to June 2018, respectively. The control gully was initially left untreated, to act as a ‘before remediation’ control treatment. As part of ongoing works, the control gully was remediated in June to August 2020, after which it is then considered a remediated gully. Gully 13 was also remediated in June to August 2020, having one season of samples collected in 2019-2020 wet season as an untreated control, and the following season sampled as a remediated gully. Description of the gully amendment works carried out after reshaping the gullies are summarised in *Table 1*. A single comprehensive record of gully amendment works was not maintained across all gullies, so this works summary was compiled from several sources as outlined in and following Table 1.

Table 1. Description of the amendment layers added to each sub-area of the reshaped surface of each gully in order from bottom to top.

Site	Date of Remediation	Sub-Areas	Surface Area (m^2)	Source	Amendment Layers from bottom to top	Source (see footnotes)
T1	Oct - Dec, 2017 (Table 1, Report 6)	Bed	1,505	A	Gypsum Application (18t/ha) to soil surface and incorporation to a depth of 150mm.	D, F
					Graded rock bed (nom. depth of 100mm) consisting of 50-150mm quarry materials for the upper two thirds of the bed and larger ~ 250mm materials used in the lower third.	D, E
		Batter	5,674	A	Gypsum Application (18t/ha) to soil surface and incorporation to a depth of 150mm.	D, F
					A layer of gravel (nom. depth of 200mm) on 75% of the batter surface area.	D, E, G
					A layer of topsoil (nom. depth of 200mm) on 25% of batter surface area. Topsoil assumed to have been scavenged from gully during reshaping.	E
					Blanket mulching of the batters with rain-spoiled Rhodes grass hay which was sourced from the Townsville meat works and was irrigated with the meat works effluent (Report 6). Of the 74 Rhodes grass hay bales (each 450kg) used on Treatment 1 (Damon Telfer, pers. comm.), 44 bales were allocated to the batters and 30 bales to the upslope area based on surface area.	F, G
					Hand seeding of the site at ~ 20kg/ha using exotic perennial grass species including Tolga Rhodes and Sabi grass	
		Up-slope Area (Scarp)	3,765	A	Gypsum Application (18t/ha) to soil surface and incorporation to a depth of 150mm.	F
					A layer of gravel (nom. depth of 200mm	F
					A layer of topsoil with a nominal depth of 100mm. Topsoil assumed to have been scavenged from gully during reshaping.	E
					Blanket mulching of the batters with rain-spoiled Rhodes grass hay which was sourced from the Townsville meat works and was irrigated with the meat works effluent (Report 6). Of the 74 Rhodes grass hay bales (each 450kg) used on Treatment 1 (Damon Telfer, pers. comm.), 45 bales were allocated to the batters and 30 bales to the upslope area based on surface area.	F, G
					Hand seeding of the site at ~ 20kg/ha using exotic perennial grass species including Tolga Rhodes and Sabi grass	F
		Whole of catchment works			Fenced for managed stock access	D
					Diversion bund to intercept catchment flows	D
		Totals	10,944			

Site	Date of Remediation	Sub-Areas	Surface Area (m^2)	Source	Amendment Layers from bottom to top	Source (see footnotes)
T4	Established in May-June, 2018 & maintenance works in July 2019. (Table 1, Report 6)	Bed	3,547	A	Gypsum Application (18t/ha) to soil surface and incorporation to a depth of 150mm.	H, O
					Graded rock bed (nom. depth of 100mm) consisting of 50-150mm quarry materials for the upper two thirds of the bed and larger ~ 250mm materials used in the lower third. Rock placement on bed (100%) (nom. 100mm).	E, H
		Batter	14,329	A	Gypsum Application (18t/ha) to soil surface and incorporation to a depth of 150mm.	H
					A layer of gravel (nom. depth of 200mm) on 75% of the batter surface area.	E, O
					A layer of topsoil (nom. depth of 200mm) on 25% of the batter surface area. Topsoil scavenged from gully during reshaping.	E
					Blanket mulching of the batters with the same rain-spoiled Rhodes grass hay as used in T1 (Report 6). Damon Telfer (pers. comm.) stated that the rate of hay application was about the same as T1. Thus (19545/9439)*74 = 153 hay bales (450kg each) were used on T4 which were allocated to the batter and up-slope areas on a surface area basis (112 on batters and 41 on up-slope area).	H, G, P
					Hay bunds on the contour - on northeast batter only.	I
					Hand seeded at two separate intervals at approximately 20kg per hectare using exotic perennial grass species including Tolga Rhodes and Sabi grass (40kg per hectare total application).	H
		Up-Slope Area (Scarp)	5,216	A	Gypsum Application (18t/ha) to soil surface and incorporation to a depth of 150mm.	H
					A layer of gravel (nom. depth of 100mm)	H
					A layer of topsoil with a nominal depth of 100mm. Topsoil assumed to have been scavenged from gully during reshaping.	E
					Blanket mulching of the up-slope area with the same rain-spoiled Rhodes grass hay as used in T1 (Report 6). Damon Telfer (pers. comm.) stated that the rate of hay application was about the same as T1. Thus (19545/9439)*74 = 153 hay bales (450kg each) were used on T4 which were allocated to the batter and up-slope areas on a surface area basis (112 on batters and 41 on up-slope area).	G, H
					Hand seeded at two separate intervals at ~ 20kg/ha using exotic perennial grass species including Tolga Rhodes and Sabi grass (40kg per hectare total application).	H
		Whole of Catchment works.			Fenced for managed stock access	I
					Diversion bund to intercept catchment flows	I
		Total	23,092			

Site	Date of Remediation	Sub-Areas	Surface Area (m^2)	Source	Amendment Layers from bottom to top	Source (see footnotes)
Control	June to August 2020 (Page 1, Report 3)	Bed	1,575	K	Gypsum Application (18t/ha) to soil surface and incorporation to a depth of 150mm. Note that this is not mentioned in the reports but was assumed to have been done	
					A layer of 50-150mm quarry rock with a nominal depth of 100mm.	L
		Batter	18,275	K	Gypsum Application (18t/ha) to soil surface and incorporation to a depth of 150mm.	K, J
					A layer of <50mm crushed aggregate with a nominal depth of 100mm.	L, K, J
					A layer of imported topsoil with a nominal depth of 100mm sourced from the ponded pasture area about 1.5km SE from gully 13.	L, K, J
					Layer of bagasse with a nominal depth of 75mm. Bagasse is usually sourced from the old cogeneration piles which can be between 6 months and 24+ months old (Damon Telfer, pers. comm.).	L, K
					Rock checks on batters at upstream end of design	K
		Up-slope Area (Scarp)	7,818	K	Gypsum application at 18t/ha to upslope disturbed areas and incorporation to a depth of 150mm	K
					A layer of <50mm crushed aggregate with a nominal depth of 50mm.	L, K
					A layer of imported topsoil with a nominal depth of 50mm sourced from the ponded pasture area about 1.5km SE from gully 13.	L, K
					Hay bunds on the contour. The hay bunds were constructed using round Rhodes Grass hay bales from near Giru (poorer quality than T1 and T4) which probably weighed between 200 and 350kg. A total of 90 hay bales were used for both Control and Gully 13 (Damon Telfer, pers. comm.). James Daley calculated from drone photos that there were 32 round bales used on the control treatment.	G, M
		Total	27,668			

Site	Date of Remediation	Sub-Areas	Surface Area (m²)	Source	Amendment Layers from bottom to top	Source (see footnotes)
Gully 13	June to August 2020 (Page 1, Report 3)	Bed	6,748	B	Gypsum Application (18t/ha) to soil surface and incorporation to a depth of 150mm. Note that this is not mentioned in the reports but was assumed to have been done	
					A layer of 50-150mm quarry rock with a nominal depth of 100mm.	B
					Two elevated rock sills. Assumed to be 50-150mm quarry rock.	B
					Rock Check Dams. Assumed to be 50-150mm quarry rock.	B
		Batter	25,186	B	Gypsum Application (18t/ha) to soil surface and incorporation to a depth of 150mm.	B, C
					A layer of <50mm crushed aggregate with a nominal depth of 100mm.	B, C
					A layer of imported topsoil with a nominal depth of 100mm sourced from the ponded pasture area about 1.5km SE from gully 13.	B, C
					Layer of bagasse with a nominal depth of 75mm. Bagasse is usually sourced from old cogeneration piles which can be between 6 months and 24+ months old (Damon Telfer, pers. comm.).	B
		Up-slope Area (Scarp)	11,535	B	Gypsum applied at 18 t/ha and incorporated to a depth of 150mm.	B
					A layer of <50mm crushed aggregate with a nominal depth of 50mm.	B
					A layer of imported topsoil with a nominal depth of 50mm sourced from the ponded pasture area about 1.5km SE from gully 13.	B
					Hay bunds on the contour. The hay bunds were constructed using round forage sorghum hay bales which probably weighed between 200 and 350kg. A total of 90 hay bales were used for both Control and Gully 13 (Damon Telfer, pers. comm.). James Daley calculated from drone photos that there were 58 round bales used on the control treatment.	G, M
		Total	43,469			

[A] Appendix A Schedule of Quantities in Report 3

[B] Item 3 Gully Remediation Gully 13 in Appendix A – Schedule of Quantities of Report 3

[C] Drawing 19182-G13-10 in Appendix B – Design Drawings of Report 2

[D] Table 2 in Report 4 & Table 6 in Report 1

[E] Appendix A Schedule of Quantities in Report 3

[F] Page 10 of Report 4

[G]Damon Telfer (pers. comm.)

[H]Page 17 of Report 4

[I]Table 2 in report 4

[J]Drawing 19182-NCG-08 in Appendix B – Design Drawings of Report 2

[K] Item 1 Gully Remediation Northern Control Gully in Appendix A - Schedule of Quantities of Report 2

[L]Figure 6 in Report 2

[M]James Daley (pers. Comm.)

[O]Figure 4 of Report 4

[P]Plate 7 of Report 4

Report 1 – Brooks A. P., Spencer J., Doriean N. J. C., Thwaites R., Garzon-Garcia, A., Hasan., S., Daley, J.., Burton., J. & Zund P. (2020) NESP Project 3.1.7 Final Report: Effectiveness of Alluvial Gully Remediation in Great Barrier Reef Catchments. Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns (205 pp.).
File Name: NESP Final report_Project_3-1-7_GU_final_post_review151020 (1).pdf

Report 2 – Damon Tefler (2020). 2020 GBRF Reef Trust Partnership Stage 1: Phase 3 Gully Remediation Works - Strathalbyh Station. Technical Specification and design Detail. Prepared by Damon Tefler (Fruition Environmental Pty Ltd), checked and approved by Rock-it Science Pty Ltd and issued to Greening Australia Ltd.
File Name: 200429_Strathalbyn_Gully_Project_2020_Phase3_Tech_and_Design_SpecFINALDRAFT.pdf

Report 3 – Nicklin Evans (2017). Technical Specification: Strathalbyn Gully Project Phase 1. Prepared by Nicklin Evans (Alluvium Consulting) for Damon Telfer (Rock-it Science Pty Ltd). Revision 2.
File Name: P217003_R01_v3_Strathalbyn_Gully_Project_Phase_1_DD_Technical_Spec_final.pdf

Report 4 – Damon Telfer (2019). Innovative Gullies Remediation Project. Strathalbyn Station Gully Remediation Works Update. July 2019. Report prepared by Damon Telfer, Fruition Environmental Pty Ltd, Townsville QLD
File Name: FRUITION-Strathalbtn_IGRP_WorksUpdate_July2019_WEB.pdf.

Part 2 – Assessment of the potential of amendments to produce dissolved inorganic nitrogen (DIN)

Overview of assessment

Several different approaches were taken to assess potential DIN generation by the amendments:

1. Total nitrogen (N) inputs from the imported amendments were calculated. Total N inputs are only indicative of potential DIN generation since N in the organic amendments is mainly in organic forms which must be mineralised by microorganisms to release DIN. Also, in the rock and aggregate inputs the N can be trapped in the rock structure and may only be released slowly.

2. To assess the DIN released from the rock and aggregate inputs, a one hour washing of intact rock and aggregate samples was used as a surrogate measure to estimate DIN generation during a runoff event.

3. To assess the effect of mineralisation of organic N on DIN generation three approaches were taken:
   (a) The organic amendments and the imported soil were sampled on 4 occasions following remediation and analysed to estimate their total, soluble and mineralisable (bioavailable) nutrient content.
   (b) A laboratory incubation of the organic amendments and the imported soil was conducted to assess the contribution of the mineralisation of organic N to DIN. The pattern of higher DIN levels in runoff from the gullies following remediation was revealed in monitoring up to 3 years following the remediation works. Therefore, for this project it was not possible to have samples of the amendments in their initial condition. Instead, samples taken between approximately 3 months and up to 3 years after remediation were used in the incubation experiment. Therefore, the initial stages of the mineralisation process could not be assessed directly.
   (c) APSIM modelling of N mineralisation in the organic amendments and the imported Vertosol soil. Using the modelling approach, N mineralisation from day 0, under the prevailing weather conditions, could be assessed.

These approaches will be discussed in the following sections.

Total nutrient inputs from amendments

Methods

Total nutrient inputs from imported amendments can be used as an initial guide to rank imported amendments on their possible contribution to runoff nutrient loads. Because runoff events are not common at Strathalbyn (See Appendix 2), the gully rehabilitation treatments had been established for some time before it was noticed that gully rehabilitation was raising soluble nutrient concentrations in gully outlet samples. As a result, fresh amendments were not available for nutrient analysis. In lieu of fresh samples, amendments sampled at 98 days for Control and Gully 13, at 891 days for T4 and at 1079 days for T1 were used for the experiments. Nutrient concentrations measured at this point in time were compared with values obtained from a literature search. The nutrients examined were Total N, total organic carbon (TOC) and Total P.

The total amount of nutrients added to the gullies in the amendments was calculated from the amendment weights and their nutrient concentrations.

Details of the calculation of the weights of amendments added to the gullies and their associated weights of total nutrients are detailed in Appendix 3.

Results

Total N inputs from each of the amendments added to the gullies are plotted in Figure 1

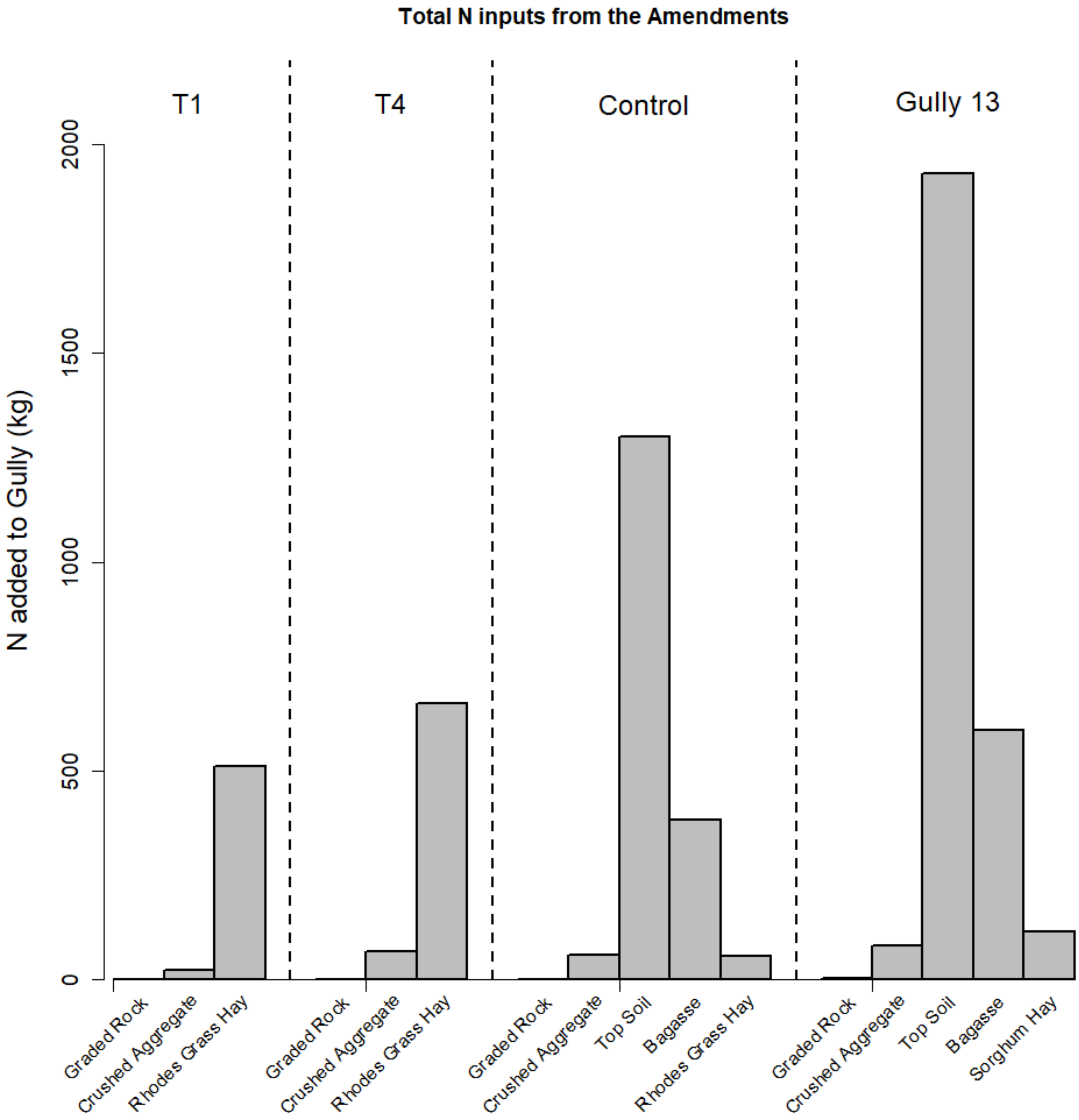


Figure 1. Total N inputs from the added amendments for each of the gullies.

For treatments T1 and T4 (similar treatments, refer to Part 1 for details), the largest total N input is from Rhodes grass hay with minor inputs from graded rock and aggregate.

For the Control and Gully 13 treatments (similar treatments, refer to Part 1 for details) the largest total N input is from the imported topsoil followed by bagasse with minor inputs from the other amendments.

Most of the total N in the organic amendments is in organic forms and needs to be mineralised to inorganic forms (NH_4^+ and NO_3^-) before it can leave the gullies in runoff as DIN. Thus, the total nutrient content of bagasse, Rhodes grass and sorghum provides an upper limit to the amount of inprganic, soluble nutrient (i.e. DIN) that could potentially be released upon complete decomposition of these materials. N mineralisation will be examined in later sections of the report. For the rock aggregate any N in the rock matrix would only very slowly make its way to the rock surface as DIN (see section on soluble nutrient inputs from coarse and fine rock aggregates

Soluble nutrient inputs from coarse and fine rock aggregates

The coarse and fine rock aggregates were a major component (in terms of weight) of the amendments used in gully remediation *Table 23*. Aggregates were placed in the bed of gullies, as check dams and sills, and as a layer beneath topsoil on the batters. Aggregates are a potential source of soluble N, particularly as DIN.

Methods

To estimate the amount of DIN released from the rock aggregate in a rain event, it was considered that a one-hour wash with deionised water was a reasonable approximation. Visual examination of the rock aggregates collected from the gullies suggested two different rock types (labelled basaltic and red) and were extracted separately.

The release of soluble N from the coarse (50-150mm) and fine (<50mm) rock aggregate samples was determined by four separate washes with deionised water. Each wash was as follows:

1. Weigh one large aggregate pellet of similar size for each sample.
2. Submerge in 100mL deionised water and stir for 1 hour at 21°C.
3. Filter extract through a 0.45µm filter.
4. Analyse filtrate for NH_4-N, NO_x-N and Organic N.

After the fourth wash as above, the coarse aggregate pellets were broken up, and a final wash performed on the aggregate pieces. Further details of the method are available in Appendix 1.

Results

The general pattern of DIN release during repeated washes of the rock aggregate with deionised water is a slow to moderate decline in the amount of DIN released (Figure 2). The average of the DIN in the four washes of the intact rock aggregate was used as an estimate of the DIN released in a rain event in calculating the potential DIN input of rock aggregate (see Figure 11 and Figure 14).

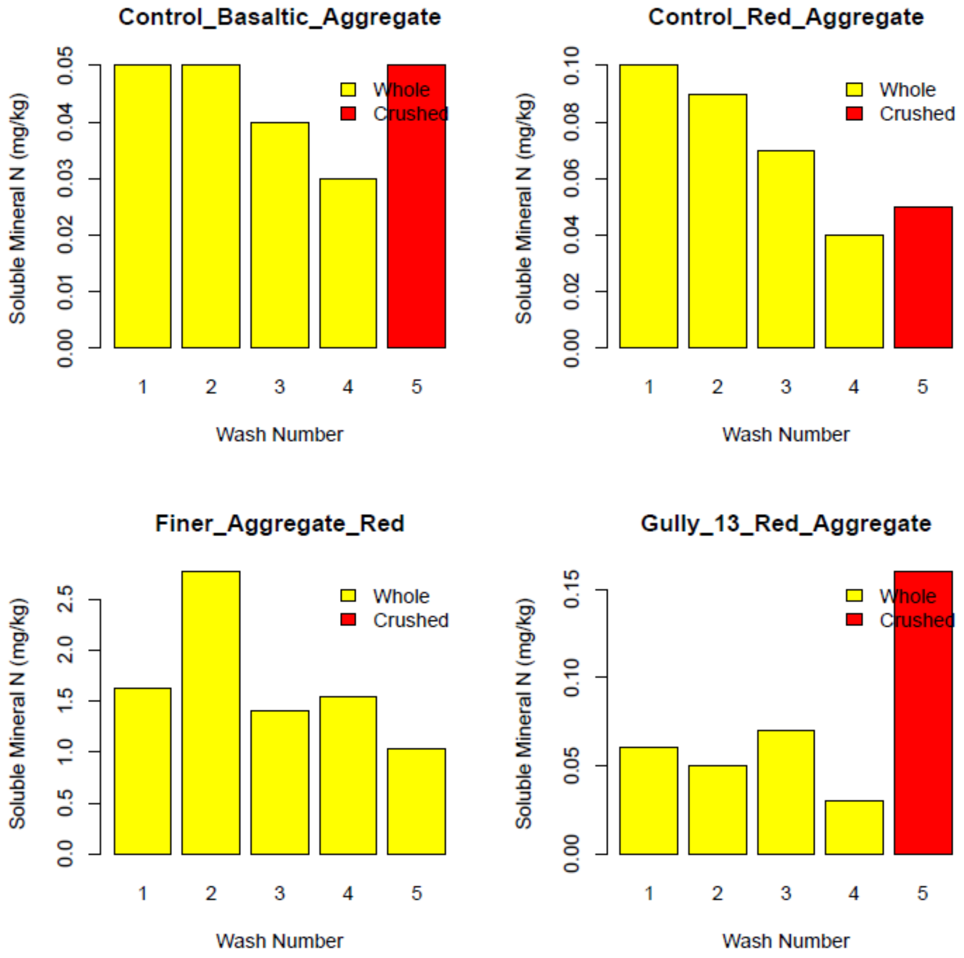


Figure 2. Release of mineral N (NH_4-N & NO_3-N) from after each of 4 washes of the intact aggregates. Subsequently the aggregate was crushed and extracted again. The rock aggregates labelled 'Red' and 'Basaltic' appeared to be different rock types. The 'Finer_Aggregate_Red' sample doesn't have a crushed rock bar as the sample was already crushed.

Nutrient characteristics of amendments sampled during the trial

Field sampling of amendments

Amendments used in gully remediation works in T1, T4, Control and Gully 13 were sampled in triplicate at each gully and at 4 points in time. Field sampling occurred on 7/12/2020, 10/02/2021, 21/06/2021 and 4/11/2021. Samples were taken before, during and after the wet season and after a long dry period to account for variable conditions associated with the hydrologic cycle. The days after remediation that each sampling occasion occurred are detailed in Table 2. Samples were packed in plastic bags and kept cool for processing and submission to the laboratory. Detailed methods for processing these samples in the lab can be seen in Appendix 1.

Table 2. Time (days) after remediation for each of the sampling times of the amendments added to the gullies at remediation. Use in conjunction with the following bar plots.

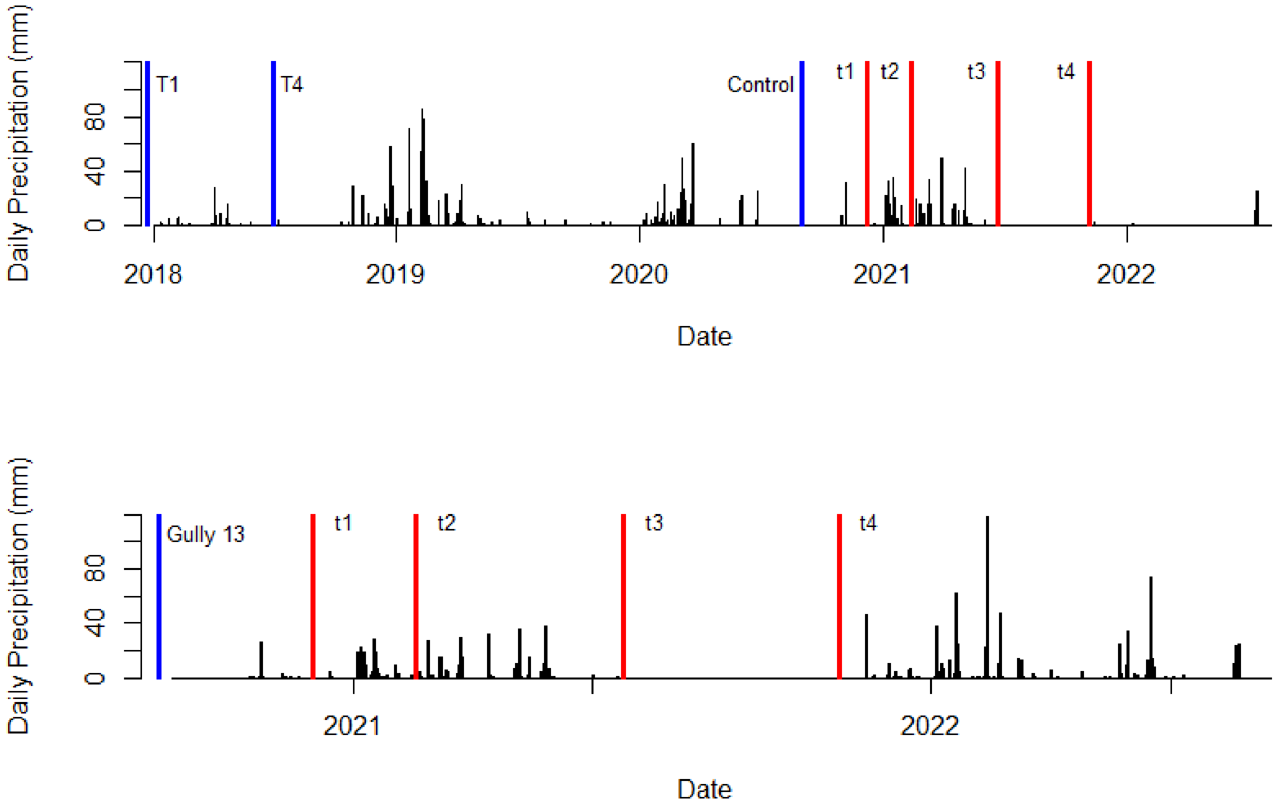
Treatment	Sampling Time (days after remediation)			
	t1	t2	t3	t4
Treatment 1	1079	1144	1275	1411
Treatment 4	891	956	1087	1223
Control	98	163	294	430
Gully 13	98	163	294	430

Methods of Analysis

Amendments used in gully remediation works were analysed to measure their total, soluble and mineralisable (bioavailable) nutrient content. Detailed analysis methods are outlined in Appendix 1. Having nutrient content data of the amendments enables the production of nutrient budgets for the gully remediation works, thereby enabling estimation of the potential additional nutrient pools contributing to dissolved nutrient discharge from the remediated gullies in the short and longer term.

Results and Discussion

The dates at which field samples were taken are shown in Figure 3 in relation to the dates of gully rehabilitation and daily precipitation.



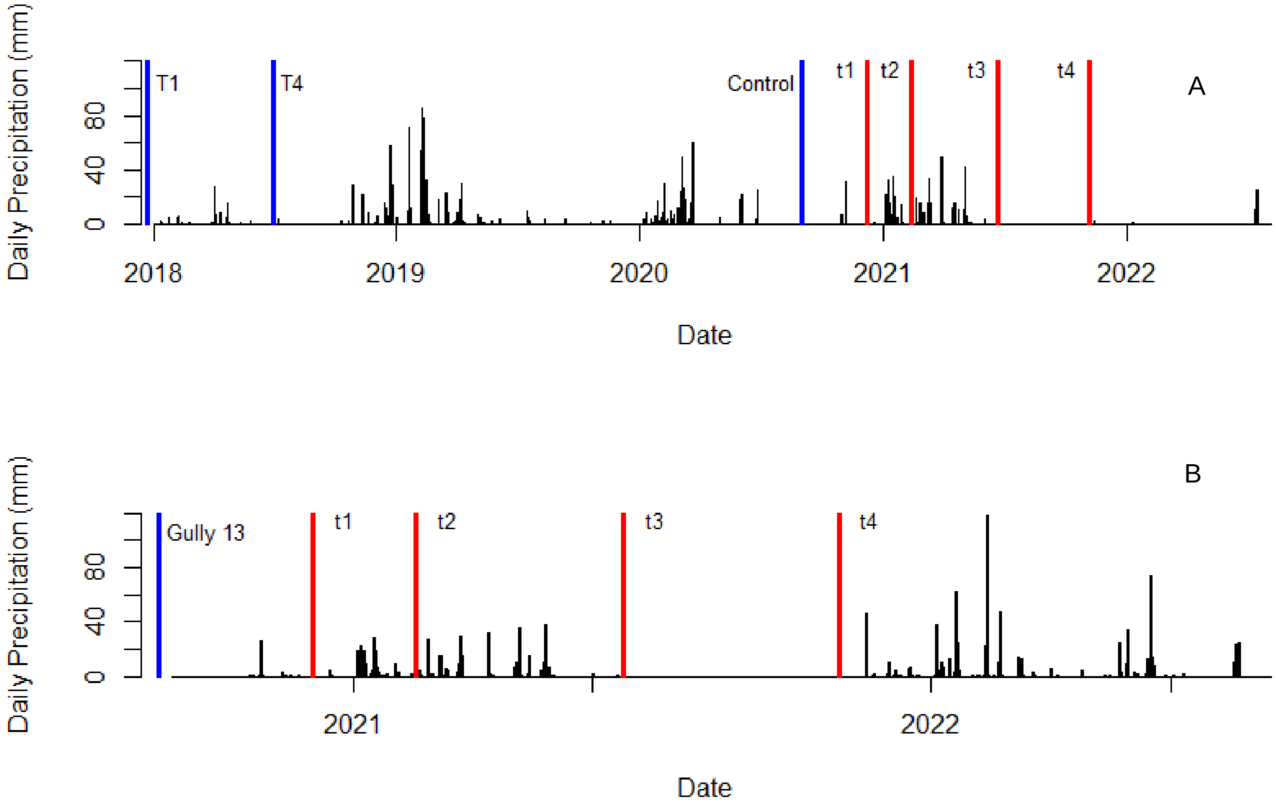
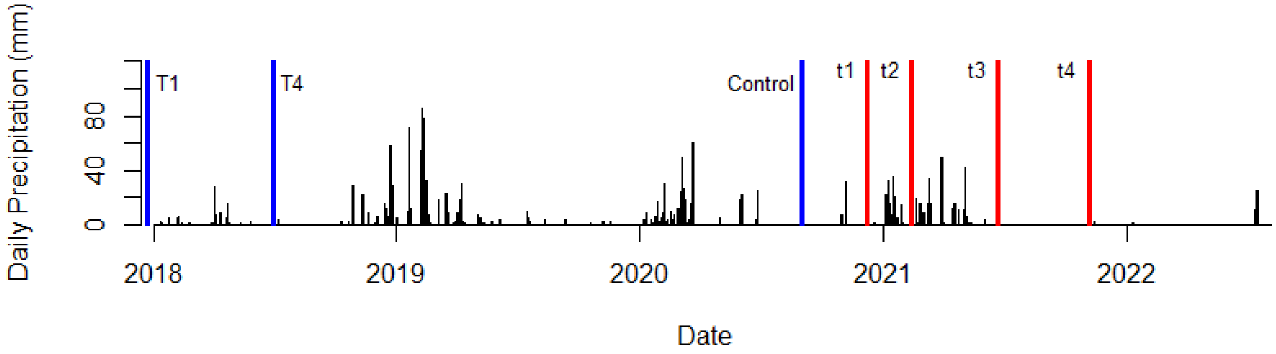


Figure 3. The timing of field sampling of the amendments (red vertical lines labelled as t1, t2, t3 and t4, Table 2) in relation to dates of rehabilitation of the gullies (blue vertical lines) overlain on a plot of the daily precipitation. A) Gullies T1, T4 and Control, B) Gully 13.

Changes in total nutrient concentrations

The Rhodes grass hay in Treatment 1 and Treatment 4 has the highest total N concentration (Dumas N) and the lowest C/N ratio of all the organic amendments (Figure 4). Also, the total N concentration in Rhodes grass hay used in Treatment 1 and Treatment 4 is higher than that in the Rhodes grass hay used in the Control gully. The P concentration of Rhodes grass and sorghum hay is higher than that of bagasse.

At the third sampling time (S3 in



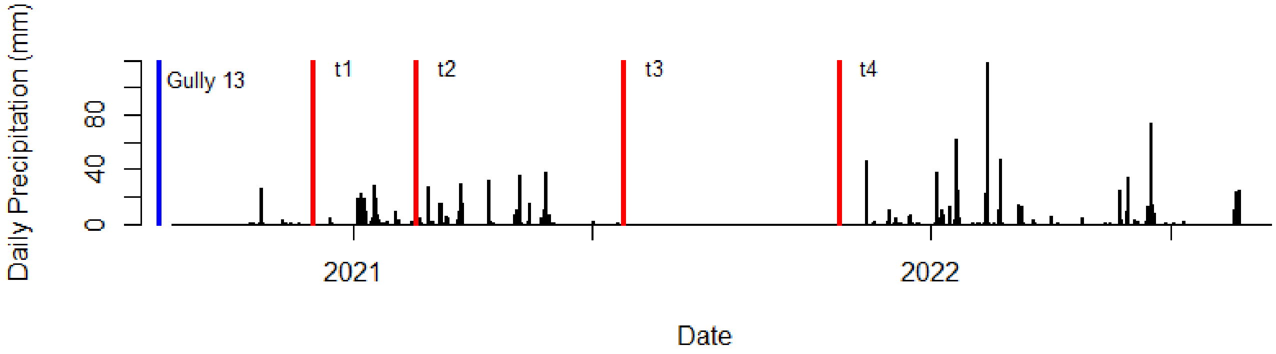


Figure 3), there is an increase in total organic carbon (TOC), Dumas N, C:N Ratio, Colwell P and Kjeldahl P in the imported Vertosol in the Control and Gully 13 (Figure 5). However, there are large error bars for these nutrient measurements. By the fourth sampling time, all these measurements have declined considerably except for Kjeldahl P which remained high. This suggests that there was a flush of decomposition of the organic amendments in these gullies prior to the third sampling and as a result C, N and P compounds have moved from the organic amendments into the soil. By the fourth sampling time, much of the C may have left the system as CO_2 and N may have been lost in runoff, by denitrification, leaching or plant uptake. Alternatively, P is strongly adsorbed by soil and tends to remain in the soil but it’s availability, as measured by Colwell P, declines.

Changes in soluble nutrient concentrations

Bagasse has the lowest DOC and DON of all the organic amendments and it also has the highest C:N in the first sampling (Figure 6). Soluble NH_4-N tends to be higher in the first two sampling rounds and this may indicate that N mineralisation is occurring since NH_4-N is the first product of N mineralisation and is later converted to NO_3-N.

Bagasse has the lowest deionised water (DI) extractable DIN for all the sampling times. In the other organic amendments, DIN tends to decrease with time (Figure 6).

For the imported Vertosol soil, there is a spike in DOC, DON and soluble NH_4-N at the third sampling (Figure 7). The timing of this spike corresponds to an increase in TOC and Dumas N in this soil (Figure 5), indicating that the products of the decomposition of the organic residues are entering the soil.

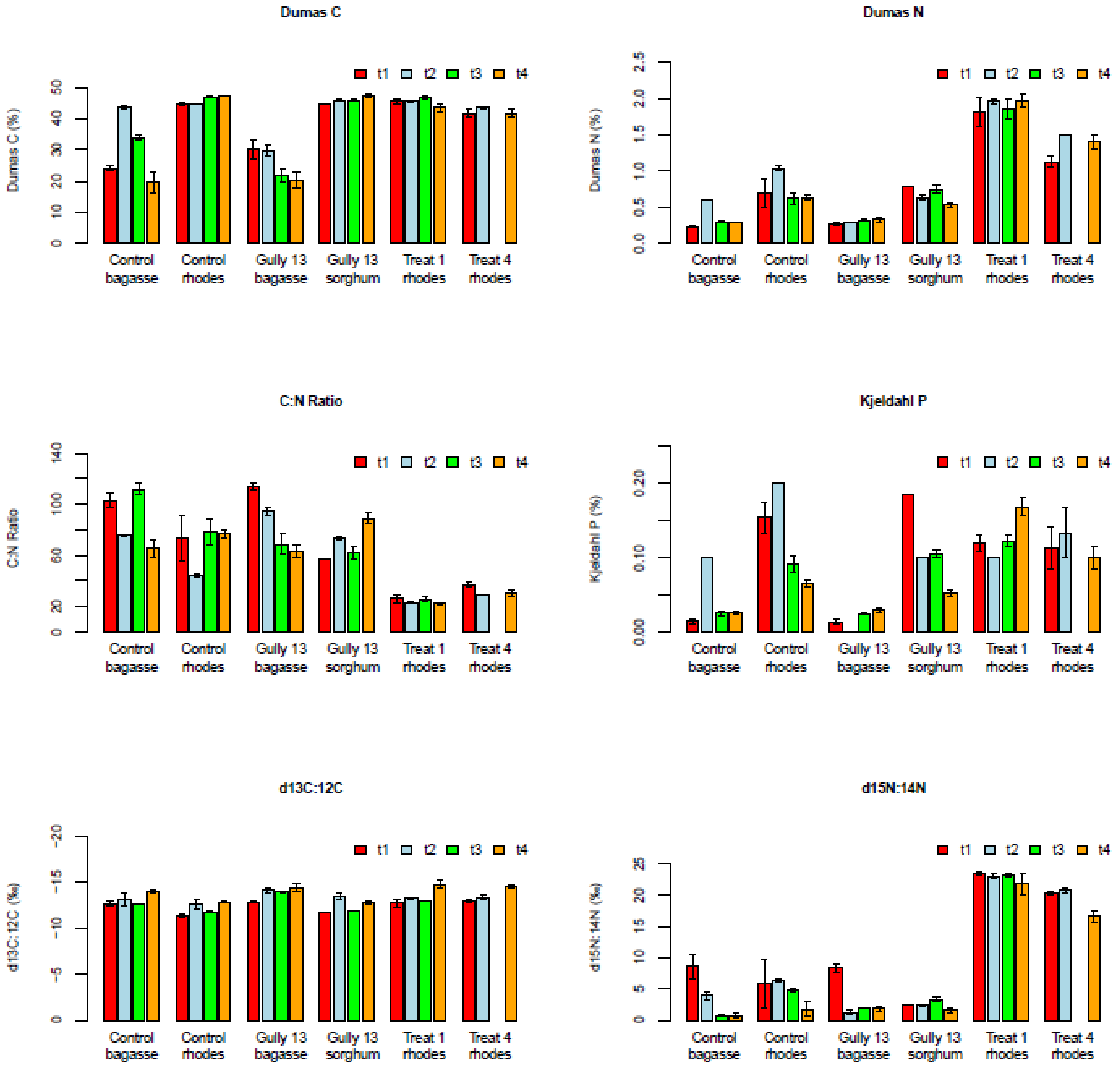


Figure 4. Change in the total nutrient concentration (% by weight) of the organic amendments added to the gullies over the four sampling dates following remediation. The error bars are ± standard error of the mean.

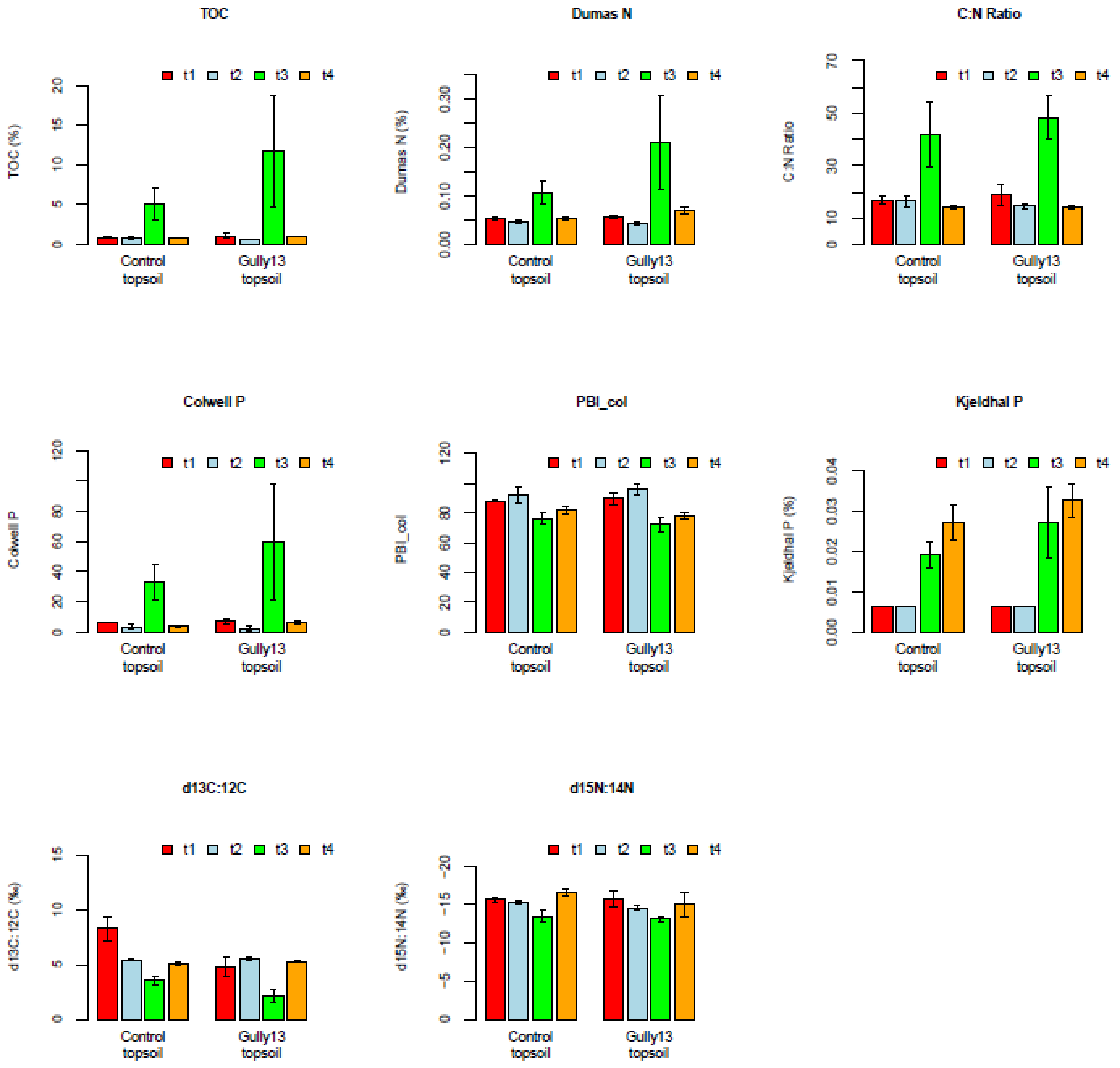


Figure 5. Change in the total nutrient concentration (% by weight) of the imported Vertosol soil added to the Control and Gully 13 treatments over the four sampling dates following remediation. The error bars are ± standard error of the mean.

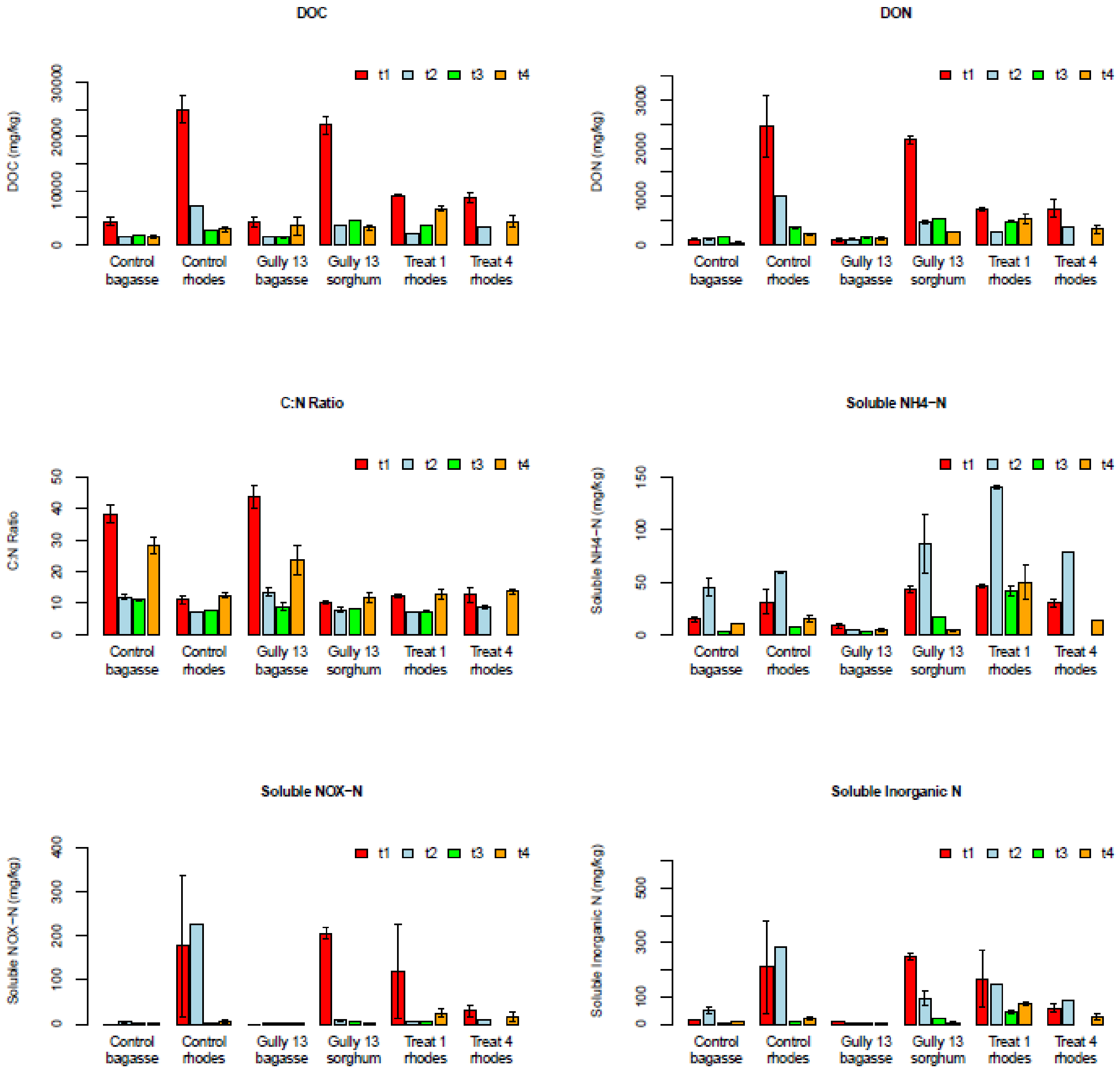


Figure 6. Change in the soluble nutrient content of the organic amendments added to the gullies over the four sampling dates following remediation. The error bars are ± standard error of the mean.

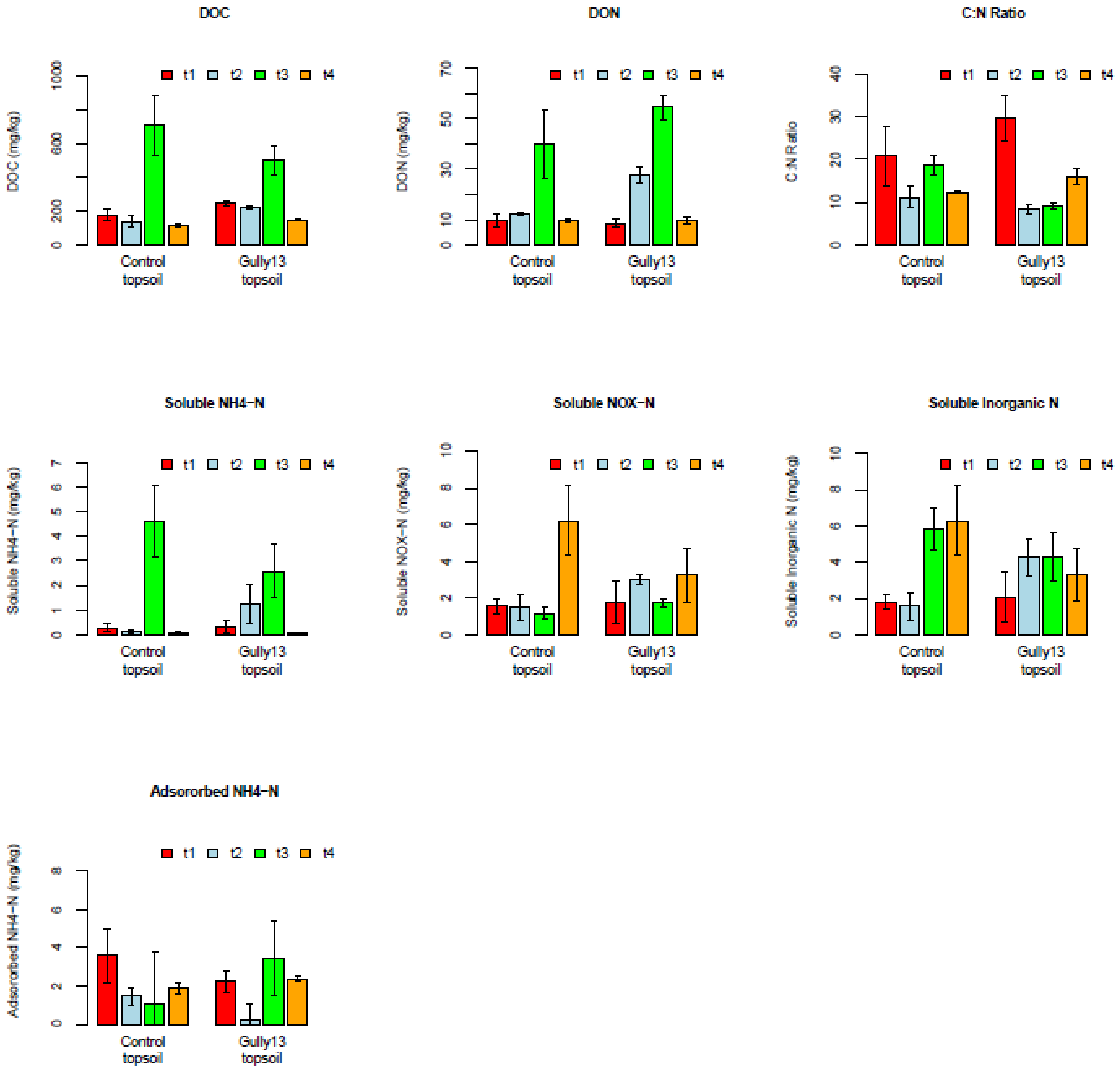


Figure 7. Change in the soluble nutrient content of the Vertosol soil added to the gullies Control and Gully 13 over the four sampling dates following remediation. The error bars are ± standard error of the mean.

Laboratory study of N mineralisation of organic amendments

Most of the total N in organic materials and soil is locked up in particulate and organic N compounds. This N can be released into inorganic, soluble forms by N mineralisation. The contribution of N mineralisation of imported amendments containing organic N (topsoil, bagasse and the two types of hay) to potentially soluble N, in particular DIN, was assessed by laboratory incubations of these materials.

Methods

The incubation of the organic amendments contained no underlying soil; however, these materials had been in contact with soil and would likely have acquired the microbial species characteristic of soils.

Laboratory incubations are generally conducted under constant moisture conditions, however in the field, surface applied materials are subject to wet and dry periods. It was hypothesised that in prolonged dry periods microbial biomass would be drastically reduced, and a consequent release of soluble N would occur, which would cause a large flush of soluble N in the first runoff event. To reflect these conditions, two watering regimes were used in the incubation experiment: continuous wet (samples maintained at field capacity) and alternating wet and dry periods (samples held for 2 weeks at field capacity, then allowed to dry for 4 weeks). Details of the incubation methods are included in Table 3 and Appendix 1.

The limited volumes of the amendment materials collected from each gully treatment resulted in the following combinations of samples for the incubations:

1. Control-Rhodes Grass and Gully 13- Sorghum Hay. Initial age of 98 days.
2. Control-Rhodes Grass and Gully 13- Sorghum Hay. Initial age of 430 days.
3. Control-Bagasse and Gully 13-Bagasse
4. Control-Imported Topsoil and Gully 13-Imported Topsoil
5. Treatment 1-Rhodes Grass and Treatment 4-Rhodes Grass

The conditions of the laboratory incubation experiments are detailed in Table 3. Detailed methods of the incubation experiment and subsequent analyses of samples are included in Appendix 1. N mineralisation was measured as the change in mineral N (NH_4-N + NO_3-N) from that at day 0. It thus represents cumulative N mineralisation.

Results and Discussion

The results of the incubation experiment are shown in Figure 8 and Figure 9 using two different scales for the y−axis. Figure 8 uses a common scale for the y-axis and allows easy comparisons of N mineralisation across the organic amendments. Figure 9 uses an optimum scale for the y-axis and allows a detailed view of changes over time for each amendment.

Examination of Figure 8 clearly shows that the Rhodes Grass (*Chloris gayana*) Hay from Treatment 1 and Treatment 4 is the only organic amendment undergoing significant N mineralisation. In the other organic amendments, the N mineralisation (despite some fluctuations) seems to hover around zero. This suggests that the microbial biomass is N limited. If a soil was present that was mineralising N this N would be used by the microbial biomass resulting in N immobilisation.

At the start of the incubation experiment it was hypothesised that prolonged dry periods would reduce the microbial biomass and release soluble N, which would cause a large flush of soluble N. However, examination of Figure 9 does not suggest any consistent effect of the dry periods in the incubations.

For the incubation of the imported topsoil, under continuously wet conditions, N mineralisation remains low with a single peak of up to 4 mgN/kg. However, there is a regular pattern of N mineralisation peaks for the alternating wet and dry periods with N mineralisation returning to approximately zero at the end of each peak. The N mineralisation at the top of the peaks varies from approximately 1 to 3 mg N/kg. This translates to approximately 2 to 7 kg of DIN in the Control and 3 to 10 kg of DIN in Gully 13.

Lack of overall significant N mineralisation in the imported Vertosol (topsoil) is unusual. From experience, topsoils will undergo some degree of N mineralisation overtime. Possible reasons for the low overall N mineralisation include:

1. The soil was sourced from a swampy area from within the property (Damon Telfer, pers. comm) that may have affected the quality of the C in the soil (i.e., soil organic C contains a high proportion of inert C). Soil microorganisms require an energy source (labile C) for N mineralisation to occur.
2. The soil may have included a lot of subsoil (not a pure topsoil) and subsoils have a high proportion of inert C.
3. The incubated soil may have been too wet resulting in denitrification removing any mineralised N and turning it into gaseous N (N_2 or N_2O).

Table 3. Conditions of the incubation experiment.

Material	Age of material at start of incubation (days)	Pre-treatment	Weight of AD material (g)	Incubation Container	Moisture at 65% of WHC (%)	Watering Regimes		Incubation temperature (°C)	Length of incubation (days)	Sampling Regime		Extraction Method	Analyses
						Wet	Wet, Dry			Wet	Wet, Dry		
Topsoil: Combined gully 13 & control	98	<2mm	30	100ml container with three2mm aeration holes in lid	32.08	Continuously wet at WHC	Repeat: 2 weeks wet at WHC & 4 weeks dry with lid off	30	210	2-week intervals	2-week intervals at changeover of watering regime and mid-dry periods	1:10 (30g:300mL) extract with 0.25M K_2SO_4	NH_4-N, NOx-N, TDN, PO_4-P & DOC
Rhodes Grass hay: combined Treatments 1 & 4	891-1079	Coarsely chopped to approx. 2 cm lengths	5		338.49							1:40 (5g:200mL) extract with 0.25M K_2SO_4	
Bagasse: combined gully 13 & control	98	Coarsely chopped to approx. 2 cm lengths	5		78.24								
Rhodes Grass & Forage Sorghum hay: combined control (Rhodes Grass) & gully 13 (Forage Sorghum)	98	Coarsely chopped to approx. 2 cm lengths	5		142.96								
Rhodes Grass & Forage Sorghum hay: combined control (Rhodes Grass) & gully 13 (Forage Sorghum)	430	Coarsely chopped to approx. 2 cm lengths	5		142.96								

AD – air dry

WHC – water holding capacity

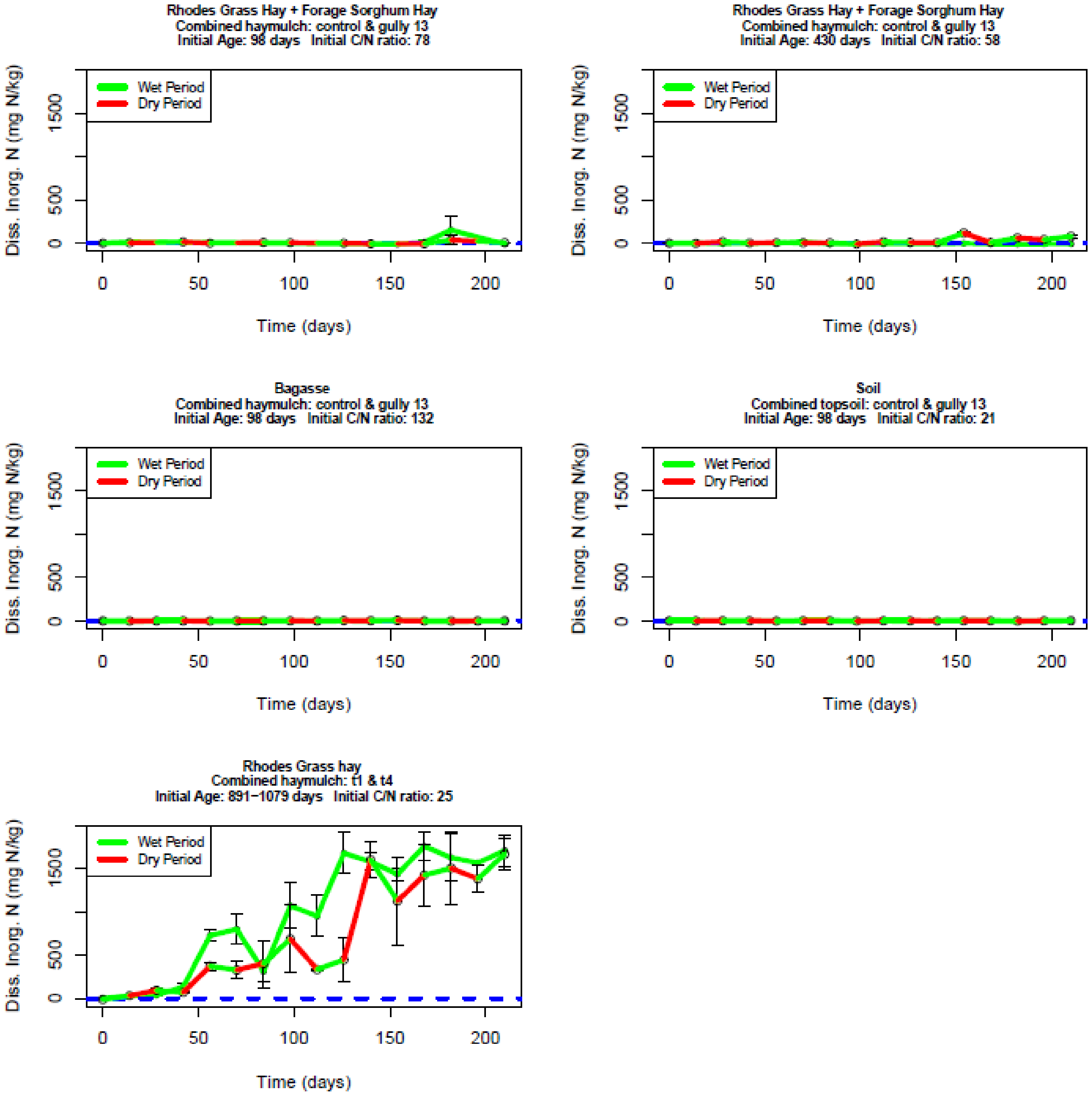


Figure 8. N mineralisation versus time for various combinations of organic amendments and also the imported Vertosol soil. Separate incubations using two different watering regimes (wet and alternating wet and dry) are shown. The same scale was used for N mineralisation in each case so that differences in N mineralisation across organic amendments could be easily seen.

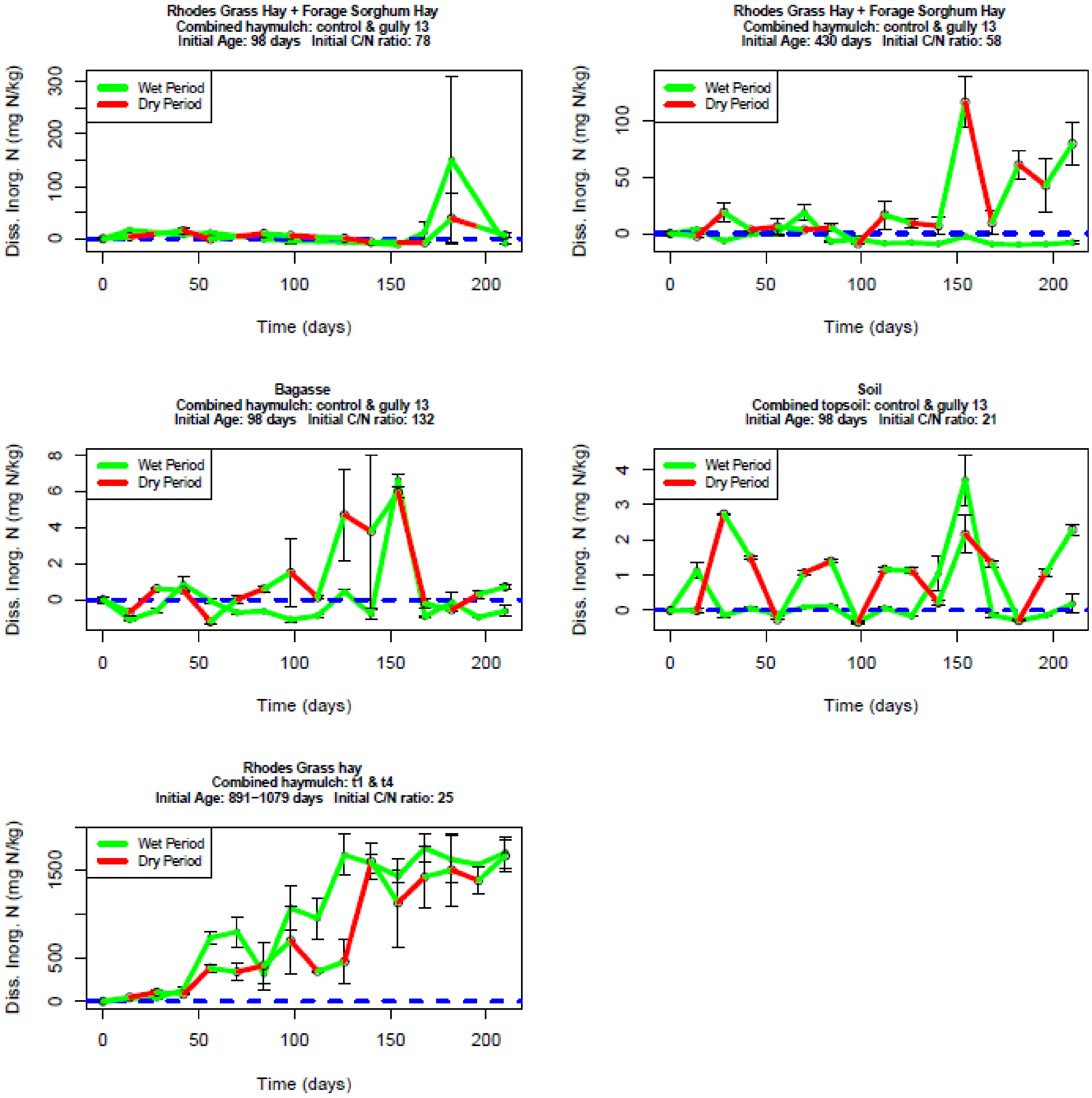


Figure 9. N mineralisation versus time for various combinations of organic amendments and also the imported Vertosol soil. Separate incubations using two different watering regimes (wet and alternating wet and dry) are shown. The optimum y-axis scale was used for N mineralisation in each case so that small changes in the rates of mineralisation over time could be easily seen.

Modelled DIN generation from organic amendments

Most of the N in the organic amendments is in the form of organic N and must undergo N mineralisation to be released as DIN. The Agricultural Production Systems sIMulator (APSIM) (Holzworth et al., 2014) was used to model DIN generation from the organic amendments. Soil water, soil nitrogen and surface organic matter modules were used (Probert et al., 1998). The water and nitrogen modules were parameterised using default parameterisation. The soil parameters were obtained from Apsoil.

Materials and Methods

Residue parameters used in APSIM modelling

The parameters related to the residue (organic amendments) that were used in the APSIM modelling are detailed in Table 4. For Rhodes grass (*Chloris gayana*), the potential rate of decomposition of surface residue was changed from the default value of 0.1 to 0.025 so that the residue biomass remaining, more closely matched that found in the field (Figure 12). This lower value was also the optimum value found for the decomposition of sugar cane residue (Thorburn et al., 2001). The critical residue weight was changed from the APSIM default of 2000 t/ha to 1000 t/ha for the same reason.

Table 4 Parameters related to the residue that were used in the APSIM modelling

Treatment	Organic Amendment	C fraction in FOM[A]	C/N Ratio[B]	Potential Rate of Decomposition of surface residue[C]	Critical Residue Wt (t/ha)[D]	Optimum temperature for decomposition (°C)[E]
T1	Rhodes Grass	0.4	19.9	0.025	1000	30
T4	Rhodes Grass	0.4	31.9	0.025	1000	30
Control	Bagasse	0.4	172	0.1	1000	30
	Rhodes Grass	0.4	51.2	0.025	1000	30
Gully 13	Bagasse	0.4	152	0.1	1000	30
	Sorghum	0.4	44.9	0.1	1000	30

[A] APSIM default value

[B] Calculated from N concentration in samples collected from gullies on 7/12/2020, APSIM default C fraction of 0.4, and the initial rates of hay application.

[C] APSIM default is 0.1; Thorburn et al. (2001) fitted a potential decomposition rate of 0.025 to decay of sugarcane residue.

[D] APSIM default is 2000 t/ha; Thorburn et al. (2001) fitted a Critical Residue weight of 10000 to decay of sugarcane residue. In this case we used 1000 t/ha since the residue layer is thinner than sugarcane and in a drier environment

[E] Optimum temperature for decomposition of sugarcane residue fitted by Thorburn et al. (2001)

As shown in Table 3, organic amendments were collected from the field between approximately 3 months and 3 years following gully remediation works. Changes in the nutrient content of the amendments may have occurred during their time in the field due to decomposition, so that the sampled material may not reflect the actual nutrients added to the gullies. However, the amendments were sampled and analysed on four occasions and examination of the plots of N concentrations over time (Figure 10) suggest that despite the period of decomposition, the N concentrations in the organic amendments do not change a lot over time and were also within the range found in the literature for fresh hay samples. Asuming this pattern of stable N content applies for fresh organic amaendments, N concentrations at the first sampling were used as estimates of N concentrations in the amendments in their initial state.

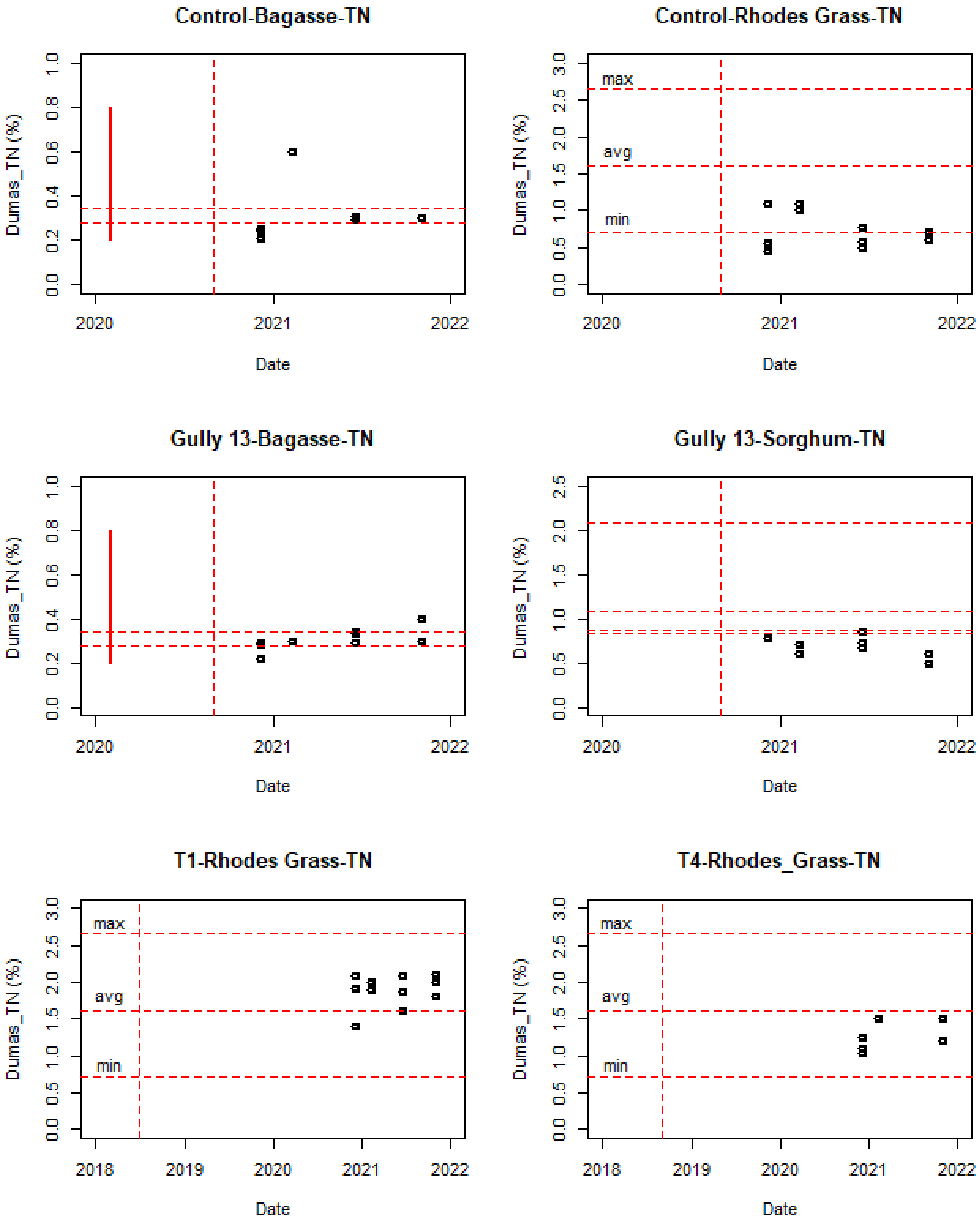


Figure 10. Total N concentrations in samples (black squares) taken from each of the 4 gullies at four times after remediation. The dashed vertical lines are dates of remediation. For bagasse, the solid vertical line is a concentration range from (Calcino et al., 2022) and the two dashed horizontal lines are concentrations from (Rezende et al., 2011) and (Bhadha et al., 2020). For Rhodes grass, the minimum, maximum and average N concentrations of 193 samples from https://www.feedipedia.org/node/12519 are displayed. For sorghum, the dashed horizontal lines are concentrations from (Henrique Melo Lima et al., 2017), (Raphael et al., 2016), (Lynch et al., 2016) and (Corredor et al., 2009).

Selection of initial values of fbiom and finert for the SoilN module of APSIM

In the APSIM SoilN module soil organic matter C is divided up into 3 pools:

1. Biom – C in soil microbial biomass
2. Inert – C assumed to be inert in the soil
3. Hum – Rest of the carbon

Initially the C fractions (fbiom and finert) in the biom and inert pools need to be specified. The C fraction in the hum pool is calculated by APSIM. The model is then run for several years to stabilise the pool structure (Biggs et al. 2021). Lack of information about C inputs and the history of the swampy area from where the imported Vertosol soil was sourced prevented taking this approach to stabilising the C pools.

In the present modelling, the N mineralisation of the organic residues is obtained by difference between models of the soil alone and soil plus organic residue. Thus, the effect of the soil is negated. Since the effect of the soil is not considered, APSIM default values (fbiom = 0.04 and finert = 0.4) were used as initial estimates of fbiom and finert without stabilisation.

Initially, N mineralisation in the imported Vertosol in the Control and Gully 13, was modelled using default values of fbiom and finert. The N mineralised was much greater than that found in the laboratory incubation. In the section on soil incubations, it was hypothesised that the low N mineralisation in the soil may have been due to the imported soil containing a large proportion of subsoil which tends to have high inert C. Therefore, the modelling was repeated using the average of typical values of Fbiom (0.0175) and Finert (0.7) found in the 15-30 and 30-60 cm soil layers of a Vertosol (Tables 5 and 6 in Dalgliesh et al., 2016).

Weather data

Rainfall data was collected at the Strathalbyn Station site from two weather stations: one adjacent to the Control, T1 and T4 gullies and one beside Gully 13. Rainfall data was only collected over the wet seasons (1st July one year to 30th June the following year) and there was one season of missing data over the 2019-2020 wet season for the Northern gullies.

For APSIM modelling a continuous weather data set is required. This was provided by the nearest SILO weather grid (https://www.longpaddock.qld.gov.au/silo/point-data/). Where available, the rainfall measured on site was used to replace the weather grid rainfall data.

Soil data

Three soil types were used in the APSIM modelling: in-situ Sodosol and Vertosol for gullies T1 and T4 and an imported Vertosol for the Control Gully and Gully 13.

Nutrient analyses are available for the in-situ Sodosol and Vertosol from soil cores taken across the Northern Gullies before remediation and for the imported Vertosol used in the Control and Gully 13 from four samplings taken after remediation. However, the physical characteristics (particle size analysis and water characteristics) of these soils were not measured. CSIRO maintains a APSoil Database of fully characterised soils from across Australia which are designed for use in simulation modelling. For the simulation modelling in this study, a typical Sodosol and Vertosol (in terms of their extractable water content) were selected from the Queensland APSoils (Vertosol APSoil 54 and Sodosol APSoil 117). All soil layers except the surface layer were discarded and the surface layer was reduced to a depth of 100mm. The organic C (OC) and C/N ratio of the chosen APSoils were replaced by the measured values (Table 5). Thus, the chosen APSoils provided the physical characteristics and inserted measured chemical values provided the relevant chemical data to model N mineralisation.

Table 5. Measured soil chemical data

Treatment	Soil	OC[A]	C/N Ratio[B]
T1 & T4	In-situ Sodosol	1.53	12.8
	In-situ Vertosol	1.98	10.7
Control	Imported Vertosol	0.989	18
Gully	Imported Vertosol	0.989	18

[A] Dumas TOC

[B] Dumas TOC/Dumas TN

Modelling Scenarios

The various modelling scenarios examined are listed in Table 6. To determine the N mineralisation in an organic amendment, N mineralisation in the soil and in the soil plus amendment were modelled separately and N mineralisation in the organic amendment was obtained by difference. Since the Vertosol and Sodosol have different water holding characteristics that may influence the decomposition of overlying hay both these soils were modelled separately. Since the imported Vertosol soil was added to gully 13 and the Control, N mineralisation in this soil was also modelled. The modelling units were kg/ha and were converted to amounts per gully by multiplying by the gully projected surface area.

Table 6. APSIM modelling scenarios

Model	Treatment	Sub-Area	Organic Amendments	Underlying Soil	Purpose	Further Processing
1	T1	Area of batters & up-slope underlain by Sodosol	Rhodes Grass Hay	In-situ Sodosol	N mineralisation of Rhodes Grass Hay obtained by difference	Combine to get N mineralisation of Rhodes grass for the entire gully.
2	T1	Area of batters & up-slope underlain by Sodosol	Nil	In-situ Sodosol		
3	T1	Area of batters & up-slope underlain by Vertosol	Rhodes Grass Hay	In-situ Vertosol	N mineralisation of Rhodes Grass Hay obtained by difference	
4	T1	Area of batters & up-slope underlain by Vertosol	Nil	In-situ Vertosol		
5	T4	Area of batters & up-slope underlain by Sodosol	Rhodes Grass Hay	In-situ Sodosol	N mineralisation of Rhodes Grass Hay overlying the Sodosol obtained by difference	Combine to get N mineralisation of Rhodes grass for the entire gully.
6	T4	Area of batters & up-slope underlain by Sodosol	Nil	In-situ Sodosol		
7	T4	Area of batters & up-slope underlain by Vertosol	Rhodes Grass Hay	In-situ Vertosol	N mineralisation of Rhodes Grass Hay overlying the Vertosol obtained by difference	
8	T4	Area of batters & up-slope underlain by Vertosol	Nil	In-situ Vertosol		
9	Gully 13	Batters	Bagasse	Imported Vertosol	N mineralisation of Rhodes Grass Hay obtained by difference	
10	Gully 13	Batters	Nil	Imported Vertosol		

Model	Treatment	Sub-Area	Organic Amendments	Underlying Soil	Purpose	Further Processing
11	Gully 13	Hay bund but modelled as if spread over up-slope area	Forage Sorghum Hay	Imported Vertosol	N mineralisation of Sorghum Hay obtained by difference	
12	Gully 13	Up-slope Area	Nil	Imported Vertosol		
13	Gully 13	Batters & Up-Slope Area	Nil	Imported Vertosol	N Mineralisation in Imported Vertosol	
14	Control	Batters	Bagasse	Imported Vertosol	N mineralisation of Bagasse obtained by difference	
15	Control	Batters	Nil	Imported Vertosol		
16	Control	Hay bund but modelled as if spread over up-slope area	Rhodes Grass Hay	Imported Vertosol	N mineralisation of Rhodes Grass Hay obtained by difference	
17	Control	Up-slope Area	Nil	Imported Vertosol		
18	Control	Batters & Up-Slope Area	Nil	Imported Vertosol	N Mineralisation in Imported Vertosol	

Model validation

There are two ways the modelling results can be validated:

1. The amount of hay residue remaining in the field measured on the 7/12/2020 can be compared with that predicted by modelling. The field sampling consisted of weighing the amount of hay remaining in the field in three replicates of a 30 x 30cm square sampling frame.
2. Compare APSIM modelling results with the laboratory incubation.

Results

Comparison of modelled remaining hay with field measurements

The choice of the initial values of fbiom and finert had no effect on the modelled remaining hay in the field and the common results are shown in Figure 12 and Figure 13. The replicate field measurements of the bagasse/hay remaining in the field vary a lot due to the uneven distribution of the bagasse/hay, but the modelled remaining bagasse/hay is within the range measured in the field.

N mineralisation

Two different modelling scenarios are presented in Figure 11 and Figure 14 which differed in the choice of the initial values of fbiom and finert. In Figure 11, only default values of fbiom and finert were used. In Figure 14, the average of typical values of Fbiom and Finert found in the 15-30 and 30-60 cm soil layers of a Vertosol Tables 5 and 6 in Dalgliesh et al., 2016) were used in the modelling of Control and Gully 13. Default values of fbiom and finert were again used for treatment T1 and T4.

This modelling was done in the absence of plant uptake. It is anticipated that a lot of the mineralised N will be taken up by grass growth. However, the modelling allows the ranking of the amendments as producers of mineral N.

Thus, if the DIN increases following rehabilitation, then the probable source can be identified by modelling. The probable sources of DIN are discussed as follows:

Treatments T1 and T4

The same modelling results for T1 and T4 are presented in Figure 11 and Figure 14.

The biggest source of DIN is the mineralisation of the Rhodes grass (*Chloris gayana*) hay. Very little DIN comes from the rock aggregate. These results are consistent with the laboratory incubation where Rhodes grass from T1 and T4 showed considerable N mineralisation.

Control Treatment

Two different modelling scenarios were used for the Control Treatment:

1. Figure 11 shows the modelling results using the APSIM default values of fbiom and finert as initial values.
2. Figure 14 shows the modelling results using the average of typical values of Fbiom and Finert found in the 15-30 and 30-60 cm soil layers of a Vertosol (Tables 5 and 6 in Dalgliesh et al., 2016).

The amount of N mineralised or immobilised differs between the two cases, but the trends are the same. The sources of DIN are rock aggregate (very small contribution) and N mineralisation of the imported Vertosol soil. Rhodes grass (*Chloris gayana*) hay and bagasse are both taking up mineral N from the soil because the microbial biomass decomposing these materials is N limited. This process is called N immobilisation. Summation of the mineral inputs from rock aggregates and the imported Vertosol soil with the uptake of mineral N by bagasse and Rhodes grass decomposition results in a net positive production of mineral N. The Rhodes grass in the control treatment immobilises N in contrast to that in Treatments T1 and T4 because the C/N ratio of Rhodes grass in the control is much higher than that in T1 and T4 (Table 4).

Laboratory incubation of bagasse (combined Control and Gully13) and combined Rhodes grass and sorghum hay (from Control and Gully13) both show little to zero N mineralisation. This indicates that bagasse and Rhodes grass in the control treatment is N limited as found by modelling. In the laboratory incubation there is no soil, therefore N mineralisation can only go to zero as there is no mineral N from soil to be taken up by the microorganisms as occurs in the field.

Using values of Fbiom and Finert characteristic of Vertosol subsoils greatly reduced overall N mineralisation from the imported Vertosol compared to using default values. It also increased the initial period where little N mineralisation occurred to approximately 220 days. This agrees with the soil incubation where little overall N mineralisation also occurred over this period. Thus, the imported Vertosol seems to be more subsoil in character.

In summary both laboratory incubations and modelling suggest that bagasse and Rhodes grass hay are not sources of DIN but may immobilise DIN during the measurement period. For the imported soil, significant N mineralisation is delayed for ~220 days and when it does start mineralising most of the N produced is immobilised by the decomposing bagasse and hay. The only source of additional DIN from the amendments appears to be from the rock aggregate.

Gully 13

Two different modelling scenarios were used for the Gully 13:

1. Figure 11 shows the modelling results using the APSIM default values of fbiom and finert as initial values.
2. Figure 14 shows the modelling results using the average of typical values of Fbiom and Finert found in the 15-30 and 30-60 cm soil layers of a Vertosol (Dalgliesh et al., 2016).

The amount of N mineralised or immobilised differs between the two cases, but the trends are the same. The sources of DIN are rock aggregate (very small contribution) and N mineralisation of the imported Vertosol soil. Sorghum hay and bagasse are both taking up mineral N from the soil because the microbial biomass decomposing these materials is N limited. This process is call N immobilisation. Summation of the mineral inputs from rock aggregates and the imported Vertosol soil with the uptake of mineral N by bagasse and sorghum hay decomposition results in a small net positive production of mineral N.

Laboratory incubation of bagasse (combined Control and Gully13) and combined Rhodes grass and sorghum hay (from Control and Gully13) both show little to zero N mineralisation. This indicates that bagasse and sorghum hay in Gully 13 are N limited as found by modelling. In the laboratory incubation there is no soil underlying the amendments, therefore N mineralisation can only go to zero as there is no mineral N from soil to be taken up as occurs in the field.

Using values of Fbiom and Finert characteristic of Vertosol subsoils greatly reduced overall N mineralisation from the imported Vertosol compared to using default values. It also increased the initial period where little N mineralisation occurred to approximately 220 days. This agrees with the soil incubation where little overall N mineralisation also occurred over this period. Thus,the imported Vertosol seems to be more subsoil in character.

In summary both laboratory incubations and modelling suggest that bagasse and sorghum hay are not sources of DIN but may immobilise DIN over thecourse of the trial. For the imported soil, significant N mineralisation is delayed for ~220 days and when it does start mineralising most of the N produced is immobilised by the decomposing bagasse and hay. The only source of additional DIN from the amendments appears to be from the rock aggregate with a small amount coming from soil mineralisation.

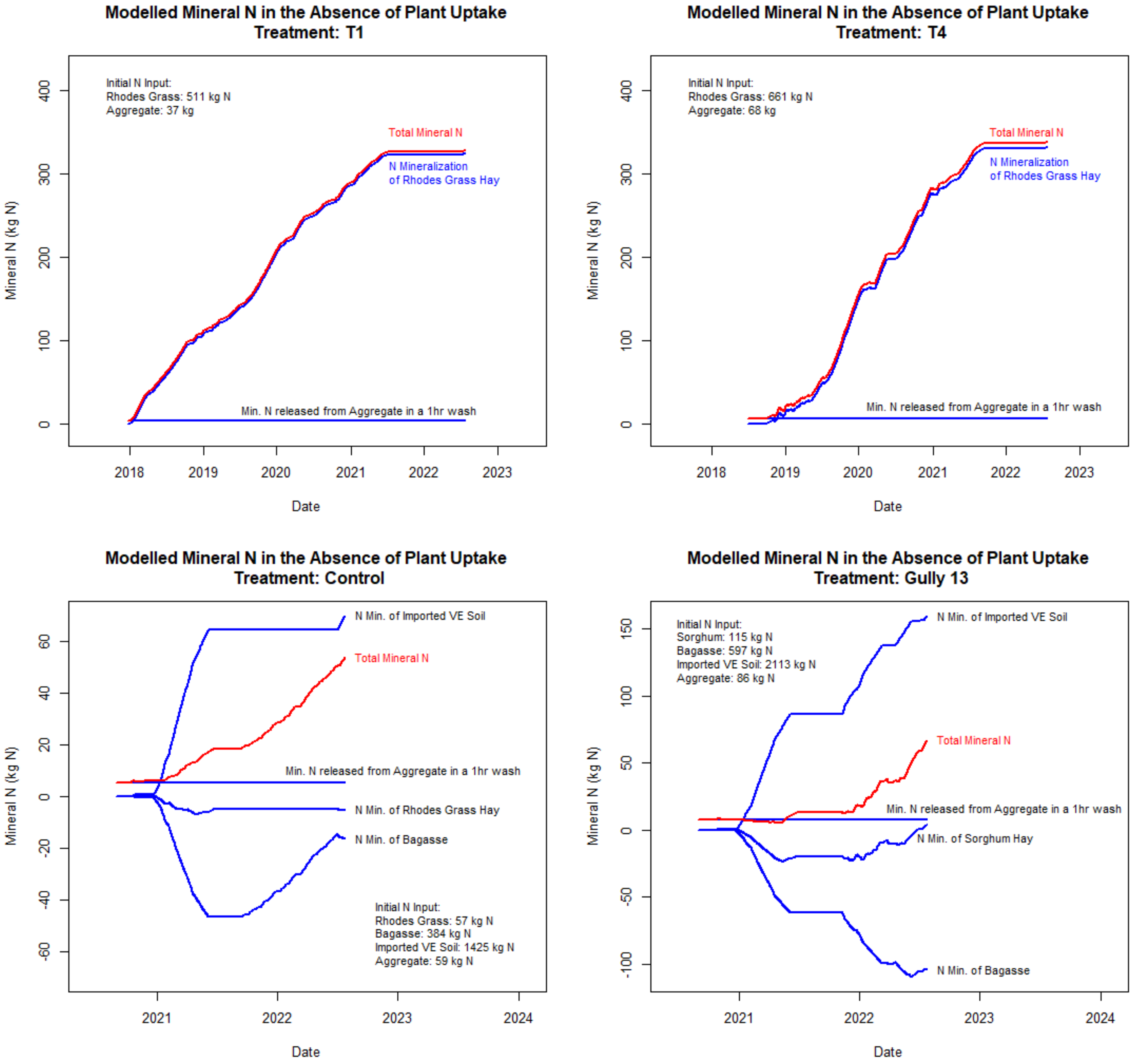


Figure 11. Plots of N mineralisation from the organic amendments predicted by APSIM modelling in each of the four gullies together with the estimated mineral N released from the rock aggregate using a 1-hour wash designed to simulate a rainfall event. APSIM default values of FBiom and FInert were used in the APSIM Modelling.

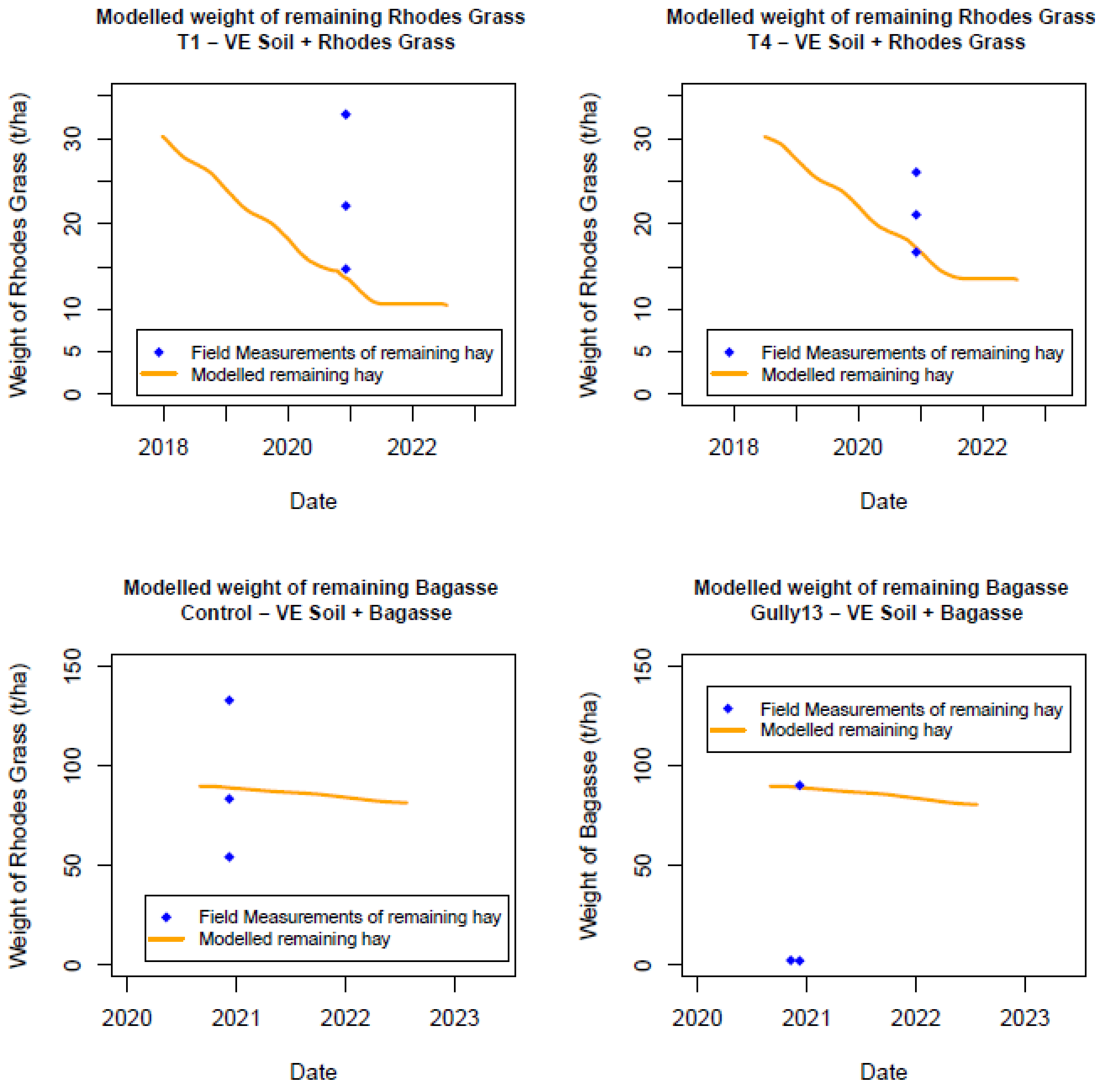


Figure 12. Comparison of the modelled weight of remaining bagasse/hay with that measured in the field (3 replicates) on the 7/12/2020.

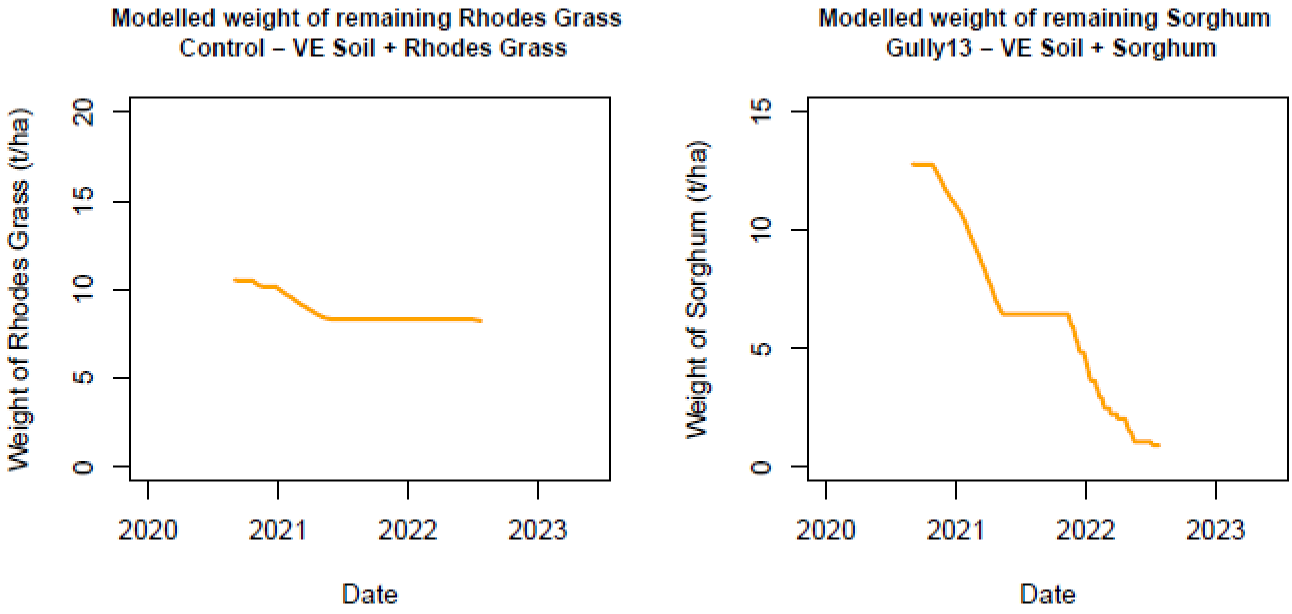


Figure 13. Modelled weight of remaining Rhodes grass or sorghum hay remaining in the field. There are no field measurements for comparison in this case.

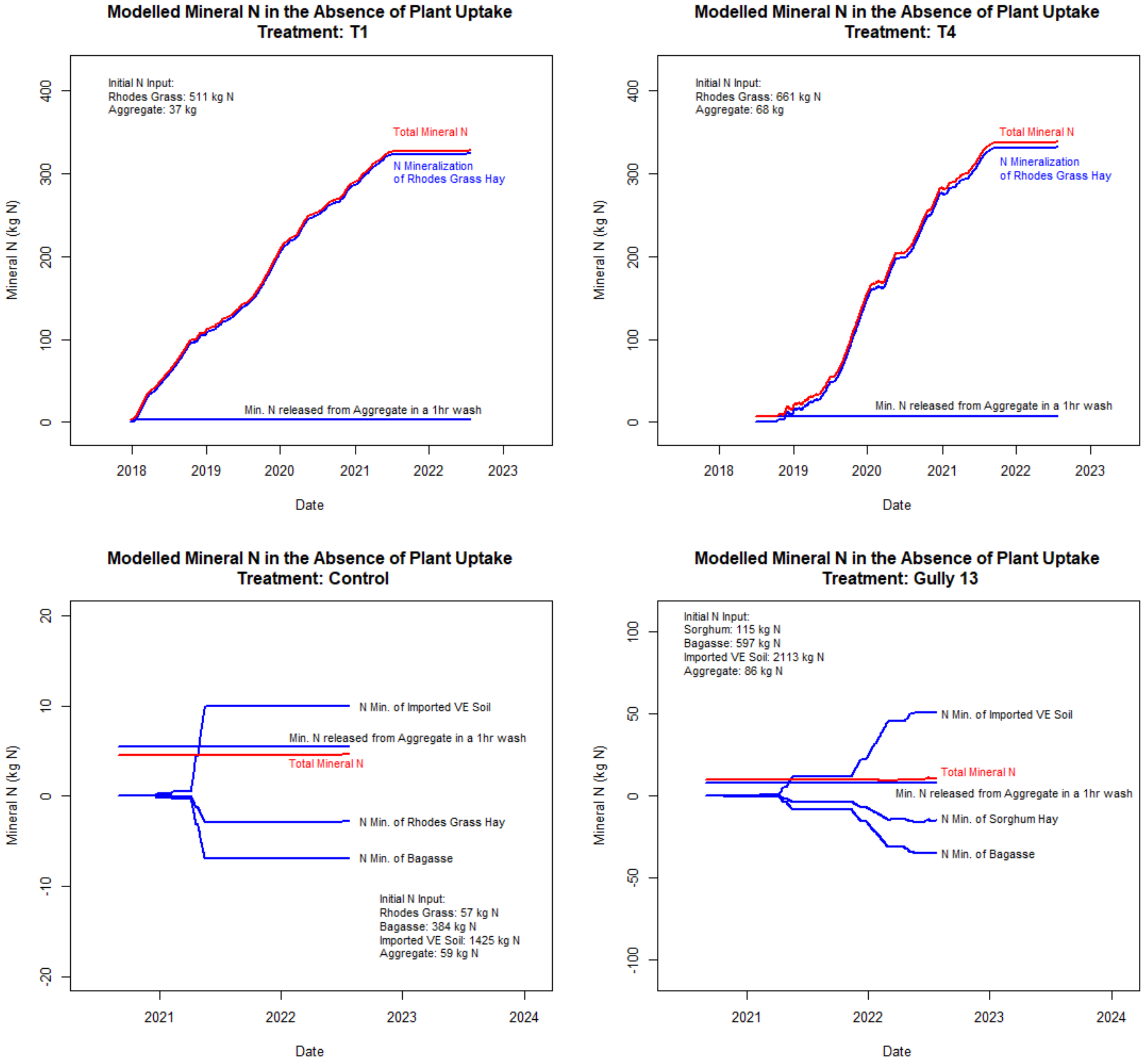


Figure 14. Plots of N mineralisation from the organic amendments predicted by APSIM modelling in each of the four gullies together with the estimated mineral N released from the rock aggregate using a 1-hour wash designed to simulate a rainfall event. The average of typical values of Fbiom and Finert, found in the 15-30 and 30-60 cm soil layers of a Vertosol (Dalgliesh et al., 2016), were used in the APSIM modelling of the Control and Gully 13. Default values of Fbiom and Finert were used in the modelling of T1 and T4.

Conclusions

The hay and bagasse added during remediation of the gullies would serve the following functions:

1. Protect the soil surface from rainfall impact and reduce soil aggregate breakdown.
2. Slow down runoff and reduce erosion.
3. Reduce evaporation from the soil surface, thereby conserving soil moisture and promoting growth of vegetation.
4. Introduce carbon and nutrients to support soil rehabilitation.

Thus, it is desirable to have materials that breakdown slowly and continue to provide these services.

Rhodes grass hay in T1 and T4, which had a low C/N ratio, decomposed rapidly, and started releasing mineral N from the start of the trial. This mineral N is available for offsite movement in runoff.

On the other hand, bagasse, Rhodes grass and sorghum hay used in the Control and Gully 13 treatments had high C/N ratios, decomposed slowly and immobilised mineral N during the course of the trial. These materials were able to take up N mineralised by the imported soil component added to the Control and Gully 13 gullies Those amendments, which immobilised N during the trial, will eventually swap to N mineralisation releasing organic N as inorganic N.

Thus, it is desirable to use organic amendments with a high C/N ratio to delay its breakdown and to delay the release of mineral N through N mineralisation so that vegetation has a chance to become established in the rehabilitated gully. This vegetation would as a sink for mineral N and reduce the amount of N that could potentially be available to leave the gullies in runoff.

Part 3 Event discharge and nutrient export from remediated gullies

Wet season monitoring

Wet season monitoring of the treated and control gullies involved collecting water quality samples for analysis of suspended sediments and various nutrient forms in runoff from the gully outlets and some catchment runoff samples above the gully head. Water quality samples were collected using a range of equipment including automated samplers (ISCO System), rising stage samplers (RSS), and pumped active suspended sediment (PASS) samplers. Details of the sampling equipment set-up can be found in Brookes et al. 2020.

Water quality sampling and analysis methods

Water quality samples from gully outlets were collected during the 2018/19 wet season (December - April) as part of a previous project (Queensland Water Modelling Network - Towards the standardisation of bioavailable particulate nitrogen in sediment methods) for a control (untreated) gully and two treated gullies (treatments 1 and 4, Figure 15) (Northern gullies) at Strathalbyn Station (Garzon-Garcia et al., 2019). During the wet seasons 2019/20 and 2020/21 water quality samples from gully outlets were again collected as part of another study from the same control and two treated gullies (treatments 1 and 4) (Figure 15) (Garzon-Garcia et al., 2021a). An additional gully (gully 13 -Southern gullies) was monitored during the 2019/20 and 2020/21 wet seasons (Figure 16). During the 2019/20 wet season gully 13 had not yet been remediated and data obtained for that wet season was used as an untreated control. Both control and gully 13 were remediated in June 2020, hence all monitored data obtained during the 2020/21 and 2021/22 wet seasons (this project) were used as treated gully data. Treatment construction dates and main characteristics of remediation actions can be observed in Table 1.

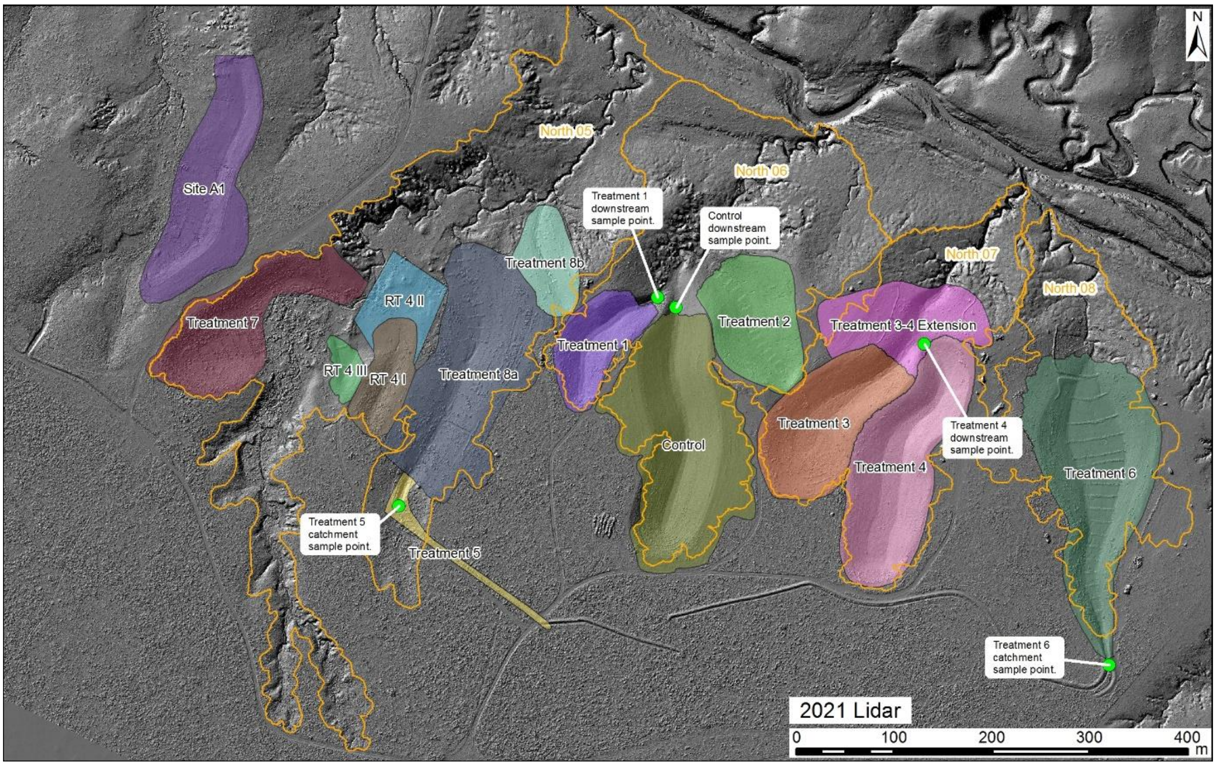


Figure 15 Northern gullies monitoring locations overlaid on 2021 imagery. Control gully (yellow) remained untreated for years 2018-2020.

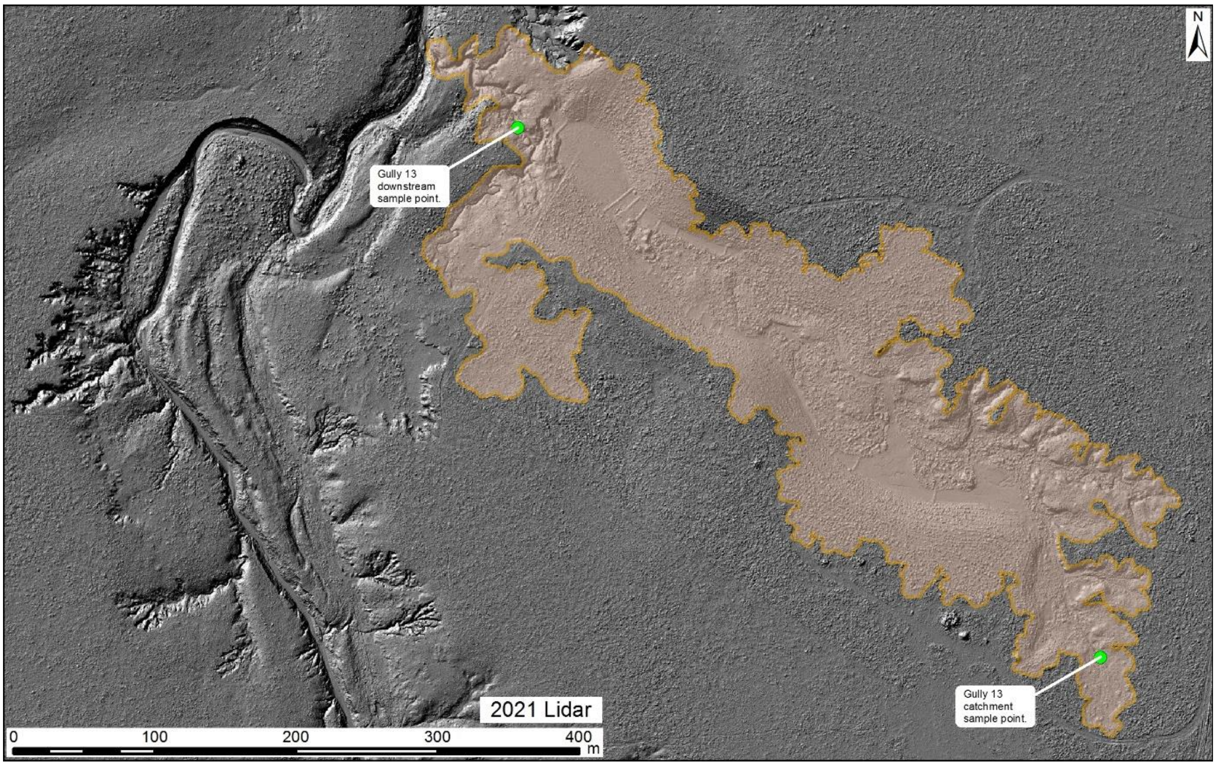


Figure 16 Gully 13 monitoring locations. This gully was an untreated control during 2019-2020, and a treated gully in 2021-2022 wet season.

The aim of the monitoring between 2018-2021 was to obtain water samples for three flow events from each gully during the wet season, with the best possible cover across the hydrograph (three samples: rising, peak and falling stages of the hydrograph) to analyse the more traditional water quality parameters and bioavailable nutrients (Table 7). However, a combination of infrequent runoff events, low water levels at sampling points, equipment failure, and backwater flooding issues, meant that actual number of samples collected was generally less than targeted. In the wet season 2021-2022, the intention was to better understand the behaviour and sources of nutrients during high-flow events and a greater number of samples across the hydrograph was targeted. This resulted in a larger number of samples collected across at least one flow event for the season. Although two further events occurred in the season, an unaccounted flow event on January 8 triggered the water quality samplers and these were not collected at that time. Samples were not collected until after the following event of January 27-28, which was not fully sampled due to sample bottles being occupied by sample left over from the previous event.

Samples were collected by Greening Australia using the selected methods for sampling water quality at each gully outlet site, which included:

- Control – automated (ISCO system) sampling, PASS sampling and rising stage sampler at 100, 200 and 300 mm,
- Treatment 1 – automated (ISCO system) sampling and rising stage sampler at 50,100 and 150 mm,
- Treatment 4 – automated (ISCO system) sampling, PASS sampling and rising stage sampler at 50, 100 and 150 mm,
- Gully 13 automated (ISCO system) sampling, PASS sampling and rising stage sampling at 150, 300 and 450 mm.

Some opportunistic samples were taken at overland PASS samplers labelled as ‘treatment 5’ (Figure 15) (what would have been the catchment contribution for the monitored northern gullies before remediation) and overland PASS sampler above the head of gully 13 (Figure 16). Refer to Brooks et al., 2020 for details regarding the monitoring equipment and techniques used to collect samples from the monitored gullies. The water quality parameters (Table 7) were analysed at the Department of Environment and Science (DES) Chemistry Centre laboratory.

Table 7. Nutrient pools analysed or calculated on water quality samples from gullies and their associated analytical methods. PMN1, PMN3 and PMN7 were not monitored in the wet season 2021-2022.

Element	**Nutrient pool**	**Method**
Carbon	Total organic carbon (TOC)	NDIR
	Dissolved organic carbon (DOC)	NDIR
	Particulate organic carbon (POC)	calculated (POC = TOC - DOC)
Nitrogen	Total Kjeldahl N (TKN)	Kjeldahl digest
	Dissolved Kjeldahl N (DKN)	Kjeldahl digest on filtered sample <0.45 μm
	Particulate organic N (PON)	calculated (PON = TKN - DKN - adsorbed NH4-N)
	Dissolved organic N (DON)	calculated (DON = DKN - NH_4^+-N)
	Dissolved inorganic N (DIN)*	calculated (DIN = NH_4^+-N + NO_x^-)
	Ammonium N (NH_4^+-N)*	Dissolved segmented flow analysis (<0.45 μm)
	N oxides (NO_x^--N)*	Dissolved segmented flow analysis (<0.45 μm)
	Extracted NH_4^+-N *See BAN methods (Appendix 1)	0.5M K2SO4 extract
	Adsorbed NH_4^+-N (Ads NH4-N) *See BAN methods (Appendix 1)	calculated (Ads NH_4^+-N = Extracted NH_4^+-N - NH_4^+-N)
	Potential mineralisable N at 1 days (PMN1) *See BAN methods (Appendix 1)	calculated (PMN1 = DIN at 1 days - DIN at 0 days)
	Potential mineralisable N at 3 days (PMN3) *See BAN methods (Appendix 1)	calculated (PMN3 = DIN at 3 days - DIN at 0 days)
	Potential mineralisable N at 7 days (PMN7) *See BAN methods (Appendix 1)	calculated (PMN7 = DIN at 7 days - DIN at 0 days)
Phosphorus (P)	Total Kjeldahl phosphorus (TKP)	Kjeldahl digest
	Particulate Kjeldahl phosphorus (PP)	calculated (PP = TKP - DKP)
	Dissolved Kjeldahl phosphorus (DKP)*	Kjeldahl digest on filtered sample <0.45 μm
	Phosphate phosphorus (PO_4^{-3}-P)	Dissolved segmented flow analysis (<0.45 μm)
	Dissolved organic P (DOP)	calculated (DOP = DKP - PO_4^{-3}-P)
	Colwell P	0.5M $NaHCO_3$ extractable P
	Phosphorus buffer index (PBI)	Total amount of P sorbed by sediment
Bioavailable nitrogen (BAN)	BAN in 1 day (BAN1)	Calculated (BAN1 = DIN at 0 day + adsorbed NH_4^+-N + PMN1)
	BAN in 3 day (BAN1)	Calculated (BAN3 = DIN at 0 day + adsorbed NH4-N + PMN3)
	BAN in 7 days (BAN7)	Calculated (BAN7 = DIN at 0 day + adsorbed NH4-N + PMN7)

*Filtered pool analysed during potential mineralisation experiment at 1, 3 and 7 days (see methods in Appendix 1)
** Analytical methods standard procedures(APHA/AWWA/WPCF, 2012)

Samples obtained from wet season monitoring

The data presented here represents the short-term effects (four wet seasons) of remediation techniques on water quality and should be understood as such. Longer-term monitoring (e.g., four to ten years) and load and yield calculations are required for the evaluation of the longer-term effects of gully remediation on water quality.

The number of samples collected by all sampling methods/equipment obtained for each gully/treatment across each high-flow event and wet season sampled can be observed in Table 8.

Although the initial aim for the 2018-2021 monitoring was to sample three events per gully and to cover those events by at least three samples (one at the rising stage, one at the peak and one at the drawdown), there was a very limited number of samples per event (sometimes only one) (Table 8) and in some cases there were no samples for all gullies for all events (e.g. Event 3 in wet season 2019-2020 was only sampled for Gully 13). When there was good coverage in a treatment, there may not have been a good coverage for controls. This is evidence of the difficulty of sampling these flashy runoff events in remote locations with limited equipment/resources and highly variable rainfall to generate flow events. The limited sampling did not allow for event-based comparisons to be made for the 2018/19 and 2019/20 wet seasons. During the 2020/21 wet season, two backwater events flooded the sampling equipment at the outlet of gully 13 and contaminated the samples, hence no samples were collected for that gully (Daley et al., 2021). Flow event water levels were not high enough to collect samples at the outlet of the control.

Because of these reasons, more resources were allocated to sample nutrients in the wet season 2021-2022 and at least one high-flow event was well covered for most treatments (Table 8). Although three events occurred in the season only one event on January 7 was comprehensively sampled for water quality. An unaccounted-for flow event on January 8 triggered the water quality samplers, though the samples were not collected at that time, exceeding sample holding periods for analysis. As sample bottles were occupied, the subsequent event of Jan 27 was not fully sampled.

After four wet seasons of monitoring gullies at Strathalbyn station we have identified the following challenges:

- Ephemeral and flashy flows following rainfall
- Sampling equipment deployed in remote field location for lengthy periods in anticipation of events – time between visits increases chances of unaddressed equipment failure at time of sampling.
- Relatively low water heights across gully cross-section and likely through-flow in crushed aggregate layer – addressed with installation of weirs at gully outflow points.
- Occurrence of backwater events which contaminate the samples.

Table 8 Monitoring nutrient samples obtained during the 2018-2019, 2019-2020, 2020-2021 and 2021-2022 wet seasons for each event and gully/treatment sampled at Strathalbyn Station. This includes all samples collected by autosamplers, rising stage samplers (RSS)

Wet season	**Event**	**Gully/Treatment**							**Event Name for hydrologic model**
		Control	**Gully 13**	**Gully 13 OFPASS***	**Treatment 1**	**Treatment 4**	**Treatment 5***	**Treatment 6***	
2018-2019	E1	1 sample 13/12/2018				13 samples 13/12/2018			***EV7_2018***
	E2					13 samples 16/12/2018			***EV7_2018***
	E3	3 samples 10/01/2019							***EV6_2019***
2019-2020	E1		1 sample 21/01/2020			4 samples 28/01/2020		1 sample 28/01/2020	***EV5_2020***
	E2	1 sample 05/02/2020	3 samples 05/02/2020						***EV5_2020***
	E3/3A	4 samples 24/02/2020	6 samples 23-24/02/2020		1 sample 24/02/2020	1 sample 24/02/2020	1 sample 24/02/2020	1 sample 24/02/2020	***EV4_2020***
2020-2021	E1			1 sample 07/01/2021	4 samples 07/01/2021	3 samples 07/01/2021			***EV3_2021***
2021-2022	E1	2 samples 07/01/2022	4 samples 07/01/2022		11 samples 07/01/2022	5 samples 07/01/2022	1 sample 07/01/2022		***EV2_2022***
	E2	2 samples 28/01/2022	3 samples 28/01/2022	1 sample 28/01/2022	6 samples 28/01/2022	10 samples 28/01/2022			***EV1_2022***

*Indicates catchment or overland flow sampling point.

Nutrient concentration trends following gully remediation

After a fourth consecutive wet season of monitoring at Strathalbyn, the following observations can be made (Figure 17):

- There are effective reductions in the concentrations of total and particulate carbon (>90%), particulate nitrogen (>90%) and particulate phosphorus (>90%) with gully remediation (see treatment concentrations compared to control and gully 13, which were treated before wet season 2020-2021) (from one to two orders of magnitude in some cases) (Figure 17a, b and c).
- The dissolved fraction concentrations tended to be significantly higher in the treated gullies than in the controls. There were significantly higher concentrations of DOC and DON (treatment 1 and 4 for the first 3 seasons after treatment) and DRP (treatment 4 for the first 3 seasons after treatment), but this was not observed for the control and gully 13 after treatment. There were significantly and consistently higher DIN concentrations for all treatments (including gully 13 and control after treatment) relative to controls for all the four sampled seasons [NOx-N (treatment 1, 4, control and gully 13), NH4-N (treatment 4)]. DIN increased by an order of magnitude or more (>10x) (Figure 17d, e, f, g, h and j).
- Adsorbed NH4-N (one of the particulate BAN pools) had significant reductions in the first three monitoring seasons (treatment 1 and treatment 4), but not in the fourth one nor for control and gully 13 after remediation (Figure 17k).
- For three seasons, the total bioavailable nitrogen (BAN) was higher in the treated gullies than in the controls. The BAN exported from the gully treatments increased by around an order of magnitude. This increase has been predominantly driven by the increase in DIN, which is why potential mineralisable N was not monitored in the 2021-2022 wet season. This indicates soil amendments are influencing exported

bioavailable nutrients from gully treatments, which was also verified with experimental work and modelling (see Parts 1 and 2 of this report) (Figure 17m, n). Higher concentrations in remediated gully outlets (average = 0.58 mg l^{-1}, SD=0.57) when compared to overland PASS samplers (0.02-0.23 mg l^{-1}, n=4) also indicate that at least an important part of the increase would be associated with amendments and not a shift in sediment source.

- The majority of carbon, nitrogen and phosphorus in the samples collected from the gully outlets were particulate before gullies were remediated. Whereas the majority then shifted to dissolved fractions after the gullies were remediated (except treatment 4 for phosphorus)
- The majority of dissolved nitrogen consists of DON before remediation and in first years after, then DIN becomes as large or larger.
- The majority of DIN is oxidised N (NOx-N) (except treatment 4 in 2020-2021 in which NH4-N was present in similar concentrations).
- Adsorbed NH4-N can be an important bioavailable nitrogen (BAN) fraction (can be larger than water soluble ammonium) before and after gullies are treated (Figure 17h and k).

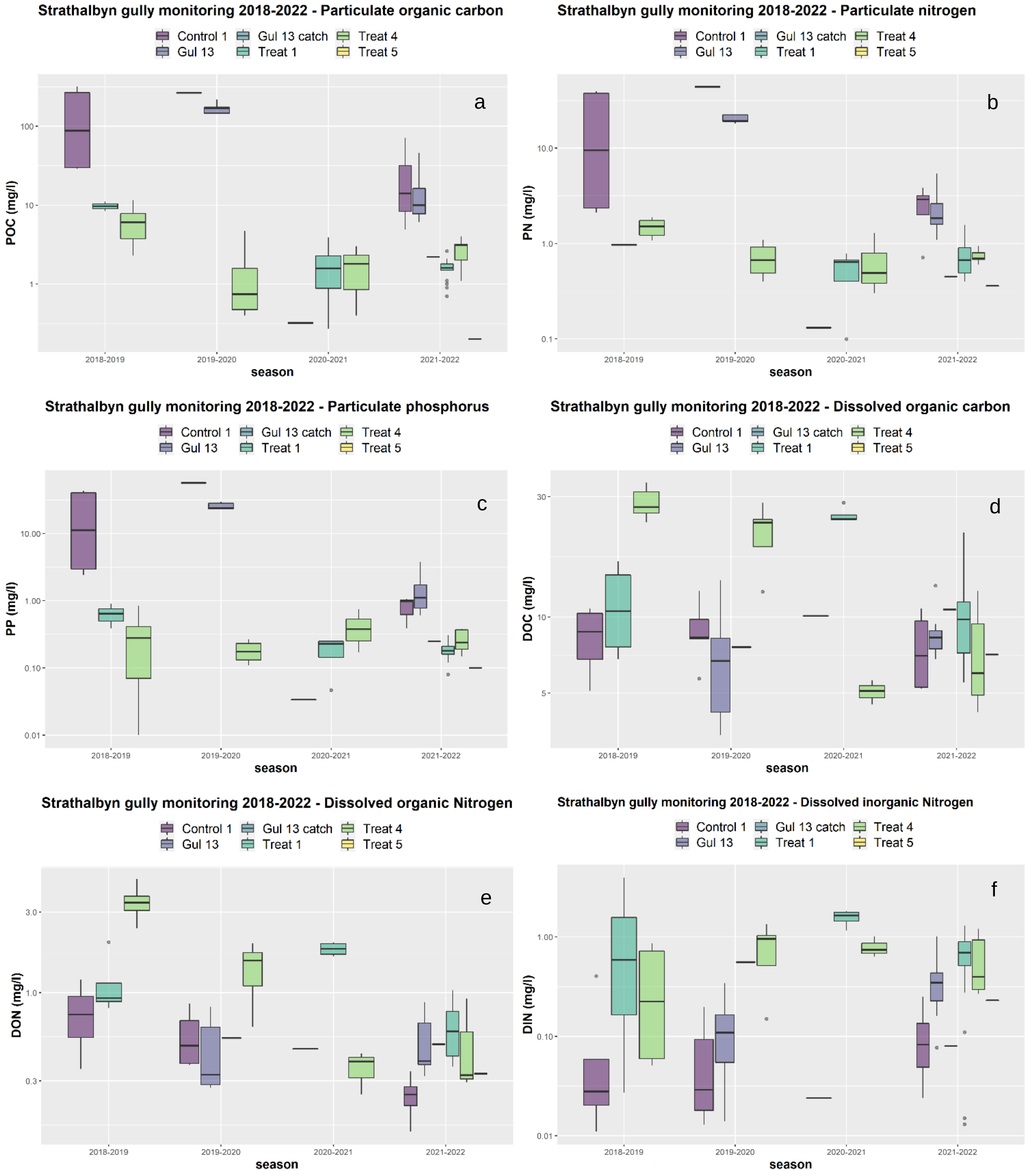


*Figure 17 Monitored particulate organic carbon (POC) (a), particulate nitrogen (PN) (b), particulate phosphorus (PP) (c), dissolved organic carbon (DOC) (d), dissolved organic nitrogen (DON) (e) and dissolved inorganic nitrogen (DIN) (f) concentrations in the outlet of controls (Control 1 and Gul 13 – only for the 2018/19 and 2019/20 wet seasons), remediated gullies (*Note Control 1 and Gul 13 were remediated in 2021) and their catchments (Gul 13 catch and treat 5) for high-flow events in the 2018/19, 2019/20, 2020/21 and 2021/22 wet seasons.*

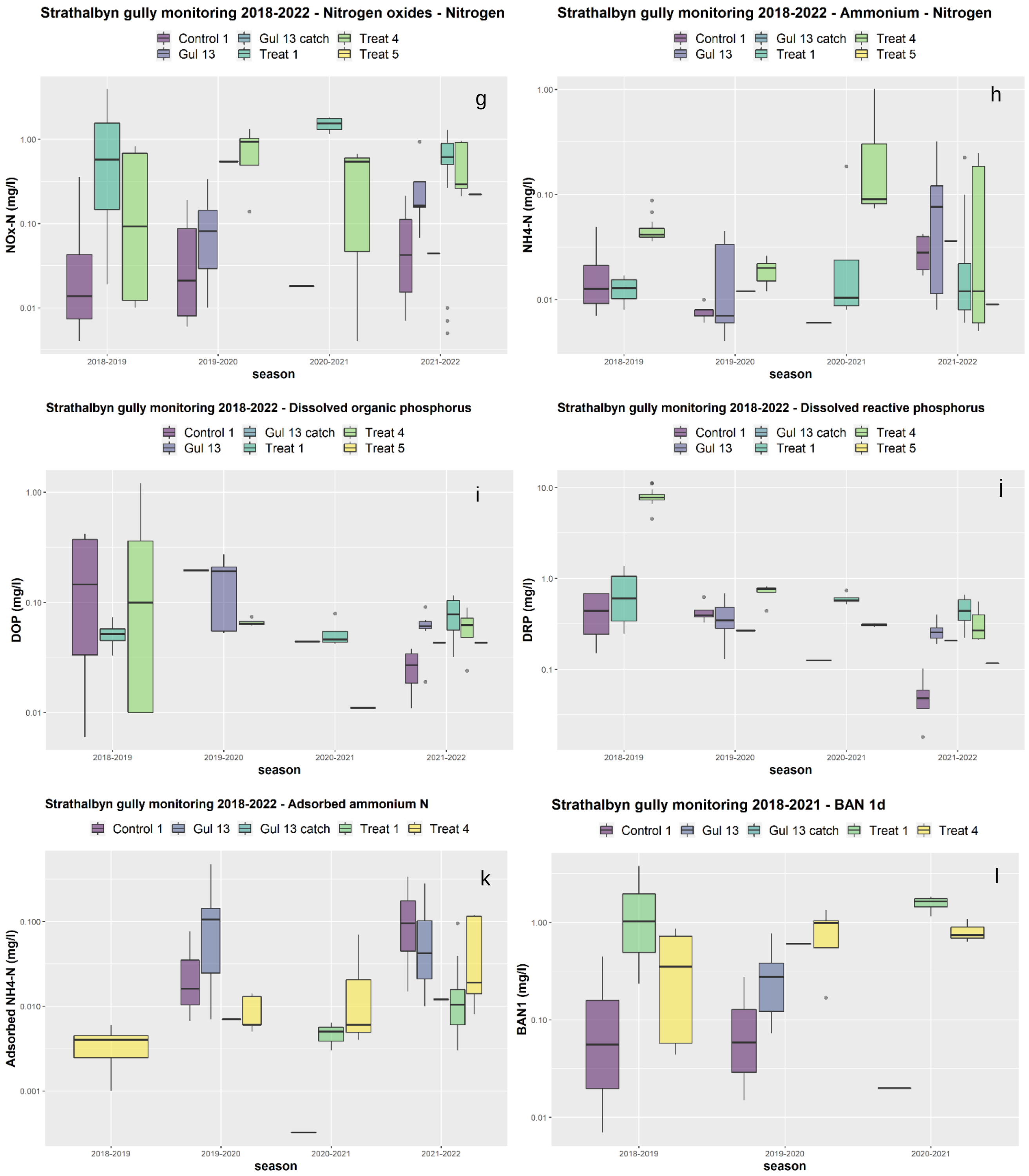


*Figure 15 (cont). Monitored nitrogen oxides nitrogen (NOx-N) (g), ammonium nitrogen (NH4-N) (h), dissolved organic phosphorus (DOP) (i), dissolved reactive phosphorus (DRP) (j), adsorbed ammonium nitrogen (Adsorbed NH4-N) (k) and bioavailable nitrogen in 1 day (BAN1) (l) concentrations in the outlet of controls (Control 1 and Gul 13 - 2018/19 and 2019/20 wet seasons), remediated gullies (*Note Control 1 and Gul 13 were remediated in 2021) and their catchments (Gul 13 catch and treat 5) for high-flow events in the 2018/19, 2019/20, 2020/21 and 2021/22 wet seasons.*

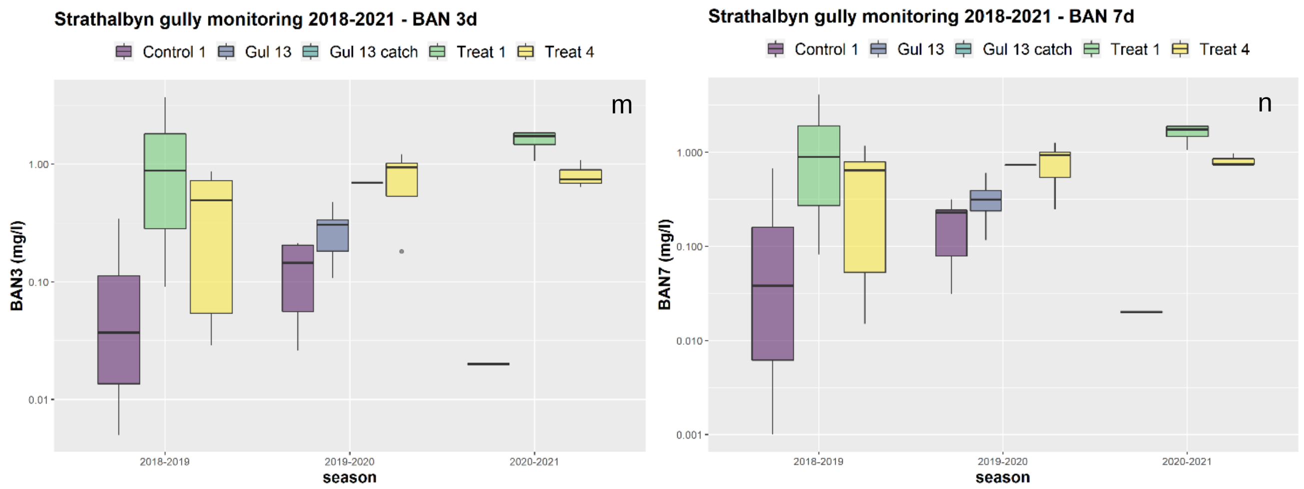


*Figure 15 (cont). Monitored bioavailable nitrogen in 3 days (BAN3) (m) and bioavailable nitrogen in 7 days (BAN7) (n) concentrations in the outlet of controls (Control 1 and Gul 13 - 2018/19 and 2019/20 wet seasons) remediated gullies (*Note Control 1 and Gul 13 were remediated in 2021) and their catchments (Gul 12 catch and treat 5) for high-flow events in the 2018/19, 2019/20, 2020/21 and 2021/22 wet seasons.*

Event based nutrient loads from remediated gullies

Event loads of suspended sediment and nutrients were calculated for each runoff event and gully where water quality sampling data allowed. The calculation of sediment and nutrient loads aligns with the project objective to understand the effects of gully remediation on nutrient export from gully systems.

Water quality samples

Water quality samples were collected from gullies during the wet seasons between 2018 and 2022 using a range of sampling methods: automated (ISCO system) samplers, RSS and PASS samplers. For use in calculation of loads, water quality samples need to be discrete in time and volume, meaning that only samples collected by the automated (ISCO system) sampling were appropriate to use for this purpose. RSS samples only sample on rising limb of events and do not have associated time of sample record (but may be possible to infer from stage height), and PASS samplers integrate samples over time or entire events, so are not suitable for load calculation purposes. Therefore, the total number of water quality samples available for load calculation is less than the total number listed in the previous section (Table 7).

Modelled gully discharge

Event discharges from each of the monitored gullies were estimated using Tuflow direct rainfall model output carried out as part of this project (Appendix 2) for each sampled rain event over the wet seasons between 2018 and 2022. Rainfall data used in the Tuflow model was available from an onsite rain gauge installed with discharge sampling equipment. Details of the Tuflow model are presented in Appendix 2. The Tuflow model output provided discharge (m^3/second) and stage height (m) for each gully outflow, allowing for load calculations to be completed using the modelled hydrographs.

Nutrient load calculation method

To calculate nutrient and suspended sediment loads for the sampled rainfall events, water quality samples from automated (ISCO system) samplers, and the modelled event hydrographs were used. To align water quality sample data with the modelled hydrographs, recorded sample times were adjusted so that the initial sample of each event occurred at the same time that the modelled stage height reached the nominal autosampler intake height. Modelled discharge was provided in 5-minute time intervals, and this interval was used for load calculations. The gullies are ephemeral systems, with flow only occurring following rainfall. Events began with the start of flow from the modelled hydrographs, and ended either when flow returned to zero, or at the lowest discharge rate before the beginning of the rising limb of the following event peak.

Nutrient and sediment loads for each event were calculated using R (4.0.5) and RStudio, with the ‘RiverLoad’ package version 1.03 (Nava et al., 2019). The Beale ratio estimator (Beale, 1962) method was used to calculate event loads for all events and gully treatments. The Beale ratio estimator method is generally the most robust method for small sample sizes and/or poor coverage of event hydrographs (Quilbé et al., 2006). For events where several water quality samples were collected across the hydrograph (collected over rising, peak and falling limbs of hydrograph), loads were also calculated using the linear interpolation method (RiverLoad package ‘method6’). This was to provide comparison to the Beale ratio method. Event Mean Concentrations (EMC) were calculated from load results as a way of comparing results for each event while taking account of differences in discharge volume. EMC was calculated by dividing the calculated load by total event discharge volume.

Event based nutrient loads from gullies

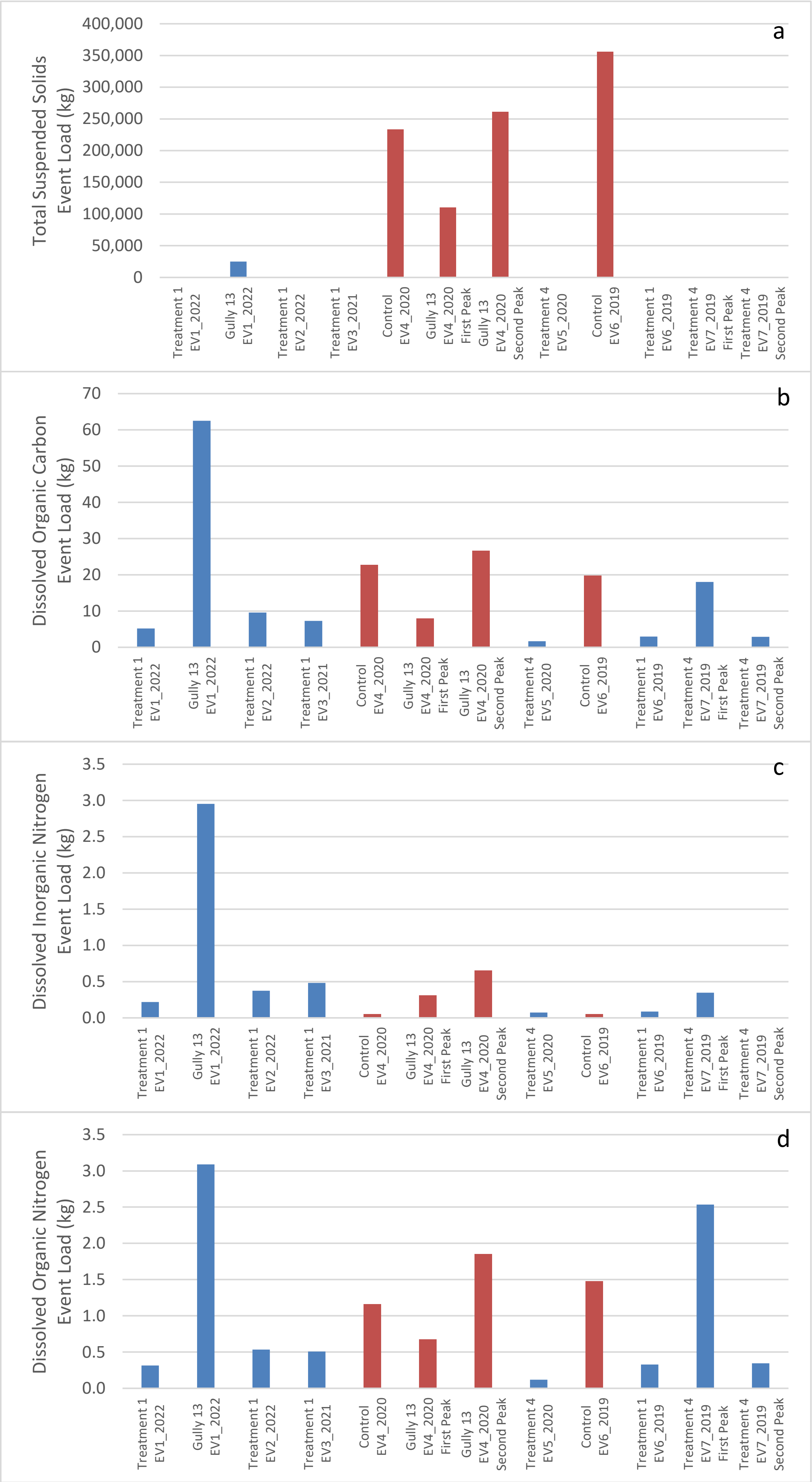
Across the four wet seasons of water quality sampling, event loads for a total of 12 events could be calculated for a range of parameters from the available data (Table 9, Figure 18, Figure 19). This includes 4 events from untreated gullies as ‘controls’ and 8 events from treated gullies, including one event in 2022 from Gully 13 post-treatment (previously a ‘control’ site). For the 2019-2020 wet season total nutrients were not analysed on water quality samples collected by the autosamplers, thus limiting the results for total and particulate nutrients available for load calculation purposes for this wet season.

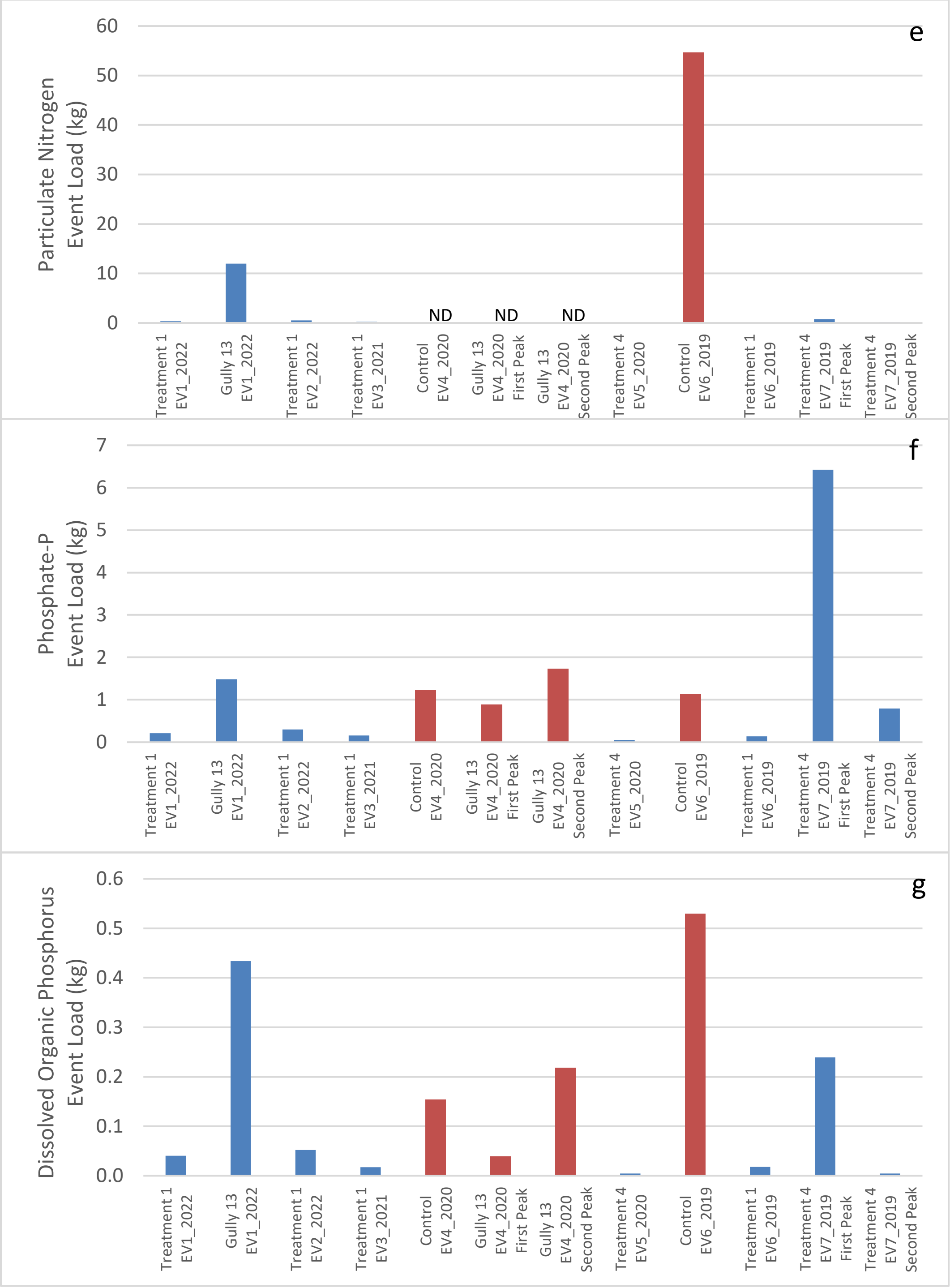
Untreated ‘control’ gullies had consistently higher load and EMC of TSS (Figure 18a, Figure 19a) and particulate nutrients (Figure 18e, 16h, Figure 19e, Figure 19h) compared to the treated gully events. EMC of TSS for the treated gully events was more than 10 times lower than the untreated ‘control’ gully event, and both particulate N and P had more than 15 times greater concentration in the untreated event than events from treated gullies.

DIN load results were influenced by event discharge volumes, with no clear difference between event loads of treated and untreated control gullies (Figure 18c). However, EMC showed that concentration of DIN was generally greater in treated gullies compared to untreated gullies (Figure 19c). Seven of the eight treated gully events had DIN EMC (0.239-1.714 mg/L) 2-10 times greater than the highest DIN EMC of an untreated gully (0.133 mg/L, Figure 19c). Dissolved organic nutrients (DOC, DON and DOP) behaved similarly to DIN, with no evident differences in load (Figure 18b, d, g), but EMC from treated gully events tending to be higher than for the untreated ‘control’ gully events (Figure 19b, d, g). DRP event loads or EMC did not show a difference between treated and untreated gullies, with results to date showing no significant impact of gully treatment to DRP discharge (Figure 18f, Figure 19f). Only one event of an untreated control gully had load and EMC calculated for particulate nitrogen and phosphorus, though this result shows a substantial difference to all treated gully results. Both the load and EMC of particulate nitrogen and phosphorus were an order of magnitude greater for the untreated control gully than any of the treated gully events (Figure 18e, h and Figure 19e, h).

Table 9 Event load and event mean concentration (EMC) for sediment (TSS) and nutrient parameters calculated for each event of Table 7. Shaded rows indicate events of untreated 'control' gullies.

Event (see Table 7)	Gully	Treatment	Event Start	Event End	Number of Samples	Event Volume (m^3)	Load Calculation Method	Event Load (kg)								Event Mean Concentration (mg/L)							
								TSS	**DOC**	**DIN**	**DON**	**PN**	**DRP**	**DOP**	**PP**	**TSS**	**DOC**	**DIN**	**DON**	**PN**	**DRP**	**DOP**	**PP**
EV1_2022	Treatment 1	Treated	07/01/22 18:00	08/01/22 14:50	8	548	Beale Ratio	57	5.20	0.22	0.32	0.36	0.21	0.04	0.10	104	9.49	0.40	0.58	0.65	0.39	0.07	0.17
							Linear Interpolation	59	5.75	0.37	0.39	0.39	0.27	0.04	0.11	107	10.48	0.67	0.71	0.71	0.49	0.08	0.21
EV1_2022	Gully 13	Treated	07/01/22 18:30	08/01/22 14:40	2 (TSS=4)	7140	Beale Ratio	25,013	62.51	2.95	3.09	12.00	1.48	0.43	7.52	3,503	8.76	0.41	0.43	1.68	0.21	1.32	1.05
EV2_2022	Treatment 1	Treated	27/01/22 0:00	28/01/22 9:00	3	856	Beale Ratio	83	9.60	0.38	0.53	0.51	0.30	0.05	0.17	97	11.22	0.44	0.62	0.59	0.35	0.06	0.19
EV3_2021	Treatment 1	Treated	05/01/21 21:10	07/01/21 2:55	3	282	Beale Ratio	**ND**	7.30	0.48	0.51	0.20	0.15	0.02	0.07	**ND**	25.92	1.71	1.80	0.71	0.55	0.06	0.25
EV4_2020	Control	Untreated	24/02/20 13:40	25/02/20 23:55	3	2840	Beale Ratio	233,214	22.79	0.05	1.16	**ND**	1.22	0.15	**ND**	82,128	8.03	0.02	0.41	**ND**	0.43	0.05	**ND**
EV4_2020 First Peak	Gully 13	Untreated	23/02/20 1:30	24/02/20 13:50	2	2339	Beale Ratio	110,179	7.93	0.31	0.68	**ND**	0.89	0.04	**ND**	47,108	3.39	0.13	0.29	**ND**	0.38	0.02	**ND**
EV4_2020 Second Peak	Gully 13	Untreated	24/02/20 13:50	24/02/20 22:50	3	60701	Beale Ratio	261,076	26.66	0.65	1.85	**ND**	1.73	0.22	**ND**	43,004	4.39	0.11	0.31	**ND**	0.28	0.04	**ND**
EV5_2020	Treatment 4	Treated	28/01/20 0:00	28/01/20 4:10	3	67.8	Beale Ratio	**ND**	1.70	0.08	0.12	0.04	0.05	0.01	0.01	**ND**	25.11	1.11	1.75	0.61	0.75	0.07	0.16
EV6_2019	Control	Untreated	10/01/19 7:55	12/01/19 0:00	3	2077	Beale Ratio	355,521	19.77	0.05	1.48	54.62	1.13	0.53	63.32	171,191	9.52	0.03	0.71	26.30	0.54	0.26	30.49
EV6_2019	Treatment 1	Treated	10/01/19 7:40	12/01/19 5:00	3	360	Beale Ratio	507	2.93	0.09	0.33	0.05	0.14	0.02	0.29	1,408	8.14	0.24	0.91	0.14	0.38	0.05	0.81
EV7_2019 First Peak	Treatment 4	Treated	13/12/18 17:30	14/12/18 0:00	13	627	Beale Ratio	321	18.02	0.35	2.54	0.77	6.42	0.24	0.05	513	28.74	0.55	4.04	1.22	10.24	0.38	0.08
							Linear Interpolation	321	18.98	0.35	2.72	0.76	6.66	0.27	0.04	512	30.27	0.55	4.34	1.22	10.63	0.43	0.06
EV7_2019 Second Peak	Treatment 4	Treated	16/12/18 9:05	16/12/18 23:35	13	100	Beale Ratio	105	2.89	0.01	0.35	0.17	0.79	0.01	0.16	1,047	28.87	0.06	3.47	1.70	7.90	0.05	1.56
							Linear Interpolation	103	2.87	0.01	0.35	0.16	0.77	0.01	0.14	1,031	28.67	0.06	3.45	1.63	7.65	0.09	1.42


a
Total Suspended Solids Event Load (kg)
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Treatment 1 EV1_2022
Gully 13 EV1_2022
Treatment 1 EV2_2022
Treatment 1 EV3_2021
Control EV4_2020
Gully 13 EV4_2020 First Peak
Gully 13 EV4_2020 Second Peak
Treatment 4 EV5_2020
Control EV6_2019
Treatment 1 EV6_2019
Treatment 4 EV7_2019 First Peak
Treatment 4 EV7_2019 Second Peak
b
Dissolved Organic Carbon Event Load (kg)
70
60
50
40
30
20
10
0
c
Dissolved Inorganic Nitrogen Event Load (kg)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
d
Dissolved Organic Nitrogen Event Load (kg)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0


e
Particulate Nitrogen Event Load (kg)
0
10
20
30
40
50
60
ND
ND
ND
f
Phosphate-P Event Load (kg)
0
1
2
3
4
5
6
7
g
Dissolved Organic Phosphorus Event Load (kg)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Treatment 1 EV1_2022
Gully 13 EV1_2022
Treatment 1 EV2_2022
Treatment 1 EV3_2021
Control EV4_2020
Gully 13 EV4_2020 First Peak
Gully 13 EV4_2020 Second Peak
Treatment 4 EV5_2020
Control EV6_2019
Treatment 1 EV6_2019
Treatment 4 EV7_2019 First Peak
Treatment 4 EV7_2019 Second Peak

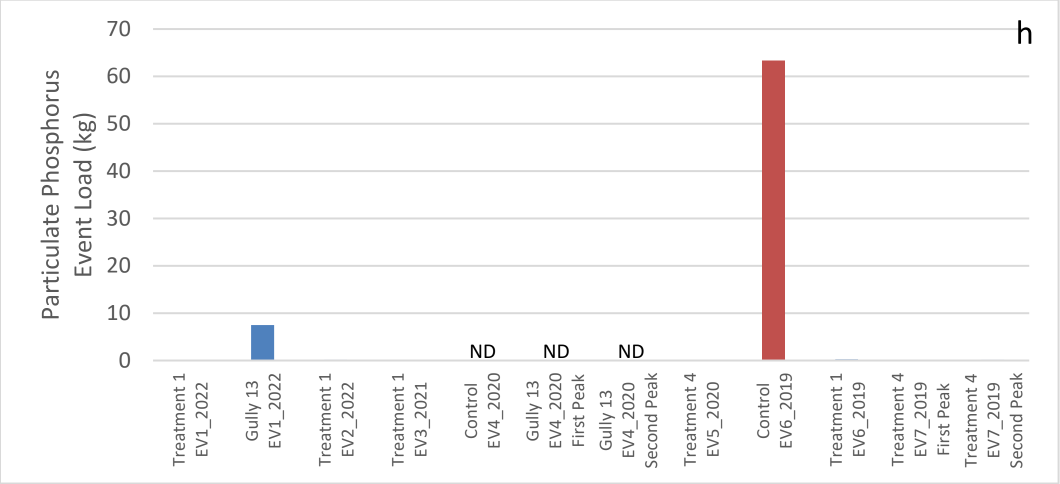
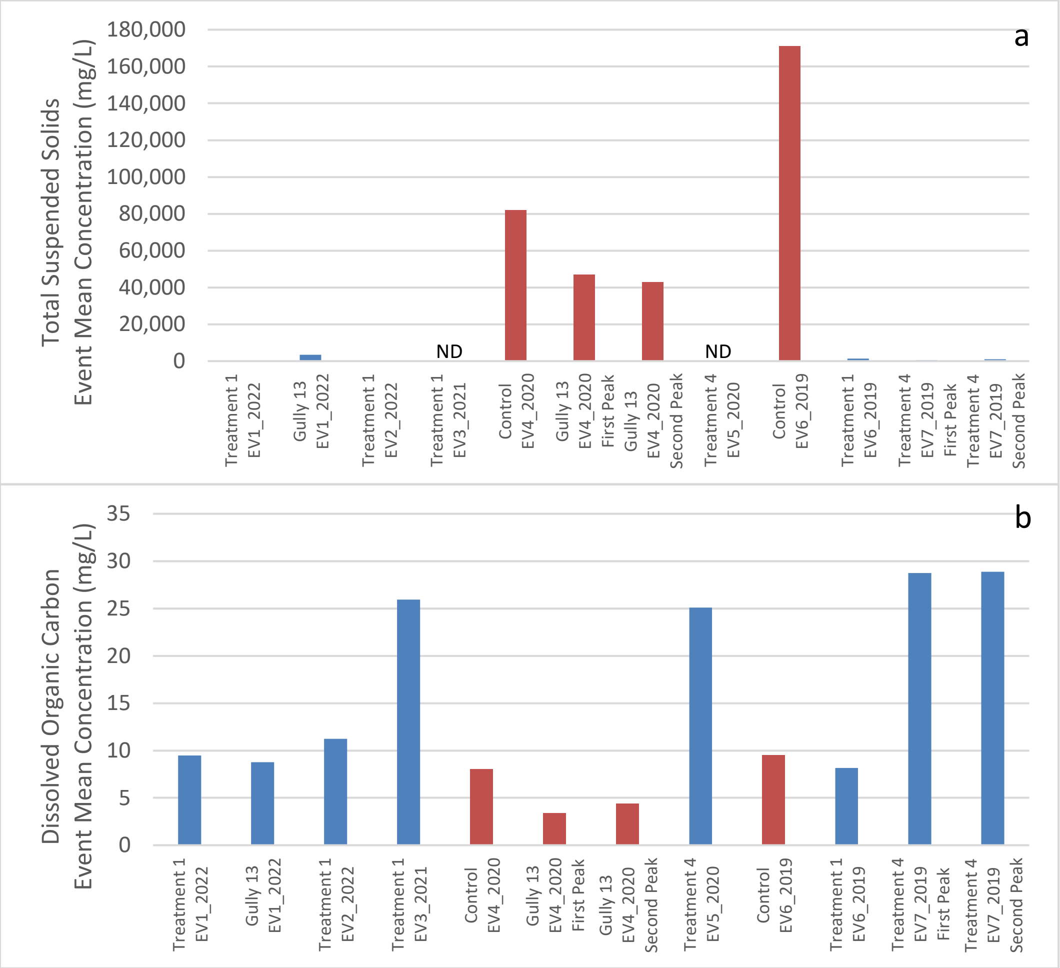
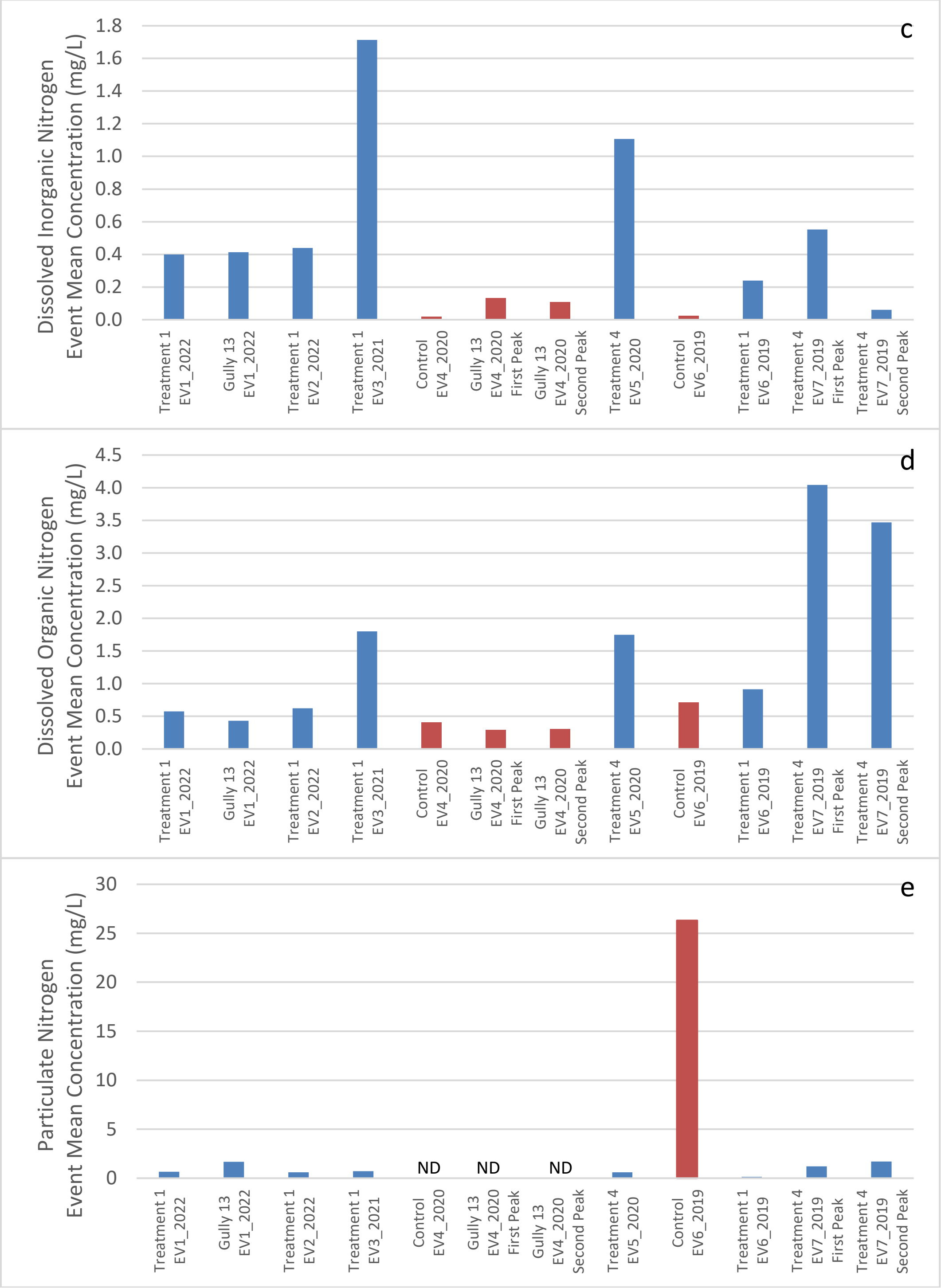


Figure 18 Event loads (kg) for sediment and nutrient parameters, a) TSS, b) DOC, c) DIN, d) DON, e) PN, f) Phosphate-P, g) DOP, h) PP. Red columns represent untreated 'control' gully events, blue columns represent treated gully events. ND- no data.




c
Dissolved Inorganic Nitrogen
Event Mean Concentration (mg/L)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Treatment 1 EV1_2022
Gully 13 EV1_2022
Treatment 1 EV2_2022
Treatment 1 EV3_2021
Control EV4_2020
Gully 13 EV4_2020 First Peak
Gully 13 EV4_2020 Second Peak
Treatment 4 EV5_2020
Control EV6_2019
Treatment 1 EV6_2019
Treatment 4 EV7_2019 First Peak
Treatment 4 EV7_2019 Second Peak
d
Dissolved Organic Nitrogen
Event Mean Concentration (mg/L)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Treatment 1 EV1_2022
Gully 13 EV1_2022
Treatment 1 EV2_2022
Treatment 1 EV3_2021
Control EV4_2020
Gully 13 EV4_2020 First Peak
Gully 13 EV4_2020 Second Peak
Treatment 4 EV5_2020
Control EV6_2019
Treatment 1 EV6_2019
Treatment 4 EV7_2019 First Peak
Treatment 4 EV7_2019 Second Peak
e
Particulate Nitrogen
Event Mean Concentration (mg/L)
30
25
20
15
10
5
0
ND
ND
ND
Treatment 1 EV1_2022
Gully 13 EV1_2022
Treatment 1 EV2_2022
Treatment 1 EV3_2021
Control EV4_2020
Gully 13 EV4_2020 First Peak
Gully 13 EV4_2020 Second Peak
Treatment 4 EV5_2020
Control EV6_2019
Treatment 1 EV6_2019
Treatment 4 EV7_2019 First Peak
Treatment 4 EV7_2019 Second Peak

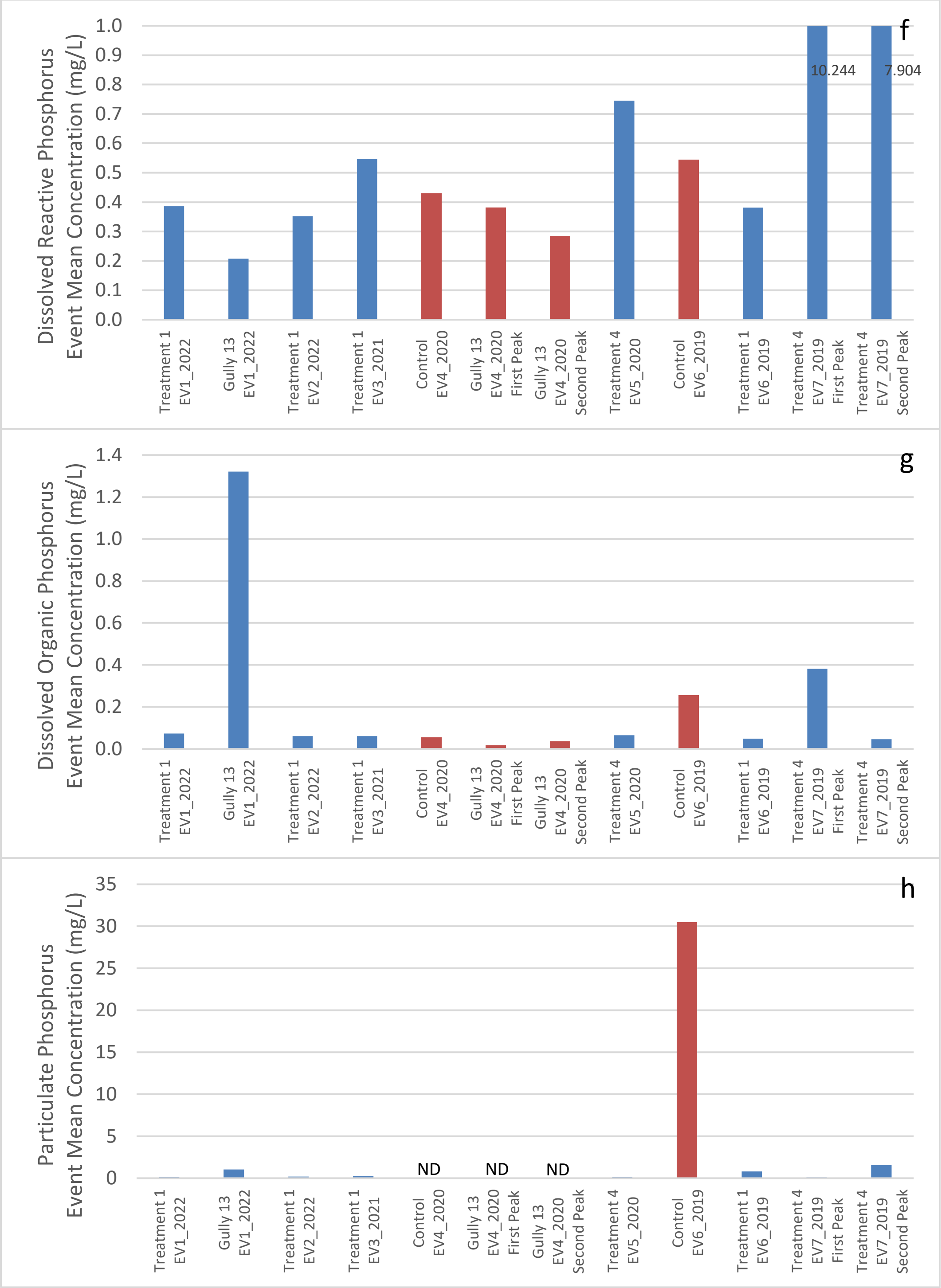


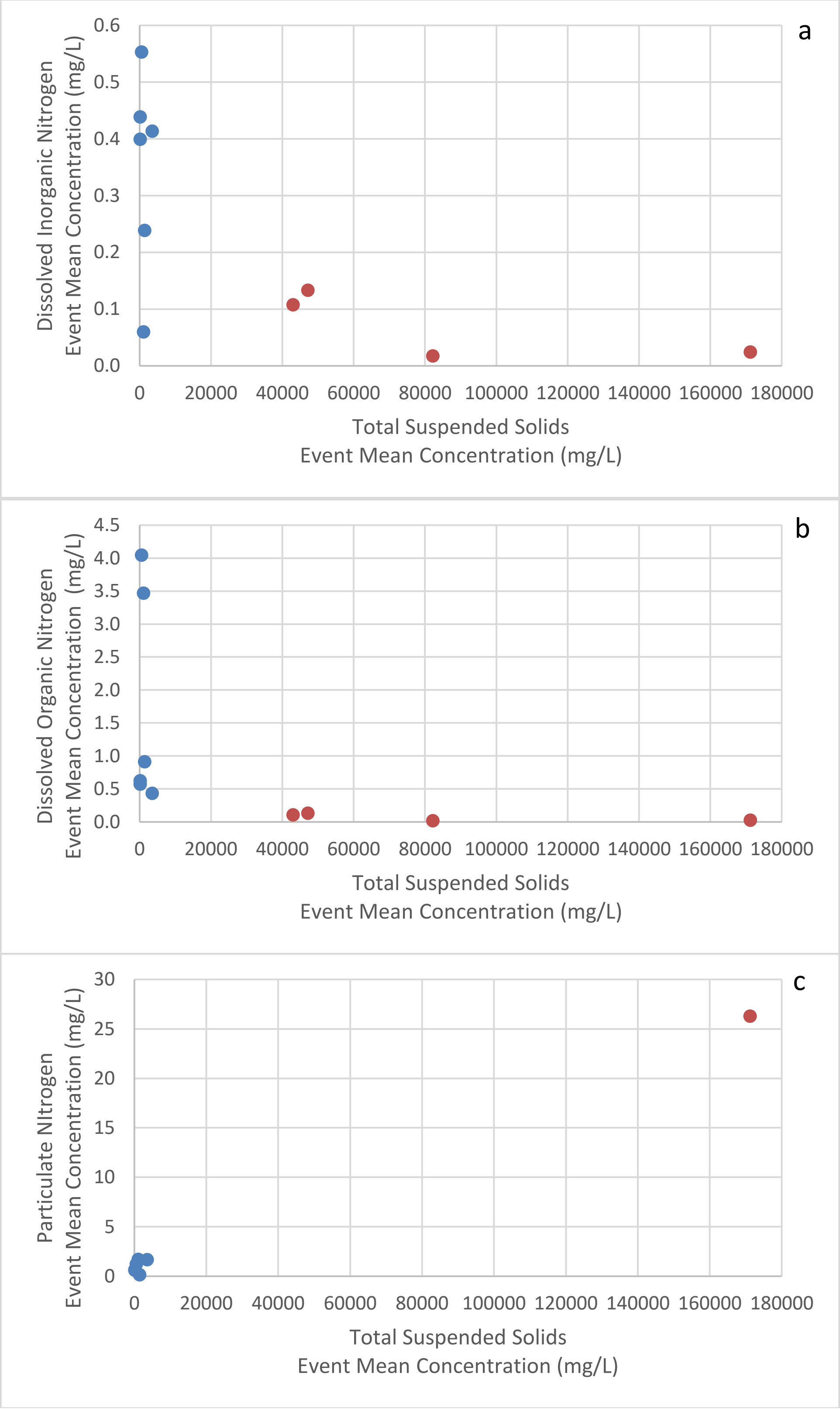
Figure 19 Event mean concentration (mg/L) for sediment and nutrient parameters, a) TSS, b) DOC, c) DIN, d) DON, e) PN, f) Phosphate-P, g) DOP, h) PP. Red columns represent untreated 'control' gully events, blue columns represent treated gully events. ND- no data.

Relationships between event mean concentration of total suspended solids and nutrient parameters

Calculated EMC values for nutrient parameters and TSS were plotted to investigate potential relationships between sediment and nutrient exports under treated and untreated ‘control’ gully conditions (Figure 20). The plots indicate negative correlations between inorganic and dissolved forms of nitrogen and phosphorus with TSS. TSS EMC for treated gullies were low through all measured events compared to untreated gullies. Untreated ‘control’ gullies had TSS EMC values between 40,000 and 170,000mg/L, while values for treated gullies were at least ten times lower with values less than 4,000mg/L. However, treated gullies generally had higher EMC of all dissolved forms of nutrients, producing the apparent negative correlations (Figure 20a, b, d, e).

EMCs of particulate nitrogen and phosphorus were only available to be calculated for one event from an untreated ‘control’ gully. The single untreated ‘control’ gully event had EMCs for particulate nitrogen of 26mg/L (Figure 20c) and particulate phosphorus of 30mg/L (Figure 20f). This is many times greater than treated gully events which had maximum EMCs of particulate N of 1.7mg/L and particulate P of 1.6mg/L.

The apparent negative correlation between dissolved nutrients and total suspended solids indicate that treated gullies may increase their export of dissolved nutrient forms following treatment. Although there is limited data (only 1 EMC) for untreated ‘control’ gully events, the decrease in particulate nutrient EMC for treated compared to the untreated gully event, appears to be much greater than the apparent increase in dissolved nutrients. The overall change in particulate versus dissolved nutrient exports, and the influence on bioavailable nutrient export, are explored further in the following section.


a
Dissolved Inorganic Nitrogen
Event Mean Concentration (mg/L)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20000
40000
60000
80000
100000
120000
140000
160000
180000
Total Suspended Solids
Event Mean Concentration (mg/L)
b
Dissolved Organic Nitrogen
Event Mean Concentration (mg/L)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20000
40000
60000
80000
100000
120000
140000
160000
180000
Total Suspended Solids
Event Mean Concentration (mg/L)
c
Particulate NItrogen
Event Mean Concentration (mg/L)
30
25
20
15
10
5
0
0
20000
40000
60000
80000
100000
120000
140000
160000
180000
Total Suspended Solids
Event Mean Concentration (mg/L)

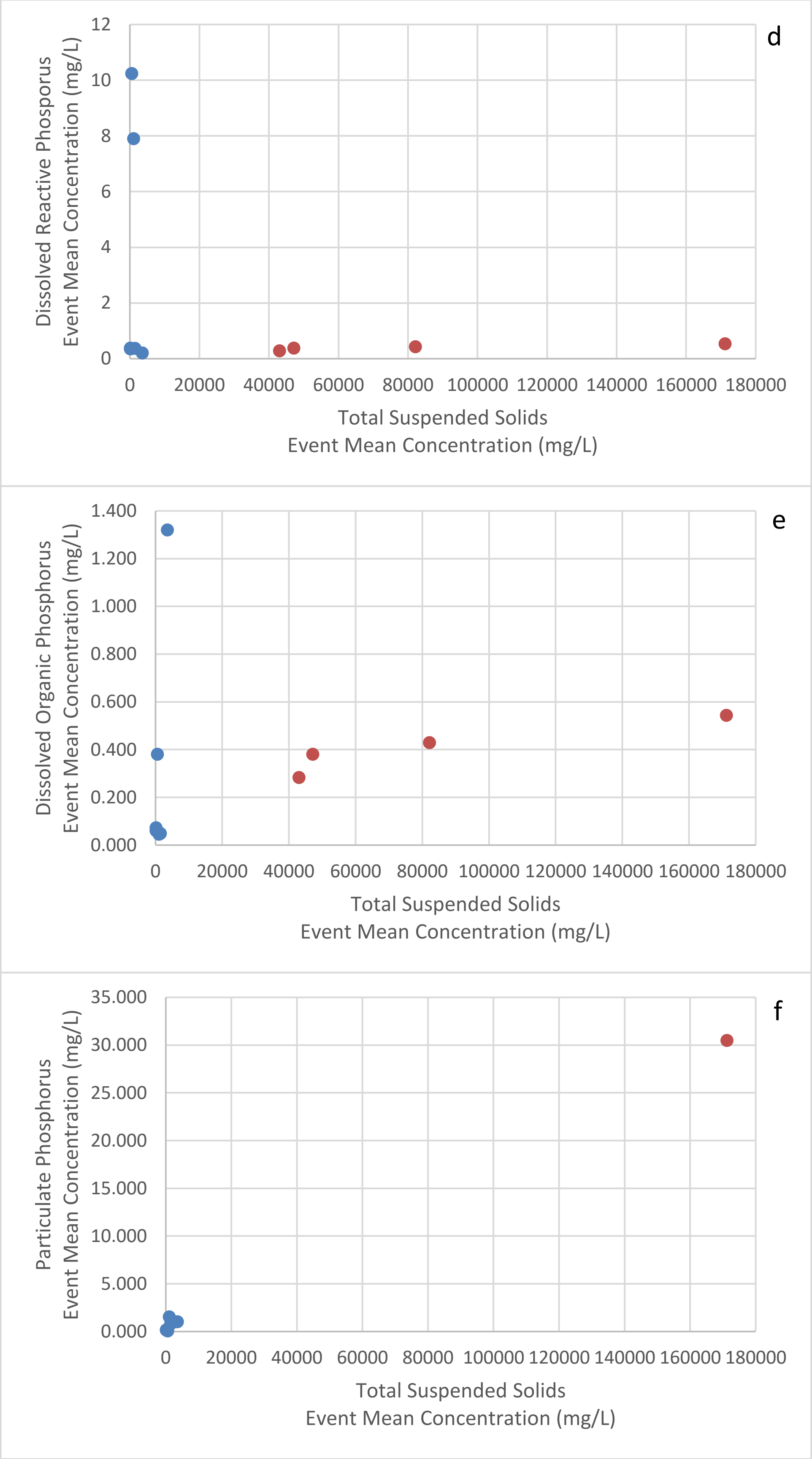


Figure 20 Plots of Event Mean Concentration (mg/L) of total suspended solids and a) DIN, b) DON, c) PN, d) DRP, e) DOP, and f) PP. Red points represent untreated 'control' gully events, blue points represent treated gully events.

Relative changes in exported bioavailable nutrient loads from gullies after remediation

To better understand the links between exported sediment and nutrient fractions from gullies before and after remediation linear regressions were carried out between various N fractions (PN, DIN and DON) and TSS concentrations in discrete water samples. Good relationships between TSS and PN would imply that PN is associated with suspended sediments and derive from the same sources (similar N content). Good relationships for DIN and DON would imply the source of these fractions is associated with sediment erosion with little influence from other sources like leaching and/or subsurface flows. A practical benefit of obtaining good relationships is that it could be possible to predict nutrient export from TSS monitoring, reducing monitoring costs.

Good linear relationships were found between PN and TSS for both control and treated gullies, though the relationships differed between the control and treated gullies, and also between different treatments, indicating a different PN content in the sediment and hence different sediment sources within each gully. Controls had an average PN content in runoff sediment of 0.03%, which matches the average subsurface soil TN content at Strathalbyn Station (Table 11) (Garzon-Garcia et al., 2021a) (Figure 21a), indicating the main sediment source before remediation was subsurface soil. After remediation, the PN content of runoff sediment tended to increase but was significantly higher for older treatments (T1 and T4) averaging 0.7% and 0.1%, respectively (Figure 21b). The high 0.7% value likely indicates the presence of hay mulch in the sediment runoff as there are no other sources with higher N content. These higher values also indicate a mix of sources likely including surface soils (Table 10) and the introduced topsoil in addition to hay mulch. Recently remediated gullies Control and Gully 13 had a minor increase relative to controls matching the content of the introduced topsoil of 0.05% (see section on nutrient characteristics of amendments sampled during trial).

Relationships were not so good between DIN and DON, and TSS (Figure 22, Figure 23). Relationships were better for controls though they differed between the different controls and were much better for Gully 13, which has a high content of DIN in subsoil (Garzon-Garcia et al., 2021a) (Figure 22a). Treated gullies had lower DIN and DON with higher TSS, similar to EMCs, indicating a trend for dilution or exhaustion of DIN and DON with higher flows (Figure 22b, Figure 23b).

Using the average EMCs presented in the previous sections for controls and treatments over the monitoring period (2018-2022) (Table 9), it is estimated that PN reductions with gully remediation were 95% on average with a corresponding average reduction of 18.6 mg/L of the estimated EMC (11-33 mg/L 95%CI). On the other hand, DIN increase following gully remediation was close to an order of magnitude (10x) with an average increase of 0.54 mg/L of the estimated EMC (-0.6-1.7 mg/L 95%CI). Initially, it can be observed that reductions in PN would more than compensate for increases in DIN after remediation (34 times more) if accounting for a TN budget. But it is important to consider that PN is not immediately or fully bioavailable as DIN, and that PN bioavailability depends on factors like the characteristics of the source (e.g., lability to organic mineralisation) and timeframe for bioavailability. Net changes in BAN export would better account for the effect of gully remediation on runoff water quality and environmental response. Hence to be able to directly compare the effect of remediation on exported bioavailable nutrient loads after remediation, the PN bioavailability must be considered. Using the %BAN content range (0.5%-2.2%) (1–7-day bioavailability timeframe) in the PN of source soils at Strathalbyn station (Table 10 and Table 11) an estimated reduction in runoff BAN associated with PN was calculated.

The BAN reduction in runoff associated with the reduction of PN after gully remediation was estimated to be 0.1mg/L on average and to range between 0.06 and 0.24mg/L (95%CI). DIN increase after gully remediation was on average 5x higher (Figure 19c). The increase in DIN associated with gully remediation is expected to continue to be high at least for a few years as the hay mulch fully decomposes as indicated by the APSIM modelling (see Part 2). When a new stable equilibrium is achieved in the rehabilitated gullies, DIN in runoff may still be higher than when compared to controls (eroding gullies). For example, DIN in catchment runoff samples (0.024 – 0.23mg/L) tended to be higher than in control outlet samples (EMC average = 0.07 mg/L, SD=0.06mg/L). There is no data we are aware of which shows changes in nutrient forms in runoff from stabilised or rehabilitated gully systems that have already achieved a new dynamic stable state condition. Understanding this condition for rehabilitated gullies would give more insight into the accounting for bioavailable nutrients for these systems.

Table 10 PN and bioavailable nitrogen (BAN) content in surface soils at Strathalbyn Station as a percent of PN in a 1-, 3- and 7-day timeframe for bioavailability. Highlighted yellow values are the range used to estimate BAN from PN reductions after remediation.

Soil type	PN (%)	%BAN1/PN	%BAN3/PN	%BAN7/PN
Dermosol	0.06	0.5	0.8	0.9
Sodosol	0.08	1.4	1.7	2.2
Vertosol	0.12	0.4	0.4	0.4

Table 11 PN and bioavailable nitrogen (BAN) content in subsurface soils at Strathalbyn Station as a percent of PN in a 1-, 3- and 7-day timeframe for bioavailability. Highlighted yellow values are the range used to estimate BAN from PN reductions after remediation.

Soil type	PN (%)	%BAN1/PN	%BAN3/PN	%BAN7/PN
Sodosol	0.02	0.9	0.5	0.7
Vertosol	0.04	0.5	0.5	0.5

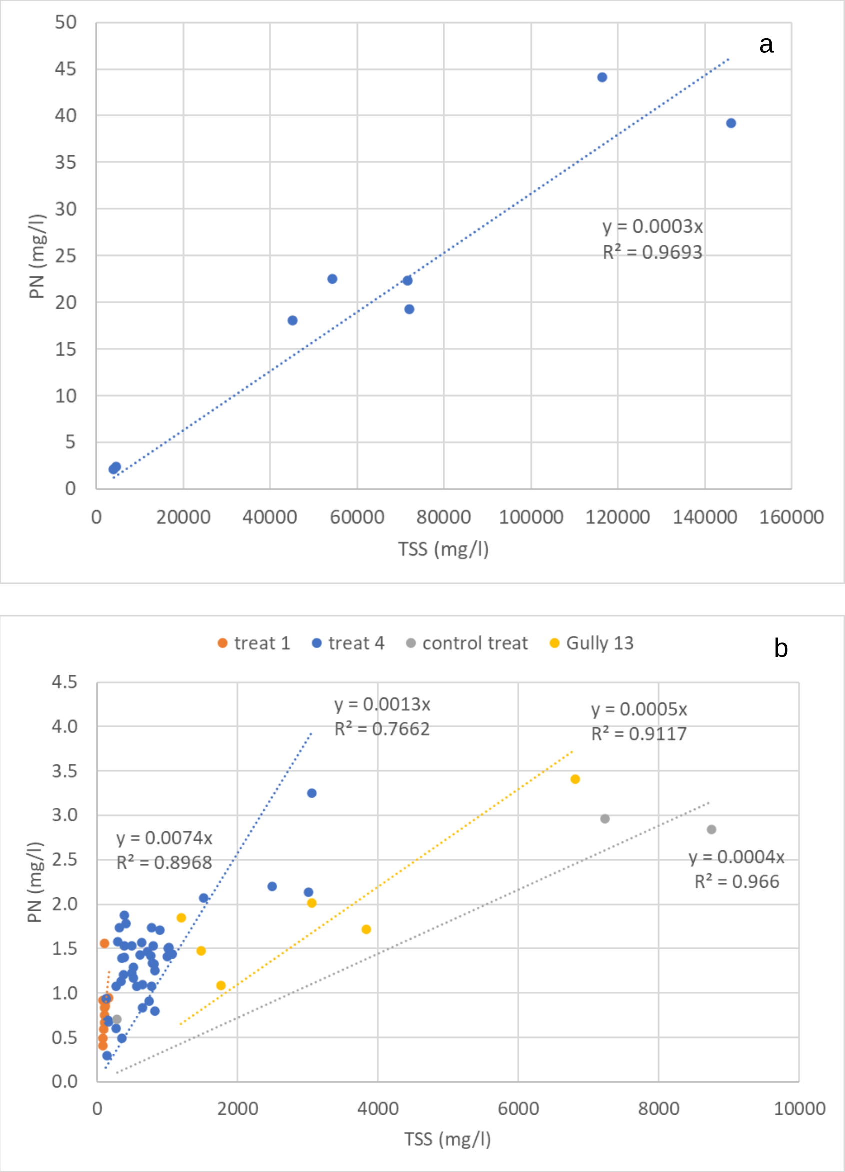
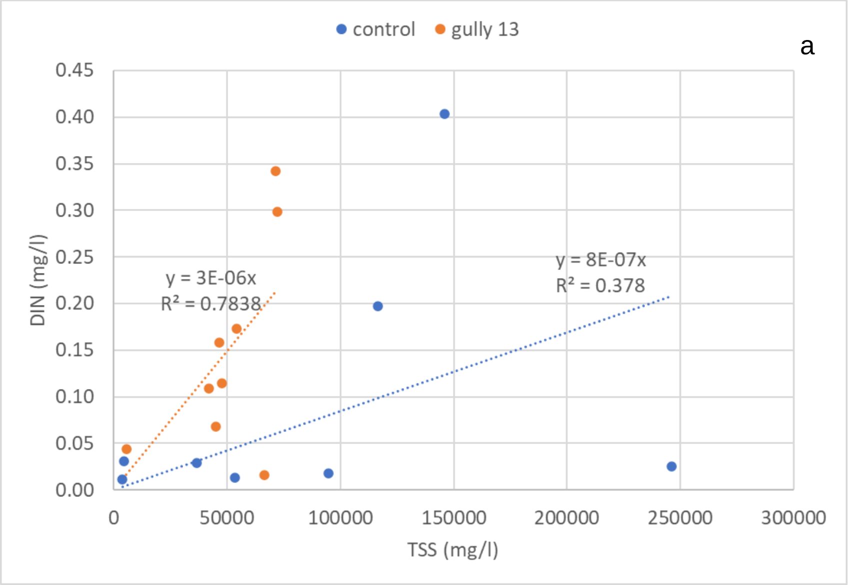


Figure 21 Linear regressions between PN and TSS for Strathalbyn gullies before remediation (controls) (a) and after remediation (treatments) (b)



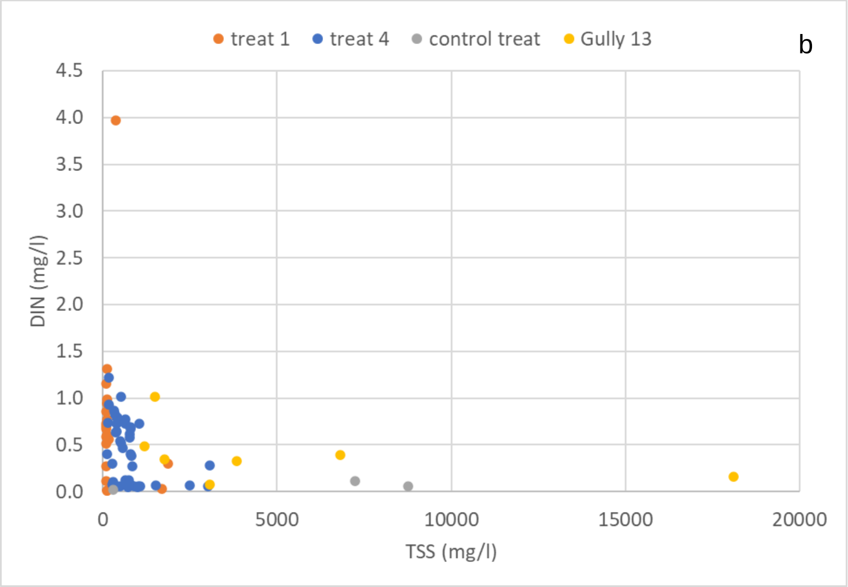


Figure 22 Linear regressions between DIN and TSS for Strathalbyn gullies before remediation (controls) (a) and scatter plot after remediation (treatments) (b)

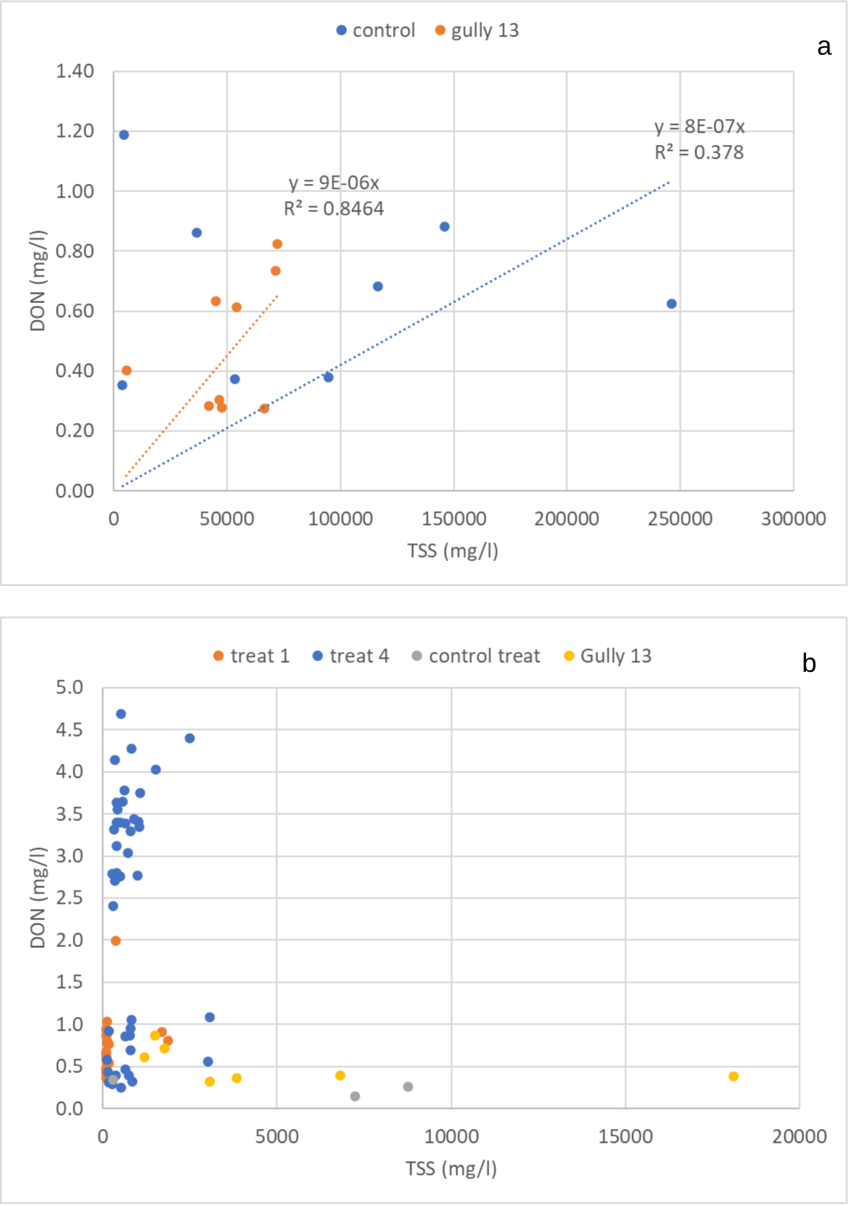


Figure 23 Linear regressions between DON and TSS for Strathalbyn gullies before remediation (controls) (a) and scatter plot after remediation (treatments) (b)

Part 4 – Potential use of carbon and nitrogen isotopes to assess the sources of nutrients from gullies

Carbon and nitrogen stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$) and elemental composition have been widely used to identify the catchment sources of sediment (Fox and Papanicolaou, 2008; Laceby et al., 2015) and of instream particulate organic matter (Garzon-Garcia et al., 2017; McCorkle et al., 2016). $\delta^{13}C$ discrimination of sources occurs mainly because of photosynthetic pathways that result in different $\delta^{13}C$ fractionations that allow differentiation between trees and temperate grass species from grass and cropping species growing in warmer climates with limited water availability. $\delta^{15}N$ fractionation is complex with a multitude of nitrogen sources and internal transformations potentially altering nitrogen isotopic ratios (Evans, 2008; Finlay and Kendall, 2008), but it has been useful in differentiating between litter and sediment in river suspended particulate matter (Garzon-Garcia et al., 2017). $\delta^{13}C$ and $\delta^{15}N$ have been demonstrated to be useful tools to evaluate sources and transformations of dissolved organic matter in catchments (Hood et al., 2005). $\delta^{15}N$ in dissolved inorganic forms of nitrogen (nitrate-N and ammonium-N) has also been useful in differentiating the sources of these forms of nitrogen including sewage treatment plant effluent (Ohte et al., 2010), fertiliser type (synthetic versus organic) (Bateman and Kelly, 2007) and the source of DIN to stream primary producers.

Considering the large potential of carbon and nitrogen stable isotope ratios for differentiating sources of dissolved N in catchments, a pilot to determine the feasibility of using this technique to differentiate the contribution of dissolved N in runoff from different amendments used as part of gully remediation was proposed.

Methods to quantify carbon and nitrogen stable isotope ratios in soil amendments

$\delta^{13}C$, $\delta^{15}N$ and elemental composition (carbon and nitrogen) were analysed in the particulate fraction of the main amendments used as part of gully remediation at Strathalbyn Station. In addition to this, $\delta^{15}N$ was analysed on the NO_3^--N and NH_4^+-N fractions of the extractable DIN from these same soil amendments. Characterised amendments can be seen in Table 12. Three replicates of each amendment were analysed.

Table 12 Amendment types characterised for carbon and nitrogen stable isotopes and fractions characterised

Amendment type	Gully source	Fraction analysed
Hay mulch (Rhodes grass)	Treatment 1	$\delta^{15}N$ on NO_3^--N and NH_4^+-N; $\delta^{13}C$, $\delta^{15}N$, TOC and TN on particulates
Hay mulch (Rhodes grass)	Treatment 4	$\delta^{15}N$ on NO_3^--N and NH_4^+-N; $\delta^{13}C$, $\delta^{15}N$, TOC and TN on particulates
Hay mulch (Rhodes grass)	Control	$\delta^{15}N$ on NO_3^--N and NH_4^+-N; $\delta^{13}C$, $\delta^{15}N$, TOC and TN on particulates
Hay mulch (Sorghum)	Gully 13	$\delta^{15}N$ on NO_3^--N and NH_4^+-N; $\delta^{13}C$, $\delta^{15}N$, TOC and TN on particulates
Introduced topsoil (vertosol)	Control	$\delta^{15}N$ on NO_3^--N and NH_4^+-N; $\delta^{13}C$, $\delta^{15}N$, TOC and TN on particulates
Introduced topsoil (vertosol)	Gully 13	$\delta^{15}N$ on NO_3^--N and NH_4^+-N; $\delta^{13}C$, $\delta^{15}N$, TOC and TN on particulates
Bagasse	Control	$\delta^{13}C$, $\delta^{15}N$, TOC and TN on particulates
Bagasse	Gully 13	$\delta^{13}C$, $\delta^{15}N$, TOC and TN on particulates
Aggregate (red)	Quarry	$\delta^{13}C$, $\delta^{15}N$, TOC and TN on particulates

Methods for processing the particulate $\delta^{13}C$ and $\delta^{15}N$ and extractable $\delta^{15}N$ are provided in Appendix 1. In summary, particulate samples of the various soil and hay mulch amendments were dried, ring-milled, and analysed for carbon and nitrogen isotopic composition. For analysis of $\delta^{15}N$ of extracted NO_3^--N and NH_4^+-N, amendments were extracted with deionised water for the hay mulch and bagasse, or 2M KCl for the soils and aggregate amendments. The extracts were processed using the micro-diffusion-IRMS method (Mary et al., 1998).

Corrections applied for data processing

Quantified sources of sample N contamination in the ^{15}N diffusion process were determined using equation 1 (Stark and Hart, 1996).

$$M_b = M_{st}(A_{st} - A_{st+b})/(A_{st+b} - A_b) \qquad \text{Equation 1}$$

Where M_b is the amount of blank N on the disk, M_{st} is the amount of standard N added into the blank, A_{st} is the ^{15}N abundance of the standard N solution, A_{st+b} is the measured ^{15}N abundance of the standard and blank, and A_b is the enrichment of the blank, assumed to be 0.366%.

Samples were then corrected for the quantified N contamination using equation 2.

$$A_{sp} = [A_{sp+b}\ (M_{sp} + M_b) - A_bM_b]/M_{sp} \qquad \text{Equation 2}$$

Where A_{sp} is the corrected ^{15}N abundance of the sample, A_{sp+b} is the measured ^{15}N abundance of the sample and blank, M_{sp} is the mass of N in the sample, M_b is the amount of blank N calculated in equation 1, A_b is the ^{15}N abundance of the blank, assumed to be 0.366%

Carbon and nitrogen isotopic signatures of particulates and DIN generated from the amendments

Organic carbon and nitrogen elemental composition and isotope ratios ($\delta^{13}C$, $\delta^{15}N$) in particulate fractions from different soil amendments used at Strathalbyn Station proved to be a viable method to differentiate between sources of particulate nutrients (POC and PN) in gully runoff. They proved to differentiate between the rock aggregate, introduced topsoil and different types of ameliorants from plant origin (hay mulch and bagasse). Carbon elemental composition was significantly different between the four potential sources of particulate nutrients with hay mulch having the higher organic C content, followed by bagasse, topsoil and the rock aggregate (Figure 24a). The carbon isotope ratio ($\delta^{13}C$) in the particulate fraction was useful to differentiate between amendments originated from plants (hay mulch and bagasse) which had a C4 photosynthetic pathway, from topsoil and rock aggregate, and between the latter two (Figure 24a). The nitrogen elemental composition was also significantly different between the different potential sources and between the different hay mulches used as part of remediation (Figure 24b). The hay mulch used in treatment 1 (Rhodes grass) had the highest TN content at the time of sampling, followed by the hay mulch used in treatment 4 (Rhodes grass), then the hay mulch used in both gully 13 and control (of different kinds – Rhodes grass and sorghum), but installed at the same time, bagasse and lastly topsoil and rock aggregate. The nitrogen isotope ratio ($\delta^{15}N$) would only be useful in differentiating between the older hay which was significantly enriched in the heavier N isotope and the other sources of particulate N (Figure 24b).

Together these four tracers could be used to estimate the contribution to particulate nitrogen in runoff from a maximum of five sources for each gully (hay mulch, bagasse, introduced topsoil, subsoil and rock aggregate). The difficulty would be in obtaining enough sediment in the runoff to do so. Pass sampler samples would be the only type of samples containing enough sediment to carry out these analyses. It would also be possible to integrate all autosampler samples in one sample and separate sediment for the analyses. None-the-less, relationships between PN and TSS and POC and TSS in runoff, which depict C and N content of the sediment are useful in indicating the most likely source of particulate N in each treatment using the potential sources content (see previous section).

$\delta^{15}N$ in the extractable dissolved inorganic N (DIN) (NO_3^--N and NH_4^+-N) from amendments used in gully remediation also proved to be a feasible technique to differentiate the source of DIN in runoff from remediated gullies. The $\delta^{15}N$ in the NO_3^--N was significantly different between the DIN extracted from Rhodes grass hay mulch and the DIN extracted from Sorghum hay mulch or topsoil, which were not significantly different (Figure 25). The $\delta^{15}N$ in the NH_4^+-N was significantly different between all hay mulches and topsoil (Figure 25). This indicates that either of the tracers could be used to differentiate the source of DIN between Rhodes grass and topsoil, but the $\delta^{15}N$ in the NH_4^+-N would have to be used in treatments that use Sorghum hay mulch.

The use of $\delta^{15}N$ in the extractable dissolved inorganic N (DIN) (NO_3^--N and NH_4^+-N) to understand source contribution is limited by the concentrations of NO_3^--N and NH_4^+-N in runoff samples and by the volume of those samples. According to our calculations, and based on a target mass of 20µg of N required for analysis, approximate volumes of 350mL (range of 15-4000mL) and 1500mL (range of 80-3300mL) would be needed to measure $\delta^{15}N$ on NO_3^--N and NH_4^+-N typically found in runoff from Strathalbyn remediated gullies. The volumes obtained for autosampler filtered samples are generally too low to estimate $\delta^{15}N$ of NH_4^+-N, so only $\delta^{15}N$ on NO_3-N is able to be measured in most runoff samples. To be able to fully apply this method to understand source contribution to DIN from remediated gullies, complete autosampler filtered samples would have to be dedicated to measure isotope content towards later developing unmixing modelling. At least 1L sample is recommended to ensure enough volume for NO_3^--N analysis and compositing samples from different sampling points or times is likely to be necessary for analysis of NH_4^+-N.

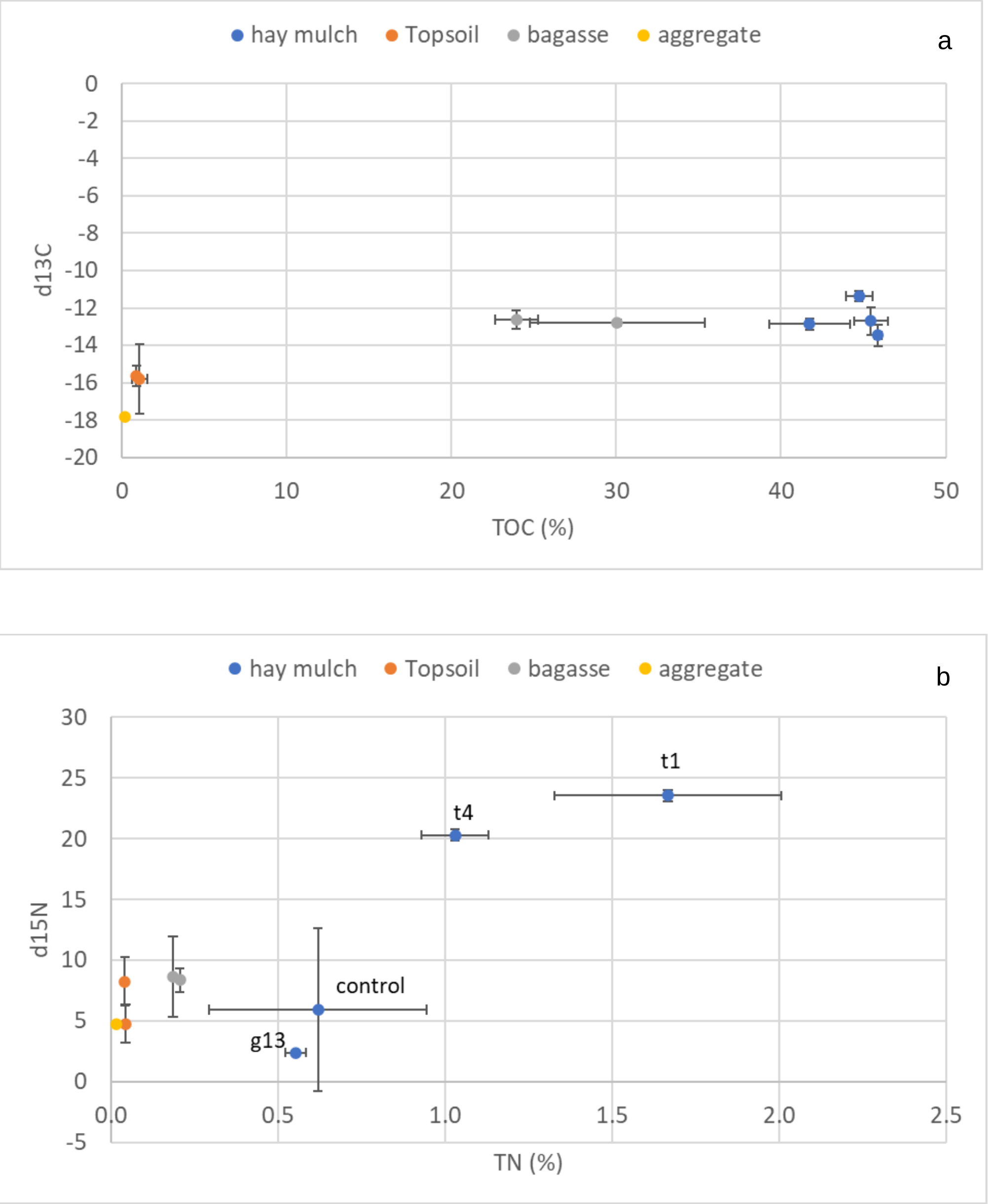


Figure 24 Mean organic carbon and d13C (a) and elemental nitrogen and d15N (b) in potential sources of particulate nutrient export in runoff after gully remediation at Strathalbyn Station. Error bars represent standard deviations of three replicates.

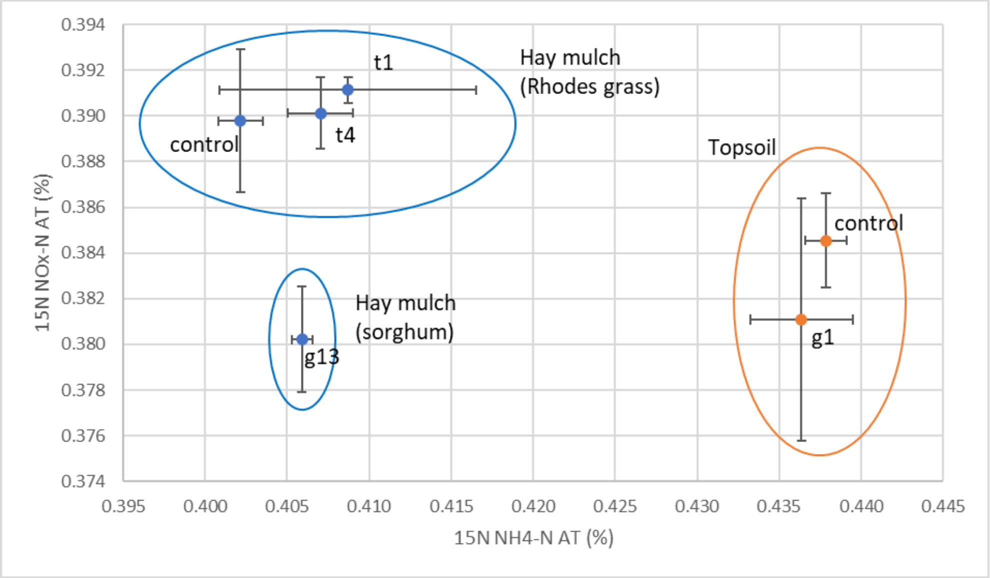


Figure 25 Mean 15N (% atoms) in NO_3^--N and NH4-N of potential sources of DIN in runoff after gully remediation at Strathalbyn Station. Error bars represent standard deviations of three replicates.

Part 5 – Refinement of baseline methodology to estimate particulate and bioavailable nitrogen from active gully systems

An applicable methodology for estimating a baseline for particulate nutrient and bioavailable nutrient yields from gully systems was developed as part of a previous project (Garzon-Garcia et al., 2021a). The application of this method would allow a benchmark for comparison of the effects of gully remediation on nutrient export in runoff when a control gully is not available for a specific gully remediation site.

In summary, the application of the baseline method to estimate particulate and bioavailable nutrient yields from gully systems would require the following:

- An accurate estimate of sediment yields (surface and subsurface soil loss in tonnes per year on average during the gully development period – see sediment Reef Credit method*)*- when soil type is not considered as an important variable in the model, sediment yield drives the nutrient and bioavailable nutrient yield
- An accurate estimate or measurements of the A-horizon original depth (before erosion) - the A-horizon depth causes large differences in the estimated contribution from surface versus subsurface soils to nutrient and bioavailable nutrient export
- An accurate understanding of types and distribution of soils in the gully catchment and within the gully itself, including three-dimensional measuring and mapping of soil characteristics including all particulate nutrients (PN, PP and POC) and all bioavailable nutrient pools (minimum water extractable DIN and DRP and adsorbed ammonium; and ideally also water extractable DOC, DON and DOP) - differences in soil type can have an important effect on nutrient and bioavailable nutrient baseline yields from gullies*.* Soil type also had an important effect on the relative contribution of subsurface soils relative to surface soils to nutrient and bioavailable nutrient export.
- Monitoring of control gullies with similar soil characteristics and sediment yields to validate the developed baseline before using it for benchmarking.

Previously, a range of scenarios were modelled to estimate a baseline for nutrient and bioavailable nutrient pool yield from the Northern gullies and gully 13 at Strathalbyn. Scenarios included uncertainties around the A-horizon depth and the contribution of different soil types to sediment export within each gully. Additionally, at the time it was not possible to validate the baseline with monitoring data from control gullies as there was not enough data to estimate loads. Other limitations included that northern sites did not have an accurate three-dimensional mapping of soil types to define with certainty the relative contribution of soil types to particulate nutrients and BAN yield. To better understand contribution of soil types to sediment export in control gullies at Strathalbyn it was proposed to use geochemical tracing on existing source and outlet control samples to be carried out as part of this project.

Refinement of sediment baseline data from Daley et al. (2020)

A full description of the baseline yield calculation is included in Daley et al. (2020), but a brief summary of the baseline yields derived for each site are included in Table 13. The data presented here is intended to form a baseline dataset on the quantity and the yield of fine sediment (<20 µm) eroded from each of the gullies prior to treatment in the Northern group. Recent research into the role of rain-splash and wash erosion (collectively known as downwearing erosion) from the internal surfaces of alluvial gullies (Daley et al., in press), indicates that these earlier estimates are likely significant underestimates of the recent baseline yields. This is due to the fact that as much as 90% of the contemporary sediment yield is sourced from the gully internal surfaces, which gives rise to an accelerating baseline yield as the internal gully surface area increases.

A combination of historical air photo and lidar datasets, GIS methods, field surveys and soil material sample analysis have been used to quantify the total yield (tonnes) of sediment derived from each of the gullies over the period of observation (1945 to 2016), and to estimate the baseline sediment yield and erosion rates presented in Table 13. Erosion rates were calculated for both the total yield of sediment and for the fine fraction (<20 µm) sediment, which comprises at least 72% of the sediment load (53,270 tonnes) and is expected to have a high sediment delivery ratio to the receiving waters of the Great Barrier Reef (GBR).

In total, the gullies in the study area contributed approximately 206 thousand tonnes of sediment since 1945, with 29% of this amount eroded in the last 20 years. The 20-year fine sediment baseline from these gullies is roughly 53,700 tonnes and overall appears to be increasing in sediment yield. Prior to remediation, these gullies were contributing on average 2,993t of fine sediment to the GBR lagoon each year.

Table 13. Summary of sediment yields for Northern Group treatments and Control along with southern gully 13. Fine sediment is the fraction <20µm

		Period of observation (1945-2016)					Baseline Period (2000-2020)	
Gully ID	**Gully Area (ha)**	**Vol Eroded (m^3)**	**Quantity eroded (t)**	**SSY (t/yr/ha)**	**Fine sed. quantity (t)**	**Fine sed. yield (t/yr)***	**Vol Eroded (m^3)**	**Fine sed. yield (t/yr)***
Treatment_1	0.96	14800	24700 ± 1700	362 ± 25	17900 ± 3700	253 ± 52	4870	283 ± 42
Treatment_4	2.24	36100	60300 ± 4200	380 ± 26	43800 ± 9000	620 ± 130	10900	620 ± 200
Control	2.42	54600	91200 ± 6300	530 ± 37	66000 ± 14000	930 ± 190	18600	1180 ± 180
South_13	8.44	72600	121000 ± 10000	51 ± 8	78000 ± 15000	1040 ± 200	18900	910 ± 170
Total	**14.06**	**178100**	**297200 ± 22200**	**202 ± 24**	**205700 ± 41700**	**2843 ± 950**	**53270**	**2993 ± 592**

*Assumes a Sediment Delivery Ratio (SDR) of 0.94

Surface soil vs sub-surface soil materials

High resolution lidar (0.1m) DEM-of-difference (DoD) data between 2017 and 2020 at the control gully shows the extent of new erosion in this period that is contributed from headscarp/gully perimeter erosion. For the purpose of determining the relative contribution of surface soil to sub-surface soil material to the net gully sediment and nutrient yield it is important to be able to isolate where new sediment is being sourced from within the gully. From this analysis (Figure 26) the position of the gully scarp in 2017 can be seen, with the zones of headscarp migration highlighted by the red lobes beyond the 2017 boundary. Different estimates of soil depth are then used to estimate the relative proportion of sediment contributed from surface or subsurface soil materials. Given the relative consistency in sub-surface nutrient concentrations, further differentiation of the different sub-surface soil material units was deemed to be unnecessary.

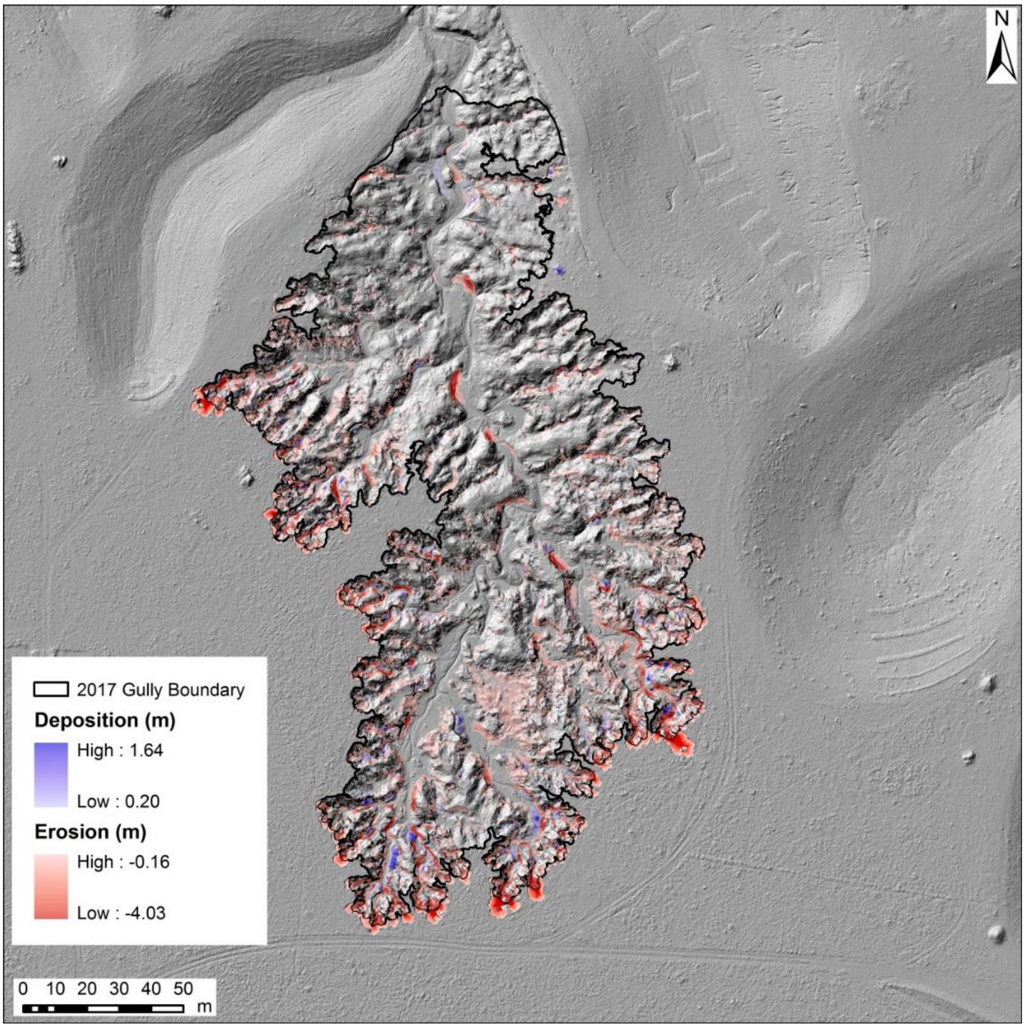


Figure 26. Image showing the DEM-of-difference (DoD) derived from 0.1m resolution lidar data between 2017 and 2020. The black line delineates the scarp edge in 2017 from which we can derive the surface soil contribution to the load at the gully outlet.

Table 14. Proportion of total baseline sediment yield derived from surface soil as determined from DoD analysis of the control gully between 2017-2020.

Total volume erosion Control gully		2700 m^3
Total volume deposition Control gully		154 m^3
Volume erosion beyond 2017 gully boundary		283 m^3
	Volume	**Percentage of total erosion**
Top 15cm of erosion beyond 2017 gully boundary	60 m^3	2.22 %
Top 20cm of erosion beyond 2017 gully boundary	79 m^3	2.94 %
Top 30cm of erosion beyond 2017 gully boundary	114 m^3	4.21 %

Table 15. Proportion of total baseline sediment yield derived from surface soil as determined from DoD analysis of gully13 between 2017-2020.

Total volume erosion Gully 13		2337 m^3
Total volume deposition Gully 13		333 m^3
Volume erosion beyond 2017 gully boundary		122 m^3
	Volume	**Percentage of total erosion**
Top 15cm of erosion beyond 2017 gully boundary	29 m^3	1.25 %
Top 20cm of erosion beyond 2017 gully boundary	39 m^3	1.67 %
Top 30cm of erosion beyond 2017 gully boundary	57 m^3	2.46 %

Results from this analysis indicates that recent surface soil contribution at the control gully outlet ranges between 2.2% to 4.2% depending on the soil depth used, while at Gully 13, the surface contribution ranges from just 1.25 to 2.46%. It is also clear from these DoD data, which themselves represent a bare minimum sediment yield given the 0.1m limit of detection used in the analysis, that the baseline sediment yields outlined here are conservative when the unmeasured downwearing erosion, which falls below the limit of detection of 0.1m, is added. Mean annual downwearing rates from similar soil units in the southern gully group (Daley et al., in press) are in the order of 20mm/year across the whole internal gully surface. This level of downwearing adds an additional ~230t/ha of fine sediment yield to the values reported here, which could mean the baseline yields are approximately double the reported values.

Geochemical tracing of gully sediment sources

Introduction

A total of 56 sediment samples were collected across three gullies as the basis for a “proof of concept” analysis to determine whether geochemical tracing can be used to isolate contributions from different soil materials from sediment samples collected at the gully outlet. Samples were collected from the Control gully, Gully 13 and Treatment 4 at Strathalbyn (Table 16). Samples were not able to be collected at Treatment 1 because this was the first gully remediated back in 2017.

Table 16. Sample distribution across gullies.

Gully	# Surface Samples	# Subsurface Samples	# Sink (WQ) Samples
Control	3	5	9
Gully 13	4	7	5
Treatment 4	5	10	8

‘Surface Samples’ are those samples collected from < 0.5m depth. For Gully 13 samples, no depth information was available, hence samples have been assigned to ‘Surface samples’ based on their labelling as ‘Unit 1’ samples, which were observed to be black clays. Subsurface samples are those collected below 0.5m, or Units 2 (observed to be yellow) and 3 (observed to be yellow-red) at Gully 13. Sink samples are those obtained from the various water quality sampling devices placed at or near gully outlets.

Each of these samples was analysed for 51 element concentrations using ICPMS, following microwave digestion in Reverse Aqua Regia. To account for possible differences due to particle size distribution differences across samples, each element concentration was normalised using the measured Th concentration, yielding 50 normalised concentration values for each sample.

Results

The Mann-Whitney test was conducted across all elements across all pairs of surface and subsurface samples to determine whether the samples were significantly different, hence whether they would have any discriminatory power. Elements which passed the Mann-Whitney Test were then examined for conservativeness, whereby the median of the Sink term falls between the medians of the two source terms.

Table 19 shows elements that passed the Mann-Whitney Test and subsequent Conservativeness Test. Elements that passed both tests were then examined using a standard 2-part mixing model, $AX+BY=C$ where A and B are median surface and subsurface concentrations and C is the median sink (WQ) concentration, and X+Y (the proportional contributions from each source) = 1. Solving for X (and by subtraction, Y) using the GRG Nonlinear engine in *Excel* yields, in this case, 5 individual mixes (Table 19, Column 4), the mean of which is taken as a reasonable first approximation of the relative contribution of subsurface materials to the sediment load exiting the gullies. Examination of the box plots (Figures 25 and 26) allow us to refine this number somewhat.

Table 17. Results of Mann-Whitney and Conservative Tests, and output of Mixing Models.

Gully	Passed MWT	Conservative	Surface/Subsurface
Control	Ti	✓	36/64
	Cd	×	
	Sb	✓	43/57
Gully 13	Na	✓	37/63
	Cu	×	
	Zn	×	
	Ga	✓	28/72
	Nb	×	
	Sn	×	
	Ba	✓	4/96
Treatment 4	Ni	×	
		Average Ratio	**30/70**

Figures 25 and 26 show box plots of normalised element concentrations. Note that only Ba in Gully 13 has the combination of complete separation of surface and subsurface samples and entirety of the sink distribution falling within one of the other populations (in this case subsurface). For these reasons the ratio value for Ba is considered the most reliable. We can see that the true value for Ba for each of the terms can fall anywhere within the respective ranges displayed and still yield a value of Surface<<<Subsurface. In contrast, the distributions shown in the other box plots are consistent with a range of possible ratios, including Surface<<<Subsurface.

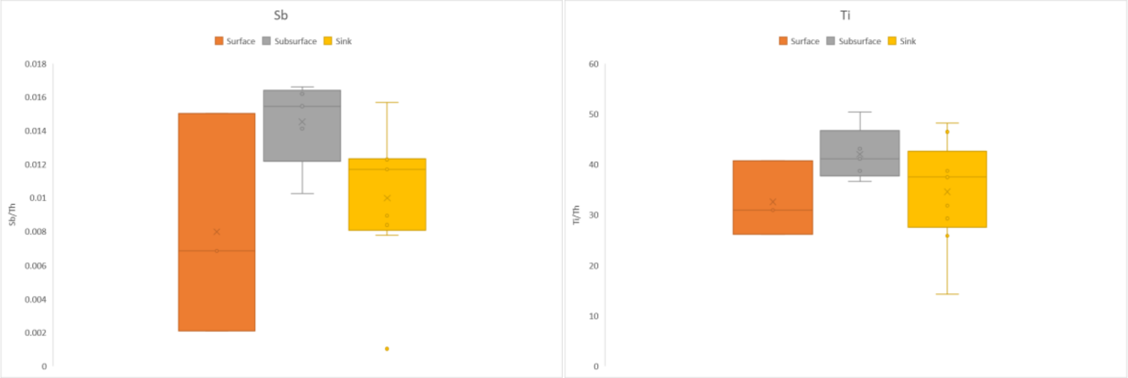


Figure 27. Control Gully Box Plots showing the relative proportions of the surface soil (orange), the sub-surface (grey) and the outlet material (yellow). The plot on the left shows the ratios of Sb/Th whereas the plots on the right show the ratios of Ti/Th.

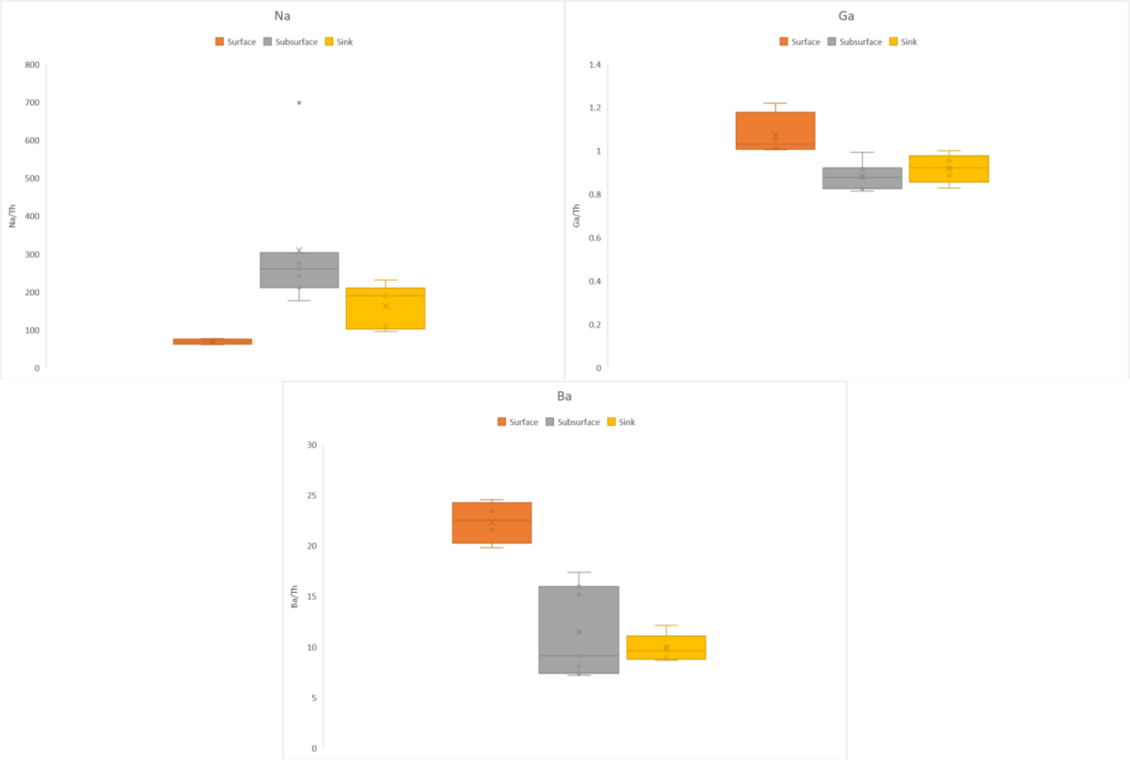


Figure 28. Gully 13 Box Plots showing the relative proportions of the surface soil (orange), the sub-surface (grey) and the outlet material (yellow). The plot on the top left shows the ratios of Na/Th whereas the plots on the top right show the ratios of Ga/Th and at the bottom Ba/Th.

Conclusion

Geochemical tracing conducted in the manner briefly described here has failed to provide conclusive results,and is unlikely to be appropriate in most gullies at this scale. Of the 150 element mixes examined (i.e. 50 for each gully) only five (~3%) yielded sensible results. Of these five, only Ba in Gully 13 provided a ratio estimate with useful precision. Hence the average ratio provided in Table 17 (i.e. 30/70) should be considered a maximum only, being comprised of 1 precise and 4 imprecise values. Examination of the boxplots indicates that average ratio should be considered in light of the relative precision of each of the individual ratios, with Ba provided greater weight than the other modelled mixes. Hence, our safest conclusion is that the yield from Subsurface units overwhelmingly dominates the load exiting the gully, with a likely Surface/Subsurface ratio < 5%. This accords with the analysis derived from the high resolution lidar DoD analysis above, but the lidar derived results can be assumed to provide a more representative estimate of the proportion of the gully outlet yield derived from surface/sub-surface soil material.

Refinement and validation of the nutrient baseline

A sensitivity analysis was carried out to understand the effect of the sediment baseline refinement on the estimation of the nutrient baseline. The refined sediment baseline indicates a reduction in the proportion of surface soils contributing to sediment export from actively eroding gullies at Strathalbyn than that estimated for the original baseline. We used the largest estimated change in the contribution from surface soils of 2.94% (Table 14) for the control gully and applied it to the North06 gully area where the control gully is located (Figure 15), to refine the nutrient baseline estimated by Garzon-Garcia et al (2021a). Garzon-Garcia et al (2021a) used a 14% surface soil contribution. From that report, we have only recalculated the scenario that assumed a 0.2 m A-Horizon depth and the average of terrace cores and gully wall values for nutrient fraction contribution from surface and subsurface sources. The baseline annual nutrient load has been normalised by gully eroding area to obtain a yield.

Results

The comparison between yields obtained for the previous and refined sediment baselines for various nutrient fractions can be seen in Figure 29. As can be observed in this Figure, there are no significant changes in nutrient yield between the previous and refined sediment baselines. This is expected to be the case for other gully areas and scenarios modelled by Garzon-Garcia et al (2021a). None-the-less, the relative contribution from surface and subsurface soils to different exported nutrient fractions changes, with a significant increase in the contribution from subsurface soils to all nutrient fraction export (Figure 30). Subsurface soils continue to be the dominant source of nutrient export and surface soils, which would have been more important during previous stages of gully evolution (up to 40% for 14% surface sediment contribution) have reduced their contribution to less than 11%.

To validate the results of the nutrient baseline developed in Garzon-Garcia et al. (2021a) annual yield estimates from monitored water quality of untreated ‘control’ gullies were recalculated from those presented in Table 10 of Garzon-Garcia et al. (2021a). The updated values are calculated using the EMCs of parameters with calculated loads from the untreated Control and Gully 13 monitored runoff events of the 2018-2019 and 2019-2020 wet seasons presented in Table 11 of that report. The active gully area and annual discharge volume are the same as those estimated for Garzon-Garcia et al. (2021a). Results are presented below in Table 18. The updated annual yield results are similar to those calculated using average values of water quality parameters by Garzon-Garcia et al. (2021a).

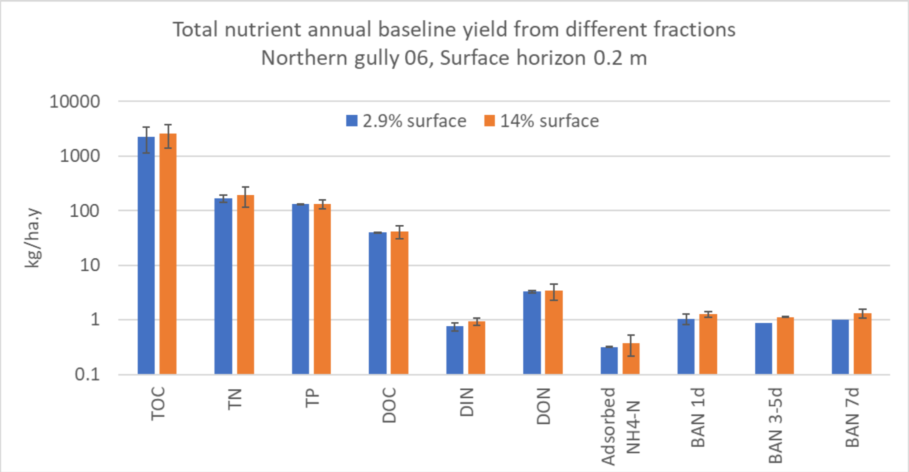


Figure 29. Total nutrient annual baseline yield from different fractions of nutrients for a 2.9% (blue) and 14% (orange) surface soil contribution to sediment export. The 2.9% contribution has been recently adjusted from the 14% used by Garzon-Garcia et al (2021a) by Daley et al. (in press).

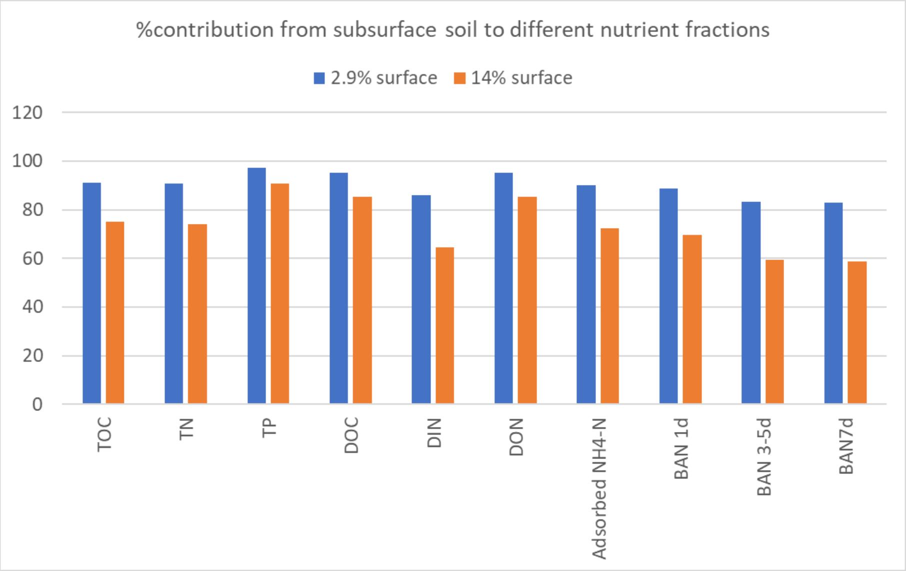


Figure 30 Percent contribution from subsurface soil to different nutrient fraction export from North06 gullies at Strathalbyn for a 2.9% surface soil contribution (blue) and a 14% surface soil contribution (orange) to sediment export.

Table 18 Annual yield from monitored data and calculated Event Mean Concentration (EMC) for nutrients from untreated 'control' gullies. EMC taken from Table 11 of this report. Gully area, annual discharge, and comparison results are taken from Tables 10 and 11 of Garzon-Garcia et al. (2021a).

Parameter	**Gully**	**Active gully area (ha)**	**Wet Season**	**Annual Discharge Volume (L)**	**Event Mean Concentration (Table 11)**		**Estimated baseline yield**	**Estimated baseline yield ±SD (Table 10 Garzon-Garcia et al. 2021a)**
					Range	**Value (mg/L)**	**t/ha**	**t/ha**
Total Suspended Solids	Control 1	2.42	2018-2019	75,335,580	Low	82,128	**2,556.7**	2,162 ± 5,232
					High	171,191	**5,329.2**	
			2019-2020	26,811,060	Low	82,128	**909.9**	733 ± 161
					High	171,191	**1,896.6**	
	Gully 13	12.2	2019-2020	60,527,280	Low	43,004	**213.4**	29 ± 11
					High	47,108	**233.7**	
					Range	**Value (mg/L)**	**kg/ha**	**kg/ha**
Dissolved Organic Nitrogen	Control 1	2.42	2018-2019	75,335,580	Low	0.409	**12.7**	23.7 ± 2.4
					High	0.712	**22.2**	
			2019-2020	26,811,060	Low	0.409	**4.5**	6.2 ± 0.5
					High	0.712	**7.9**	
	Gully 13	12.2	2019-2020	60,527,280	Low	0.289	**1.4**	2.2 ± 0.4
					High	0.305	**1.5**	
Dissolved Inorganic Nitrogen	Control 1	2.42	2018-2019	75,335,580	Low	0.018	**0.6**	3.66 ± 1.3
					High	0.025	**0.8**	
			2019-2020	26,811,060	Low	0.018	**0.2**	0.78 ± 0.19
					High	0.025	**0.3**	
	Gully 13	12.2	2019-2020	60,527,280	Low	0.108	**0.5**	0.65 ± 0.20
					High	0.133	**0.7**	
Dissolved Organic Carbon	Control 1	2.42	2018-2019	75,335,580	Low	8.026	**249.9**	250.8 ± 9.6
					High	9.520	**296.4**	
			2019-2020	26,811,060	Low	8.026	**88.9**	95.8 ± 3.2
					High	9.520	**105.5**	
	Gully 13	12.2	2019-2020	60,527,280	Low	3.392	**16.8**	30.1 ± 2.9
					High	4.391	**21.8**	
Dissolved Reactive Phosphorus	Control 1	2.42	2018-2019	75,335,580	Low	0.429	**13.4**	14 ± 1.9
					High	0.544	**16.9**	
			2019-2020	26,811,060	Low	0.429	**4.8**	4.8 ± 0.3
					High	0.544	**6.0**	
	Gully 13	12.2	2019-2020	60,527,280	Low	0.284	**1.4**	1.9 ± 0.3
					High	0.381	**1.9**	

Conclusions and Recommendations

Nutrient export from gully systems after remediation

After four wet seasons (2018-2022) of monitoring nutrients in runoff from actively eroding and remediated gullies at Strathalbyn Station, we have compiled an important body of work and dataset, significantly advancing our understanding of the export of nutrients from these systems.

The main conclusions from the four wet seasons of monitoring nutrients in runoff from gullies at Strathalbyn are:

- Gully remediation has contributed to a significant reduction in the export of TSS (10x lower EMC, 98.9% reduction on average) and particulate nutrients (PN and PP) (>10x lower EMC, 92-95% reduction on average) from gully outlets
- Gully remediation has caused a net increase in the EMC of soluble organic nutrients (DOC, DON and DOP) and DIN (2-10 times greater than the highest DIN of an untreated gully) from gullies and there is no evidence of these going down up to 4 years after remediation.
- The majority of carbon, nitrogen and phosphorus export was in particulate fractions before gullies were remediated*.* Whereas the majority then shifted to dissolved fractions after the gullies were remediated.
- Most of the dissolved nitrogen consists of DON before remediation and in first years after*,* then DIN becomes as large or larger.
- The majority of DIN is oxidised N (NOx-N).
- Adsorbed NH_4-N can be an important bioavailable nitrogen fraction *(*can be larger than water soluble ammonium) before and after gullies are remediated. This implies that it is important to monitor adsorbed NH_4-N before and after remediation to understand reductions and impact as it is a fraction that would become bioavailable when the sediment enters the estuaries (Garzon-Garcia et al., 2021b).
- Although Total Nitrogen discharge from gullies massively decreases following gully remediation, due to the reduction of particulate fractions, the bioavailable nitrogen (BAN) discharge increases, due to an increase in the concentration of DIN.

The role of soil amendments in generating bioavailable N from remediated gullies

Initial findings of an increase in soluble nutrients, particularly DIN, after gully remediation prompted this project to explore if the increase was caused by soil amendments used as part of gully remediation. After carrying out a long-term incubation experiment, using APSIM to model the mineralisation of N in different amendments and a fourth monitoring season as part of this project, we have concluded the following:

- Soil amendments are the main cause of the increase in soluble organic nutrients and DIN from remediated gullies.
- The decomposition of organic amendments (soil and hay) can either consume DIN (high C:N ratio) or produce DIN (low C:N ratio). Rhodes grass (*Chloris gayana*) (T1 and T4) and the imported soil (control and gully 13) produce DIN whereas the Rhodes grass, sorghum and bagasse (Control and Gully 13) consume DIN. The balance between DIN producers and consumers determines whether there is a net production or consumption of DIN from the amendments.
- DIN generation potential is not the only important characteristic in selecting an amendment for gully remediation, although it should be considered. Ideally, the amendment should have a high C:N ratio so that DIN production is delayed until vegetation is established in the gully which can act as a sink for DIN produced.
- At Crocodile Station in the Normanby catchment of Cape York, the use of rock surface capping without organic amendments in gully remediation produced a net reduction in total, particulate and dissolved forms of N and P.

Accounting for nutrient export from gullies

Baseline methodology to estimate export from active gully systems

A baseline methodology to estimate nutrient and bioavailable nutrient pool yields from eroding gullies was developed by Garzon-Garcia et al. (2021) and applied to the Northern gullies and gully 13 at Strathalbyn. In this report we refined and validated this baseline method as follows:

- The sediment baseline used towards estimating the nutrient baseline at Strathalbyn was refined using recent research findings (Daley et al., *in press*) indicating that the earlier used estimates are underestimates. This is due to the fact that as much as 90% of the contemporary sediment yield is sourced from the gully internal surfaces which was unaccounted for. Considering this, the surface soil contribution to sediment export is also significantly lower than initially thought.
- The implications of these new insights is that it is critical to utilise the appropriate conceptual model of gully evolution for the gully in question, which accounts for the changing relative proportion of surface to sub-surface soil and associated nutients through the gully's evolutionary history.
- Geochemistry of sediment sources explored in this report, has failed to provide conclusive results and is unlikely to be appropriate in most gullies at this scale to trace surface and subsurface sources of sediment. Consequently, it was not possible to refine the nutrient baseline for Strathalbyn gullies in terms of soil type contribution to export for the Northern gullies.
- Changes in the surface soil contribution to the baseline sediment export did not cause significant changes in the nutrient and bioavailable nutrient baseline yields estimated by Garzon-Garcia et al (2021). None-the-less, the contribution from surface soil to baseline nutrient yields reduced significantly, with subsoil now clearly being the main nutrient and bioavailable nutrient source associated with contemporary sediment export from alluvial gullies at Strathalbyn.
- Nutrient loads calculated as part of this report, were used to further validate the nutrient baseline methodology.

Monitoring of nutrients towards assessment of the effects of gully remediation in runoff water quality

After four wet seasons of monitoring nutrients in runoff from active and remediated gullies at Strathalbyn Station, we have several learnings about the best practice to monitor nutrients and calculating loads for these systems:

- There are good linear correlations between PN and TSS concentrations in untreated control gullies. This implies that for gullies of similar characteristics (geomorphology and soil type) it is possible to monitor TSS and PN with sufficient resolution (e.g., autosampler samples covering the hydrograph evenly for at least 3 events for each of 2-3 wet seasons) to establish the relationship. After this either the Reef credit method or monitoring TSS could be used to establish the TSS baseline for export and then estimate the baseline for PN export from the TN versus TSS relationship.
- There are good linear correlations between PN and TSS in treated gullies, though those relationships vary with the type of remediation (amendments used as part of the remediation) and gully type (geomorphology and soil type). Monitoring TSS and PN with high resolution (autosampler samples covering the hydrograph evenly for at least 3 events for each of 2-3 wet seasons) would be enough to determine the relationship and then estimate PN reductions from TSS reductions (Reef Credit method).
- There were no clear relationships evident between soluble nitrogen or DIN and TSS for controls nor treatments. To get an understanding of the export of these fractions from controls and treatments it would be necessary to monitor them directly (autosampler samples covering the hydrograph evenly for at least 3 events for each of 2-3 wet seasons). For controls the baseline methodology could be used instead.
- Event mean concentrations (EMCs) are the best method to directly compare nutrient yield between gullies (controls and treatments). EMCs are designed to normalise nutrient loads by runoff volume which standardises the load to catchment area and the intensity of the rainfall event.
- We acknowledge the difficulty of monitoring nutrients in gullies as these systems are generally remote and there is the need to use refrigerated autosamplers and recover the samples for filtering in less than 48 hours. None-the-less, it is necessary to monitor remediated gullies for at least 2-3 wet seasons to get an initial understanding of relationships and effects on particulate and dissolved nutrients.
- To be able to estimate nutrient EMCs for gully runoff we recommend to: install flumes at the outlets of gullies to better quantify discharge and to better sample the low water levels typical of these systems; use refrigerated autosamplers at gully outlets; have a good coverage of each event sampled (at least 5 samples) with samples at the rise, peak and drawdown stages; install pressure transducers to be able to validate runoff models.

Accounting for nutrient export

This project provides a better understanding of the effect of gully remediation on the export of bioavailable nutrients from gully systems in which soil amendments are used as part of remediation. Main findings are:

- The increase in DIN associated with gully remediation is expected to be high at least for a few years as the hay mulch fully decomposes as indicated by the APSIM modelling.
- The bioavailable nutrients reduced in association with PN reductions after gully remediation (of 11-33 mg/L in EMCs, 95% CI) did not compensate for the DIN increase caused by the use of soil amendments (on average 5x higher EMCs). This is because only 0.5-2.2% of the PN of source soils at Strathalbyn station is bioavailable (1–7-day bioavailability timeframe).
- When a new stable equilibrium is achieved in the rehabilitated gullies, DIN in runoff may still be higher than when compared to controls (eroding gullies). For example, DIN in catchment runoff samples (0.024 – 0.23 mg/L) tended to be higher than in control outlet samples (EMC average = 0.07 mg/L, SD=0.06 mg/L). It is expected that hydrologic and biogeochemical conditions in rehabilitated gullies would be different than that of their catchments, and the influence this may have on DIN processing and generation is difficult to predict.

These findings imply that where soil amendments, such as low C:N ratio hay mulch is used in gully remediation works, there is no immediate benefit to water quality in terms of bioavailable nitrogen export from remediated gullies, compared to a degraded gully. There is no data we are aware of with nutrient export from stabilised or rehabilitated gully systems that have already achieved a new dynamic stable state condition. Understanding this condition for rehabilitated gullies would give more insight into the accounting of bioavailable nutrients for these systems. The reduction in PN and its bioavailable component from gully remediation (potential DIN generation downstream in transport measured up to 7 days) is overshadowed by the increase in DIN from amendments, but those reductions may still be beneficial further downstream in the Reef lagoon where sediments continue to generate bioavailable nutrients in plumes and after settling and resuspending with wind and currents (Garzon-Garcia et al., 2021b). Additionally, DIN from these recently remediated systems seem to have a larger DIN export than runoff entering the gullies from their catchments (2x average EMCs). It would be expected that as they reach a new stable equilibrium DIN export in runoff may be reduced.

Proposed future works to inform gully remediation and co-benefits – Recommendations

- We recommend that remediated gullies are monitored for particulate and dissolved nutrient fractions (C,N and P) including adsorbed ammonium for at least 3 years after remediation to develop relationships between TSS and particulate nutrients, and understand gully effect on the export of dissolved nutrients.
- Follow up monitoring should be undertaken again in ~ 3 years at the sites which used hay-based soil amendments to confirm whether the predicted trends towards a net reduction in DIN production to levels below baseline have been achieved.

Implications for ongoing gully remediation

- Ongoing gully remediation should avoid the use of low C/N ratio surface amendments, such as Rhodes grass (*Chloris gayana*) or sorghum hay, and instead rely on high C/N ratio amendments such as bagasse and/or rock capping.
- Locally sourced cracking clay soils (imported Vertosol) as an amendment can be used, however the maintenance of high ground cover, and the reduction of grazing pressure is critical to prevent mobilisation of the imported soil and associated nutrients during runoff events.
- This research has suggested it is likely that a stacked reef credit for PN/DIN reduction (i.e. on top of sediment reductions) is possible for gully remediation sites using rock capping and/or high C/N ratio amendments. However, the evidence from this project does not support the production of credits for sites using low C/N ratio amendments. The viability of PN/DIN reduction credits will be determined based on the trading price of credits and the number generated from a gully remediation project, versus the cost of measuring/modelling and accrediting the credits.
- Monitoring of un-incised (non-gullied) drainage swales should be undertaken as proxies for the pre-incision landforms to establish the range of DIN and DON loads that might be expected under baseline conditions under fully grassed drainage swales (i.e. gully prior land surfaces).

References

APHA/AWWA/WPCF, 2012. Standard Methods for the Examination of Water and Wastewater, 21st and 22nd edition.

Bateman, A.S., Kelly, S.D., 2007. Fertilizer nitrogen isotope signatures. Isotopes Environ. Health Stud. 43, 237–247. https://doi.org/10.1080/10256010701550732

Beale, E.M.., 1962. Some uses of computers in operational research. Indutrial Organ. 27–28.

Bhadha, J.H., Xu, N., Khatiwada, R., Swanson, S., Laborde, C., 2020. Bagasse: A Potential Organic Soil Amendment Used in Sugarcane Production 1.

Biggs, J.S., Everingham, Y., Skocaj, D.M., Schroeder, B.L., Sexton, J., Thorburn, P.J. 2021. The potential fpr refining nitrogen fertiliser management through accounting for climate impacts: An exploratory study for the Tully region. Mar. Pollut. Bull. 170, 112664. https://doi.org/10.1016/j.marpolbul.2021.112664

Brodie, J., Fabricius, K., De'ath, G., Okaji, K., 2005. Are increased nutrient inputs responsible for more outbreaks of crown-of-thorns starfish? An appraisal of the evidence. Mar. Pollut. Bull. 51, 266–278. https://doi.org/10.1016/j.marpolbul.2004.10.035

Brooks, A.P., Spencer, J., Doriean, N.J.C., Twaites, R., A, G.-G., Hasan, S., Daley, J.S., Burton, J.M., Zund, P.R., 2020. NESP Project 3.1.7 Final Report: Effectiveness of alluvial gully remediation in Great Barrier Reef Catchments. Cairns.

Calcino, D., Schroeder, B., Panitz, J., Hurney, A., Skocaj, D., Wood, A., Salter, B., 2022. Australian sugarcane nutrition manual. Sugarcane Res. Aust. 122.

Corredor, D.Y., Salazar, J.M., Hohn, K.L., Bean, S., Bean, B., Wang, D., Wang, : D, 2009. Evaluation and Characterization of Forage Sorghum as Feedstock for Fermentable Sugar Production. Appl Biochem Biotechnol 158, 164–179. https://doi.org/10.1007/s12010-008-8340-y

Daley, J., Spencer, J., Brooks, A., Stout, J., Thwaites, R., In press. Direct Rain Splash and Downwearing of Internal Surfaces as an Important Erosion Process in Alluvial Gully Development. Catena.

Daley, J.S., Doriean, N.J.C., Brooks, A.P., Spencer, J., Garzon-Garcia, A., 2021. Great Barrier Reef Foundation Reef Trust Partnership Phase 3 - Final Report. Brisbane, Australia.

Dalgliesh, N., Hochman, Z., Huth, N., Holzworth, D., 2016. A protocol for the development of APSOIL parameter values for use in APSIM. CSIRO Agric. Food 1–24.

Dave Evans, R., 2008. Soil Nitrogen Isotope Composition. Stable Isot. Ecol. Environ. Sci. Second Ed. 83–98. https://doi.org/10.1002/9780470691854.CH4

De'ath, G., Fabricius, K., 2010. Water quality as a regional driver of coral biodiversity and macroalgae on the Great Barrier Reef. Ecol. Appl. 20, 840–850. https://doi.org/10.1890/08-2023.1

DeVantier, L.M., De'ath, G., Turak, E., Done, T.J., Fabricius, K.E., 2006. Species richness and community structure of reef-building corals on the nearshore Great Barrier Reef. Coral Reefs 25, 329–340. https://doi.org/10.1007/s00338-006-0115-8

Doriean, N.J.C., Bennett, W.W., Spencer, J.R., Garzon-Garcia, A., Burton, J.M., Teasdale, P.R., Welsh, D.T., Brooks, A.P., 2021. Intensive landscape-scale remediation improves water quality of an alluvial gully located in a Great Barrier Reef catchment. Hydrol. Earth Syst. Sci. 25, 867–883. https://doi.org/10.5194/hess-25-867-2021

Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar. Pollut. Bull. 50, 125–146. https://doi.org/10.1016/j.marpolbul.2004.11.028

Fabricius, K.E., Logan, M., Weeks, S., Brodie, J., 2014. The effects of river run-off on water clarity across the central Great Barrier Reef. Mar. Pollut. Bull. 84, 191–200. https://doi.org/10.1016/j.marpolbul.2014.05.012

Fabricius, K.E., Logan, M., Weeks, S.J., Lewis, S.E., Brodie, J., 2016. Changes in water clarity in response to river discharges on the Great Barrier Reef continental shelf: 2002-2013. Estuar. Coast. Shelf Sci. 173, A1–A15. https://doi.org/10.1016/j.ecss.2016.03.001

Fabricius, K.E., Okaji, K., De'ath, G., 2010. Three lines of evidence to link outbreaks of the crown-of-thorns seastar Acanthaster planci to the release of larval food limitation. Coral Reefs 29, 593–605. https://doi.org/10.1007/s00338-010-0628-z

Finlay, J.C., Kendall, C., 2008. Stable Isotope Tracing of Temporal and Spatial Variability in Organic Matter Sources to Freshwater Ecosystems. Stable Isot. Ecol. Environ. Sci. Second Ed. 283–333. https://doi.org/10.1002/9780470691854.CH10

Fox, J.F., Papanicolaou, A.N., 2008. Application of the spatial distribution of nitrogen stable isotopes for sediment tracing at the watershed scale. J. Hydrol. 358, 46–55.

Garzon-Garcia, A., Brooks, A., Doriean, N., 2021a. Nutrient export from Strathalbyn station alluvial gullies - Baseline methodology and 2018-2021 monitoring. Brisbane, Australia.

Garzon-Garcia, A., Burton, J., Ellis, R., Askildsen, M., Finn, L., Moody, P., DeHayr, R., 2018. Sediment particle size and contribution of eroded soils to dissolved inorganic nitrogen export in Great Barrier Reef catchments - Project RP178a. Department of Environment and Science, Queensland Government, Brisbane.

Garzon-Garcia, A., Burton, J., Ellis, R., Askildsen, M., Moody, P., DeHayr, R., n.d. The bioavailability of particulate nitrogen in sediment: catchment sources and processes. Prep.

Garzon-Garcia, A., Burton, J., Prance, M., Moody, P., DeHayr, R., 2019. Towards the standardisation of bioavailable particulate nitrogen in sediment methods. Department of Environment and Science, Brisbane.

Garzon-Garcia, A., Burton, J.M., Lewis, S., Bainbridge, Z., Dehayr, R., Moody, P., Brodie, J., 2021b. The bioavailability of nitrogen associated with sediment in riverine plumes entering coastal environments of the Great Barrier Reef. Mar. Pollut. Bull. 173, 112910.

Garzon-Garcia, A., Laceby, J.P., Olley, J.M., Bunn, S.E., 2017. Differentiating the sources of fine sediment, organic matter and nitrogen in a subtropical Australian catchment. Sci. Total Environ. 575, 1384–1394. https://doi.org/10.1016/j.scitotenv.2016.09.219

Haapkyla, J., Unsworth, R.K.F., Flavell, M., Bourne, D.G., Schaffelke, B., Willis, B.L., 2011. Seasonal Rainfall and Runoff Promote Coral Disease on an Inshore Reef. PLoS One 6. https://doi.org/10.1371/journal.pone.0016893

Henrique Melo Lima, M., Ananias de Assis Pires, D., Maria Almeida Moura, M., Ferreira Costa, R., Avelino Santos Rodrigues, J., Antunes Alves, K., 2017. Nutritional characteristics of Sorghum hybrids hay (Sorghum sudanense vs. Sorghum bicolor). Anim. Sci. Mar. 229–234. https://doi.org/10.4025/actascianimsci.v39i3.32524

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., Dalgliesh, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F.Y., Wang, E., Hammer, G.L., Robertson, M.J., Dimes, J.P., Whitbread, A.M., Hunt, J., van Rees, H., McClelland, T., Carberry, P.S., Hargreaves, J.N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., Keating, B.A., 2014. APSIM – Evolution towards a new generation of agricultural systems simulation. Environ. Model. Softw. 62, 327–350. https://doi.org/10.1016/J.ENVSOFT.2014.07.009

Hood, E., Williams, M.W., McKnight, D.M., 2005. Sources of dissolved organic matter (DOM) in a Rocky Mountain stream using chemical fractionation and stable isotopes. Biogeochemistry 74, 231–255. https://doi.org/10.1007/s10533-004-4322-5

Laceby, J.P., Olley, J., Pietsch, T.J., Sheldon, F., Bunn, S.E., 2015. Identifying subsoil sediment sources with carbon and nitrogen stable isotope ratios. Hydrol. Process. 29, 1956–1971. https://doi.org/10.1002/hyp.10311

Lambert, V., Bainbridge, Z.T., Collier, C., Lewis, S.E., Adams, M.P., Carter, A., Saunders, M.I., Brodie, J., Turner, R.D.R., Rasheed, M.A., O'Brien, K.R., 2021. Connecting targets for catchment sediment loads to ecological outcomes for seagrass using multiple lines of evidence. Mar. Pollut. Bull. 169, 112494. https://doi.org/10.1016/j.marpolbul.2021.112494

Lynch, M.J., Mulvaney, M.J., Hodges, S.C., Thompson, T.L., Thomason, W.E., 2016. Decomposition, nitrogen and carbon mineralization from food and cover crop residues in the central plateau of Haiti. Springerplus 5. https://doi.org/10.1186/S40064-016-2651-1

Mary, B., Recous, S., Robin, D., 1998. A model for calculating nitrogen fluxes in soil using 15N tracing. Soil Biol. Biochem. 30, 1963–1979. https://doi.org/10.1016/S0038-0717(98)00068-6

McCorkle, E.P., Berhe, A.A., Hunsaker, C.T., Johnson, D.W., McFarlane, K.J., Fogel, M.L., Hart, S.C., 2016. Tracing the source of soil organic matter eroded from temperate forest catchments using carbon and nitrogen isotopes. Chem. Geol. https://doi.org/http://dx.doi.org/10.1016/j.chemgeo.2016.04.025

Nava, V., Patelli, M., Rotiroti, M., Leoni, B., 2019. An R package for estimating river compound load using different methods. Environ. Model. Softw. 117, 100–108. https://doi.org/10.1016/J.ENVSOFT.2019.03.012

Ohte, N., Tayasu, I., Kohzu, A., Yoshimizu, C., Osaka, K., Makabe, A., Koba, K., Yoshida, N., Nagata, T., 2010. Spatial distribution of nitrate sources of rivers in the Lake Biwa watershed, Japan: Controlling factors revealed by nitrogen and oxygen isotope values. Water Resour. Res. 46. https://doi.org/W07505 10.1029/2009wr007871

Pratchett, M.S., Caballes, C.F., Wilmes, J.C., Matthews, S., Mellin, C., Sweatman, H.P.A., Nadler, L.E., Brodie, J., Thompson, C.A., Hoey, J., Bos, A.R., Byrne, M., Messmer, V., Fortunato, S.A.V., Chen, C.C.M., Buck, A.C.E., Babcock, R.C., Uthicke, S., 2017. Thirty years of research on crown-of-thorns starfish (1986-2016): Scientific advances and emerging opportunities. Diversity. https://doi.org/10.3390/d9040041

Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C. and Strong, W.M. 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agricultural Systems, 56, 1– 28.

Quilbé, R., Rousseau, A.N., Duchemin, M., Poulin, A., Gangbazo, G., Villeneuve, J.P., 2006. Selecting a calculation method to estimate sediment and nutrient loads in streams: Application to the Beaurivage River (Québec, Canada). J. Hydrol. 326, 295–310. https://doi.org/10.1016/J.JHYDROL.2005.11.008

Raphael, J.P.A., Calonego, J.C., Milori, D.M.B.P., Rosolem, C.A., 2016. Soil organic matter in crop rotations under no-till. Soil Tillage Res. 155, 45–53. https://doi.org/10.1016/J.STILL.2015.07.020

Rezende, C.A., De Lima, M., Maziero, P., Deazevedo, E., Garcia, W., Polikarpov, I., 2011. Chemical and morphological characterization of sugarcane bagasse submitted to a delignification process for enhanced enzymatic digestibility. Biotechnol. Biofuels 4, 1–19. https://doi.org/10.1186/1754-6834-4-54/FIGURES/11

Stark, J.M., Hart, S.C., 1996. Diffusion Technique for Preparing Salt Solutions, Kjeldahl Digests, and Persulfate Digests for Nitrogen-15 Analysis. Soil Sci. Soc. Am. J. 60, 1846–1855. https://doi.org/10.2136/SSSAJ1996.03615995006000060033X

Thorburn, P.J., Probert, M.E., Robertson, F.A., 2001. Modelling decomposition of sugar cane surface residues with APSIM–Residue. F. Crop. Res. 70, 223–232. https://doi.org/10.1016/S0378-4290(01)00141-1

Wooldridge, S.A., 2009. Water quality and coral bleaching thresholds: Formalising the linkage for the inshore reefs of the Great Barrier Reef, Australia. Mar. Pollut. Bull. 58, 745–751. https://doi.org/10.1016/j.marpolbul.2008.12.013

Appendix 1 Detailed laboratory methods

Methods to determine nutrient content of soil and organic litter amendments used in gully remediation works

1. Soil Amendments

a. Soil Amendment Preparation

Remediation works carried out on the ‘control’ gully and gully 13 involved applying imported topsoil that was taken from a ponded area of the property. Rock aggregate was used to stabilise slopes and gully floors (Part1, Table 1). These soil amendments were analysed for nutrient content as a potential source of nutrient to gully discharge.

Soil amendment samples were collected from the field and sent to the laboratory for each of 4 timepoints (T1 (7/10/2020), T2 (10/02/2021), T3 (21/06/2021) and T4 (4/11/2021) approximately 4 to 5 months apart (Part 1, Table 4). These amendments included:

- control topsoil,
- gully 13 topsoil,
- gully 13 area C soil,
- and red aggregate (1 rep and only for T1)

Unwanted materials such as rocks, roots and plant debris were removed from soil amendment samples arriving from the field. The soil amendment samples were air-dried at 40°C and ground to pass a 2mm sieve and stored in sealed plastic containers.

b. Soil Amendment Analysis

To determine chemical characteristics of each amendment at each timepoint the following analysis were performed.

1. Air dry moisture of soil was determined after drying a sub-sample at 105°C for 48 hours (2A1; Rayment and Lyons, 2011).
2. Soil pH and electrical conductivity (EC) were determined on a 1:5 soil to water suspension (4A1 and 3A1; Rayment and Lyons, 2011)
3. Water holding capacity (WHC%) was determined by packing soil into pre-made plastic cylinder with fitted fine mesh on the bottom and packing down by tapping on bench gently 10 times. The cylinder was immersed in about 2cm of water for 2 hours. The cylinder was then drained freely on a funnel for 2 hours. Water holding capacity was determined gravimetrically at 105°C (Choudhary et al., 1995; Wang et al., 2003). Field Capacity was set as 65% of WHC%.
4. A 2mm sieved sub-sample was analysed for the following:
    a. Bicarbonate extractable-P (Colwell-P), an estimate of plant available phosphorous (9B; Rayment and Lyons 2011).
    b. Phosphorous buffer index both adjusted for Colwell-P and unadjusted, a measure of a soils potential to adsorb P (P “fixing” ability) (PBI; 9I2b and 9I4b; Rayment and Lyons, 2011).
    c. Total Kjeldahl N and total Kjeldahl P (7A2a and 9A3a respectively; Rayment and Lyons, 2011).
5. A sub-sample of air-dried sample was ground to <0.05mm and total carbon and total nitrogen determined by combustion (LECO CN928 Analyser, Michigan, USA; 6B2b and 7A5; Rayment and Lyons, 2011). Another sub-sample ground to <0.5mm was treated with acid prior to combustion to remove any carbonates present and total organic carbon determined (6B3; Rayment and Lyons, 2011).
6. A sub-sample of air-dried sample was ring milled and analysed for carbon and nitrogen isotopic composition using an Isotope Ratio Mass Spectrometer (IRMS) (Delta V Advantage Isotope Ratio Mass Spectrometer, Thermo Electron Corporation)
7. Soluble nutrients were analysed on a 1:10 soil to DI water suspension, filtered to <0.45µm and analysed for:
    a. Soluble N - A modified Kjeldahl procedure followed by a colorimetric determination of soluble total Kjeldahl N (Searle, 1984).
    b. Soluble N - (Inorganic N) Ammonium-N and oxidised-N were determined using standard methods 4500-NH3 G and 4500-NO3 I, respectively (APHA/AWWA/WPCF, 2017).

   c. Dissolved Organic Carbon – Inorganic Carbon was removed in a reaction with phosphoric acid. Ultraviolet irradiation and heat then oxidised the organic carbon and the resulting carbon dioxide was quantified using a non-dispersive infrared detector (NDIR) (APHA/AWWA/WPCF, 2017, Section 5310).

8. Extractable ammonium-N was analysed on a 0.25M Potassium Sulphate (K_2SO_4) extraction and ammonium-N determined using standard method 4500-NH3 G (APHA/AWWA/WPCF, 2017).
9. Dissolved organic N (DON) was determined by subtracting soluble ammonium-N from the soluble total Kjeldahl N.
10. Dissolved inorganic N (DIN) was determined by adding soluble ammonium-N and soluble oxidised-N.
11. Adsorbed ammonium-N was determined by subtracting soluble ammonium-N from the extractable ammonium-N.

2. Organic Litter Amendments

a. Litter Amendment Preparation

Gully remediation works included the application of organic litter to soil surfaces. The different litter types used in the remediation works were analysed as a potential source of nutrients to the gully discharge.

Litter amendment samples were collected from the field and sent to the laboratory for each of 4 timepoints (T1, T2, T3 and T4) approximately 4-5 months apart (Part 1, Table 4). The litter amendments included:

- treatment 1 haymulch
- treatment 4 haymulch
- control bagasse
- control haymulch
- gully 13 bagasse
- gully 13 haymulch

Materials such as rocks and soil were removed from the litter material as best as was possible. The litter was air-dried at 40°C, cut into 2-3cm lengths, and stored in paper bags.

b. Litter Amendment Analysis

To determine chemical characteristics of each litter amendment at each timepoint the following analyses were performed on 3 replicates of each litter amendment.

1. A sub-sample was dried at 65°C for 48hrs to determine moisture content.
2. Sub-samples dried at 65°C were ground to <1.0mm and analysed for the following:
    a. Total Kjeldahl N using a modification of the method of Searle (1974) which uses the indo-phenol reaction.
    b. Total Kjeldahl P using a modification of Murphy and Riley (1962) which uses the phosphomolybdate colour reaction.
3. A sub-sample of air-dried sample was ground to <0.05mm and total carbon and total nitrogen determined by combustion (LECO CN928 Analyser, Michigan, USA; 6B2b and 7A5; Rayment and Lyons, 2011).
4. A sub-sample of air-dried sample was ring milled and analysed for carbon and nitrogen isotopic composition using an Isotope Ratio Mass Spectrometer (IRMS) (Delta V Advantage Isotope Ratio Mass Spectrometer, Thermo Electron Corporation).
5. Soluble nutrients for each litter amendment were determined from a suspension of 0.75g of litter in 300mL of deionised (DI) water, filtered to <0.45µm and analysed for:
    a. Soluble N - A modified Kjeldahl procedure followed by a colorimetric determination of soluble total Kjeldahl N (Searle, 1984).
    b. Soluble N - (Inorganic N) Ammonium-N and oxidised-N were determined using standard methods 4500-NH3 G and 4500-NO3 I, respectively (APHA/AWWA/WPCF, 2017).
    c. Dissolved Organic Carbon – Inorganic carbon was removed in a reaction with phosphoric acid. Ultraviolet irradiation and heat then oxidised the organic carbon and the resulting carbon dioxide was quantified using a non-dispersive infrared detector (NDIR) (APHA/AWWA/WPCF, 2017, Section 5310).

6. Dissolved organic N was determined by subtracting soluble ammonium-N from the soluble total Kjeldahl N.
7. Dissolved inorganic N (DIN) was determined by adding soluble ammonium-N and soluble oxidised-N.

3. Rock aggregate amendment

Soluble N fractions of the rock aggregates used in the gully remediation works were extracted using deionised water in multiple steps.

1. Aggregates of comparable size from each of the treatments were weighed and placed in a 250mL beaker with 100mL DH2O water to cover the sample stirred for 1 hour with a magnetic stirrer bar and filtered to <0.45µm.
2. This step was repeated 4 times for each of the aggregate samples and analysed for:
    a. Soluble N - (Inorganic N) Ammonium-N and oxidised-N were determined using standard methods 4500-NH3 G and 4500-NO3 I, respectively (APHA/AWWA/WPCF, 2017).
    b. Soluble N - A modified Kjeldahl procedure followed by a colorimetric determination of soluble total Kjeldahl N (Searle, 1984).

Method for ^{15}N abundance of NO_3^--N and NH_4^+-N in extracts of soil and organic litter amendments

The ^{15}N abundance in soil amendments (Appendix Section 1) and litter amendments (Appendix Section 3) for both NO_3^--N and NH_4^+-N were determined using the micro-diffusion method (Brooks et al, 1989; Stark and Hart, 1996) followed by an Isotope Ratio Mass Spectrometer (IRMS) finish.

Soils were extracted in a 1:5 suspension with 2M Potassium Chloride (KCl) solution and litter amendments were extracted using a 1:10 suspension with DI water. Prior to diffusion of NO_3^--N and NH_4^+-N, these extractions were analysed for NO_3^--N (oxidised-N) and NH_4^+-N (ammonium-N) concentrations using an autoanalyzer and standard methods 4500-NH3 G and 4500-NO3 I, respectively (APHA/AWWA/WPCF, 2017).

The concentration of ammonium-N and oxidised-N for each amendment was used to determine the volume of extract to use in the micro-diffusion method to achieve a target mass of approximately 20ug N per sample, the minimum amount of N required to get a response from the IRMS.

To achieve the target N mass of 20µg, the volume of extractant needed for each sample of NO_3^--N or NH_4^+-N was calculated using the following formula:

Volume mL (NO_3^--N or NH_4^+-N extract) = 20 / (Concentration of NO_3^--N or NH_4^+-N in mg/L)

In summary, the calculated volume of the sample extract to achieve the target N mass was placed in a 100mL container, followed by additional 2M KCl or deionised (DI) water, depending on whether it was a soil or litter sample, respectively, to obtain a final volume of 60mL. Similarly, three replicate standard samples were prepared for both 2M KCl and DI water extractions, by placing 60mL of either 2M KCl or DI water in the container, and a 40µL aliquot of prepared standard solution to achieve concentrations of 1mg/L NH_4^+-N with 1atm% ^{15}N and 1mg/L NO_3^--N with 5atm% ^{15}N. An acid-washed glass bead was added to each container to assist stirring. 1mL of 2% sulfamic acid was added and swirled to destroy any NO_2^- by reducing to N_2.

To diffuse the NH_4^+-N, approximately 0.2g of Magnesium Oxide (MgO) was added to the diffusion container to raise the pH, resulting in volatilisation of NH_3. NH_3 was collected on filter disks (6mm diameter) that had been cut from filter papers (Whatman #40), acidified with 10µL of 2.5mol $KHSO_4$ and sealed in Teflon tape attached to the underside of the container lid. After 6 days at room temperature with daily agitation to resuspend the MgO, the filter disk was removed, dried, and wrapped in a tin capsule.

To diffuse the NO_3^--N, the NH_4^+-N must be removed. MgO powder was added to the sample containers which were then left open overnight to allow NH_3 to dissipate. 0.1mL of 30% Brij-35 was added to reduce spattering and entrapment of NH_3 in H_2 bubbles during the diffusion. The acidified filter disks sealed in Teflon tape were attached to the lids and 0.4g of Devarda's alloy added and the lid closed. After 6 days at room temperature with daily agitation to resuspend the MgO, the filter paper was removed, dried, and wrapped in a tin capsule.

The tin capsules from the NH_4^+-N and NO_3^--N diffusion were then sent to the laboratory for ^{15}N abundance analysis by Isotope Ratio Mass Spectrometer (IRMS) (Delta V Advantage Isotope Ratio Mass Spectrometer, Thermo Electron Corporation).

Long-term Incubation for N mineralisation from organic litter amendments and soils

4. Sample preparation of soil and organic litter amendments used for incubation

Five amendments (4 organic amendments and 1 soil) were used for the long-term incubation experiment. These consisted of composite samples from the various control and treated gullies as described below. They were all air-dried at 40°C.

- topsoil combined: control & gully 13 (Time 1)
- bagasse combined; control and gully 13 (Time 1)
- haymulch combined: treatment 1 & treatment 4 (Time 1)
- haymulch combined: control & gully 13 (Time 1)
- haymulch combined: control & gully 13 (Time 4)

The following parameters were determined prior to the start of the incubation.

1. Air dry moisture of the combined topsoil was determined after drying a sub-sample at 105°C for 48 hours and subtracting the weight from the air-dry at 40°C weight (2A1; Rayment and Lyons, 2011).
2. Water holding capacity (WHC%) of combined topsoil was determined by packing soil into a pre-made plastic cylinder with fitted fine mesh on the bottom and packed down by gently tapping on bench ten times. The cylinder was immersed in water for 2 hours and then allowed to drain freely on a funnel for 2 hours. Water holding capacity was determined gravimetrically at 105°C (Choudhary et al., 1995; Wang et al., 2003). Field Capacity was set as 65% of WHC%.
3. Moisture content (%) of combined litter amendments were determined by drying a sub-sample at 65°C for 48 hours.
4. As a surrogate for water holding capacity, the amount of water that could be held by the combined litter material was determined by placing litter (up to about 4 cm height) into 700mL plastic jar with a lid with holes drilled. The jar was filled with DI water to cover the litter and a lid placed on top to reduce evaporation. Litter was saturated for 24 hours. Jar was then inverted onto a rack for 24 hours so water could drain freely (Naeth et al, 1991). The amount of water that was retained by the combined litter amendments was determined gravimetrically at 105°C.

5. Incubation Set-up

Two concurrent incubation designs were implemented for the experiment. This involved a permanently wet (WET) incubation, and an alternating wet and dry (WET/DRY) incubation. Both designs were incubated at 30°C for the duration of the experiment. The WET incubation had all samples wet up to field capacity with DI water twice weekly for the length of the incubation. The WET/DRY incubation cycled through a 2-week WET period where samples were wet to field capacity twice weekly, followed by a 4-week DRY period where the samples were left to dry (see Table 19 below for WET/DRY timetable). From both WET and WET/DRY incubations, three replicates of each of the five amendments were sampled every two weeks for 210 days, totalling 15 time points. An exception is the "haymulch combined: control & gully 13 (Time 1)" amendment which was sampled at only 10 time points (these 10 time points are shaded in Table 19) due to limited availability of samples.

The incubation set up had amendment samples placed in 100mL plastic jars with lids that had 3 holes (2mm) drilled in the top to allow air flow.

For the combined topsoil amendment, 30g of air-dried soil was placed into each incubation jar and made up to field capacity with DI water. The weight of the incubation jar plus wet soil at field capacity was recorded on the side of each jar and used to determine amount of DI water to add at each rewetting. The litter amendments followed the same procedure but only 5g of air-dry litter was placed in the incubation jars.

Table 19 Timetable of alternating wet and dry periods for the WET/DRY incubation. Each Wet or Dry cycle refers to the 14-day period preceding each harvest.

CYCLE	Wet	Dry	Dry	Wet	Dry	Dry	Wet	Dry	Dry	Wet	Dry	Dry	Wet	Dry	Dry
HARVEST	day 14	day 28	day 42	day 56	day 70	day 84	day 98	day 112	day 126	day 140	day 154	day 168	day 182	day 196	day 210
Haymulch combined: control & gully 13 (time 1)								10 x sampling points are shaded							

6. **Analysis of incubated amendment samples**

At each harvest time point, three reps for each amendment combination were removed from each incubation set up (wet or wet/dry cycle), extracted with 0.25M Potassium Sulphate (K_2SO_4) in a 1:10 ratio for soil amendment, and a 1:40 ratio for litter amendments, and filtered to <0.45µm. The filtered samples were analysed for the following:

a. Soluble N - (Inorganic N) - Ammonium-N (NH_4-N) and oxidised-N (NO_x-N) were determined using standard methods 4500-NH3 G and 4500-NO3 I, respectively (APHA/AWWA/WPCF, 2017) with an autoanalyzer finish.

b. Dissolved Nitrogen and Dissolved Organic Carbon – determined by a method that couples a high-temperature catalytic oxidation (or combustion) total organic analyser with a chemiluminescent nitrogen detector (Analytik Jena multi-N/C 3100 Flow injection TOC analyser).

c. Dissolved organic N (DON) was determined by subtracting soluble ammonium-N from the dissolved nitrogen.

d. Dissolved Inorganic N (DIN) was determined by adding soluble ammonium-N and soluble oxidised-N.

The accumulation of inorganic N species over time during the incubations was used as an indicator of net mineralisation and provided an estimate of total mineralisable N where values stabilised.

References

APHA/AWWA/WPCF, 2017. Standard Methods for the Examination of Water and Wastewater, 23rd ed. American Public Health Association, Washington, USA.

Brooks, P. D., Stark, J. M., McInteer, B. B., Preston, T., 1989. Diffusion method to prepare soil extracts for automated nitrogen-N analysis. Soil Science Society of America Journal 53, 1707-1711.

Choudhary, M.I., Shalaby, A.A., Al-Omran, A.M., 1995. Water holding capacity and evaporation of calcareous soils as affected by four synthetic polymers. Commun. Soil Sci. Plant Anal. 26, 2205–2215.

Murphy, J. and Riley, J.P. (1962). A single solution method for the determination of soluble phosphates in natural Waters. Anal Chim.Acta 27, 31– 6.

Naeth, M. A., Bailey, A. W., Chanasyk, D. S., & Pluth, D. J. (1991). Water holding capacity of litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta. Journal of Range Management, 44(1), 13-17.

Rayment, G.E., Lyons, D.J., 2011. Soil Chemical Methods - Australasia. CSIRO publishing, Collingwood, VIC, Australia.

Searle PL (1974) 'Automated colorimetric determination of ammonium ions in soil extracts with 'Technicon AutoAnalyzer II' equipment'. New Zealand Journal of Agricultural Research, 18: 183–187.

Stark, J. M., Hart, S. C., 1996. Diffusion technique for preparing salt solutions, Kjeldahl digests, and persulfate digests for nitrogen-15 analysis. Soil Science Society of America Journal 60, 1846-1855.

Wang, W.J., Dalal, R.C., Moody, P.W., Smith, C.J., 2003. Relationships of soil respiration to microbial biomass, substrate availability and clay content. Soil Biol. Biochem. 35, 273–284.

Appendix 2 TUFLOW direct rainfall model

The estimated volumes and discharge for each of the gullies in the study for each rainstorm event was predicted using TUFLOW GPU direct rainfall model. The direct rainfall model provides a significantly more detailed approach relative to more simplistic hydrologic models which simply apply to change in storage approach (ΔS = In – Out). The direct rainfall model applies excess rainfall as a time series directly to each active cell of the 2-dimensional TUFLOW model domain. The accumulated water is then routed through the landscape using Shallow Water Equations.

This appendix briefly outlines the general methods, assumptions, and inputs needed to compute volumes and discharges for the Strathalbyn gullies and discusses the validation data and overall results from the modelling.

Hydraulic Model Development:

Introduction

Due to the availability of high quality lidar which captured the before and after topography of the gully remediation in the study area is suitable for 2D hydraulic modelling of direct rainfall events to predict the volume and discharge for each of the gullies. We selected TUFLOW GPU which is a finite difference numerical model and is highly suited for simulating complex overland flow paths. TUFLOW GPU employs an option to sub-grid sample the underlying topography. This allows the model to be run at a coarser resolution decreasing computation time while still accounting for subtle variations in the landscape and resulting flow paths.

We ran the model as a double precision model, as this was a suggested option made in the TUFLOW manual when using direct rainfall over smaller areas. The inputs needed for a direct rainfall model is a digital elevation model, a map of different materials (used to assign roughness values to), and rainfall data to be used as the source of flowing water in the model.

Model Extent and Parameters

Each of the seven runoff events (Table 22) where samples were collected was used to subdivide the total rainfall data into storm events. These events were used as the source of flow to each of the TUFLOW models. The lidar derived digital elevation models for each time was merged with the original DEM from 2016, to ensure that the entire catchment was used to generate flow. We assume that the upland area/pasture from the 2016 DEM remained relatively unchanged, whereas each subsequent lidar capture around the gullies represented the changes in topography pre and post gully rehabilitation. See Table 22 for information for each of the seven models and DEM information.

Table 20: DEM information and total model run lengths

Event ID	Lidar capture date	DEM cell size	Model Cell size	Model Time step (seconds)	Total hours	Wet season
EV1_2022	*2021*	*1 m*	*5 m*	*1, max 5*	*77*	*2021-2022*
EV2_2022	*2021*	*1 m*	*5 m*	*1, max 5*	*60*	*2021-2022*
EV3_2021	*2021*	*1 m*	*5 m*	*1, max 5*	*139*	*2020-2021*
EV4_2020	*Sep 2019*	*1 m*	*5 m*	*1, max 5*	*242*	*2019-2020*
EV5_2020	*Sep 2019*	*1 m*	*5 m*	*1, max 5*	*374*	*2019-2020*
EV6_2019	*Sep 2018*	*1 m*	*5 m*	*1, max 5*	*62*	*2018-2019*
EV7_2018	*Sep 2018*	*1 m*	*5 m*	*1, max 5*	*202*	*2018-2019*

Initial testing of the direct rainfall model indicated presence of pits in the DEM. The DEMs were filled and hydrologically conditioned. A flow accumulation model was used to compute flowlines. The flowlines were then used to force relatively consistent flow paths from the upland areas into the gully margins. This was done by simply “burning” as shallow 5 cm channel into the DEM.

In each of study gullies, stage samplers were installed at the outlets, and 2 weirs were installed in the upland area to measure overland flow volumes prior to the flow entering the gullies. Additionally, there were 2 rain gauges installed to record rainfall at the study areas (Figure 31).

Roughness values were assigned (Table 21) to upland areas and areas within the gully. This was largely done based on the authors knowledge with the study area. These were initially set, and then varied to match the recorded discharge at the weir on Gully 13, and the stage sampler also on Gully 13. See Validation section.

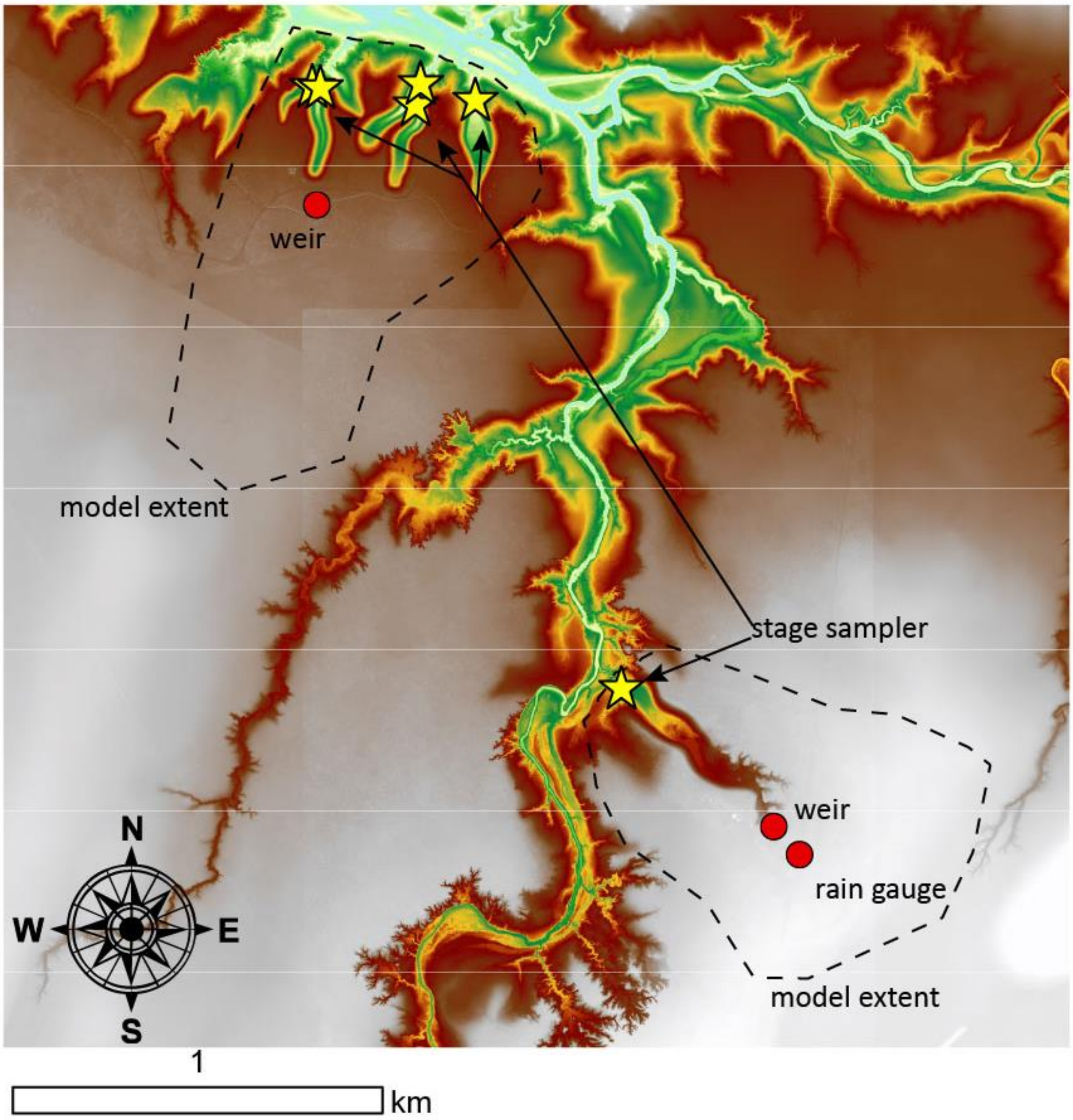


Figure 31: Location map showing the model extents (dashed line) and the locations of stage samplers (stars) and the location of the weirs and rain gauges (red dots).

Table 21: List of materials and final roughness values used in each of the models

Materials	Roughness Value
Upland/Pasture	0.07
In gully grass/cover	0.04
In gully bare earth	0.02
Gully channel	0.035

We used the direct rainfall method to supply flow to the model. We opted to use the initial loss and continuing loss method to generate excess overland flow from the rainfall. Although there are other options to simulate infiltration, we currently do not have infiltration measurements for the soils at the site. Therefore, we assumed an initial loss ranging from 20 to 15 mm, then falling to a continuing loss of 5 mm for the remainder of the model. Earlier storms in the wet season were assigned an initial loss of 20 mm and later storms in the wet season were assigned an initial loss of 15 mm. While this may result in somewhat erroneous flow data, it is consistent within events and year to year.

Model Validation:

The recorded discharge and stage data recorded at Gully 13 were used for model validation due to this data being the most consistent and continuous data for the site. Figure 31 indicates the locations of the data recorders and weir. Initial model runs were completed and the compared against the recorded data. Specifically, we checked for similarities between peak discharge and the timing and width of the simulated hydrograph relative to the recorded hydrograph. Roughness values were varied up or down to the final values reported in Table 21. Figure 32 illustrates the final simulated hydrograph. Overall, the modelled data is very similar to the recorded data, and we accepted these roughness values and applied them to all seven of the event models.

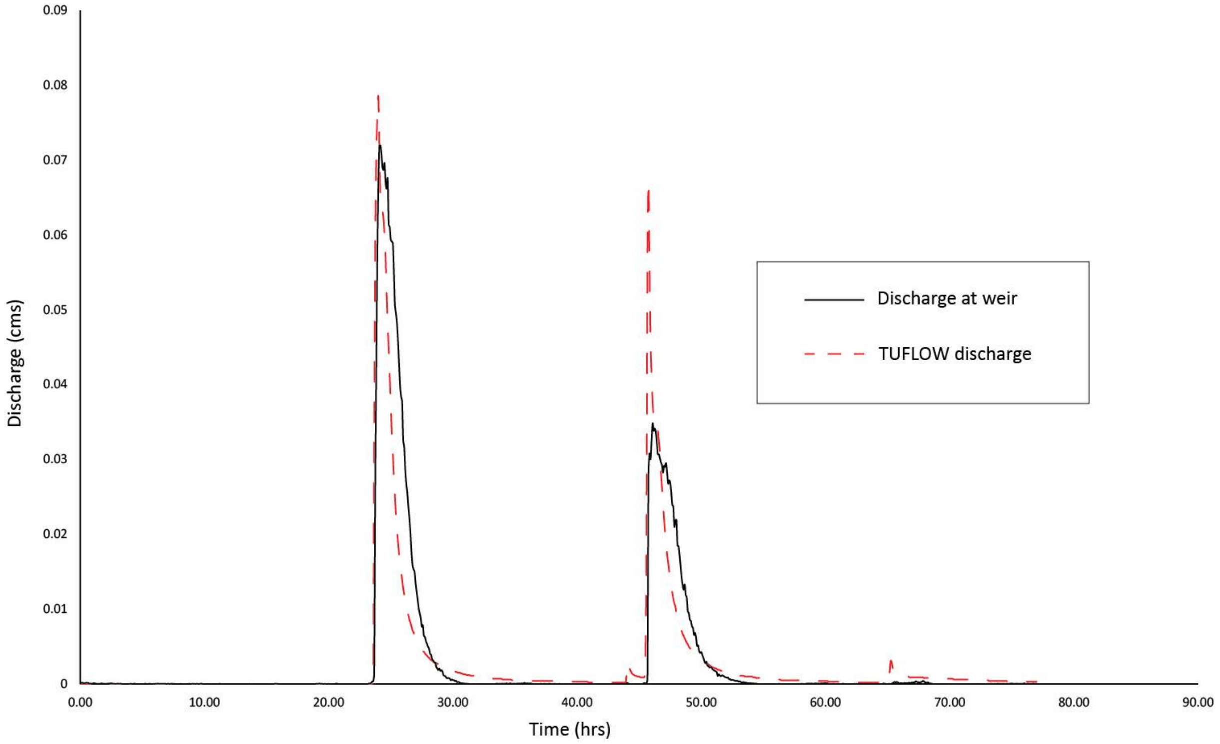


Figure 32: Model validation for the weir at Gully 13. Red dotted line is the simulated hydrograph, and the black line is the recorded discharge.

Model Results:

Output from each of the models resulted in a stage, discharge, and total volume from each of the outlets of the gullies where samples were collected. Table 22 reports the total volumes for each of the model runs at each site. Overall, the simulated runoff events fall within “real world” values that we would expect from gullies pre and post rehabilitation.

Table 22: Reported volumes from each event

	Total Volume (m^3) from each gully					
Event ID	**Control**	**G13 outlet**	**G13 OFPASS**	**Treat. 1**	**Treat. 4**	**Treat. 5**
EV1	*2951*	*13303*	*887*	*941*	*1752*	*5303*
EV2	*2614*	*10339*	*719*	*856*	*1490*	*3710*
EV3	*979*	*5006*	*350*	*331*	*580*	*1415*
EV4	*4524*	*10521*	*1229*	*437*	*870*	*4988*
EV5	*6915*	*16673*	*1830*	*648*	*1298*	*8583*
EV6	*2077*	*4850*	*578*	*360*	*477*	*2822*
EV7	*3512*	*8095*	*960*	*630*	*791*	*4833*

As a final example, we illustrate two modelled hydrographs from Event 1 at Gully 13 (Figure 33), and Event 6 at Gully Treatment 6 (Figure 34). As you can see, we generate overland flow and a hydrograph as the local rainfall intensifies.

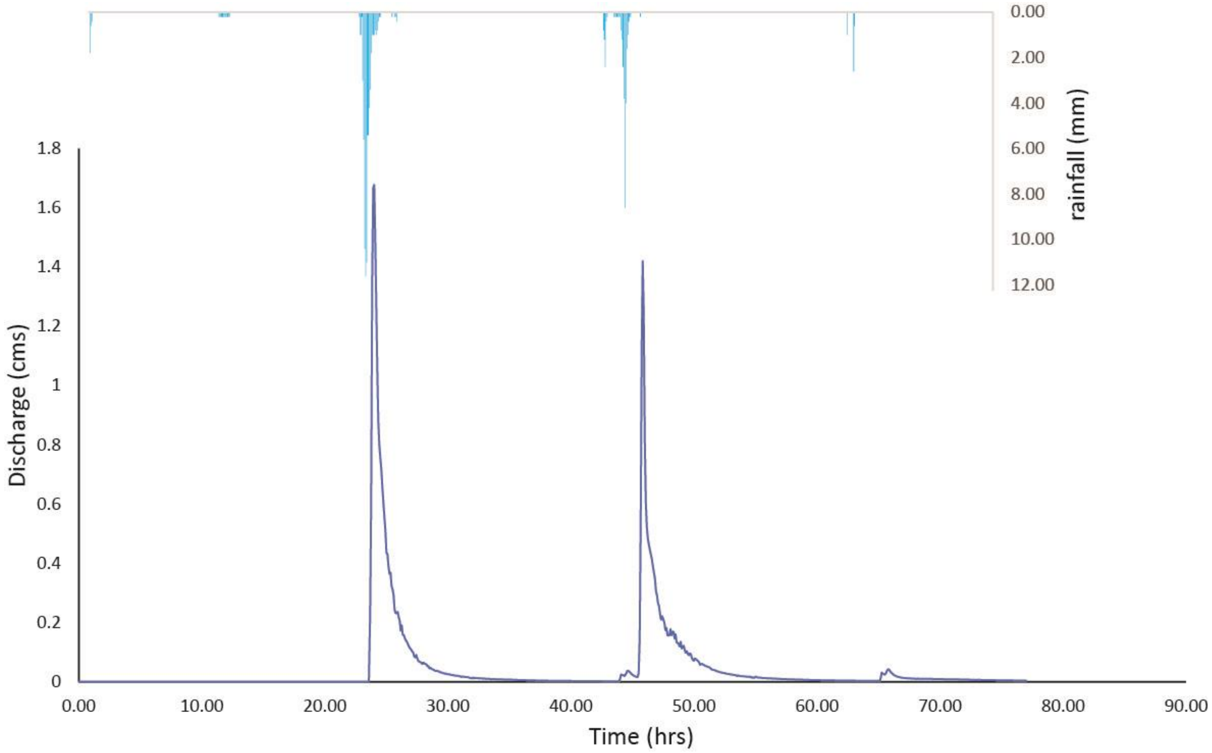


Figure 33: Modelled hydrograph for Event 1 at Gully 13.

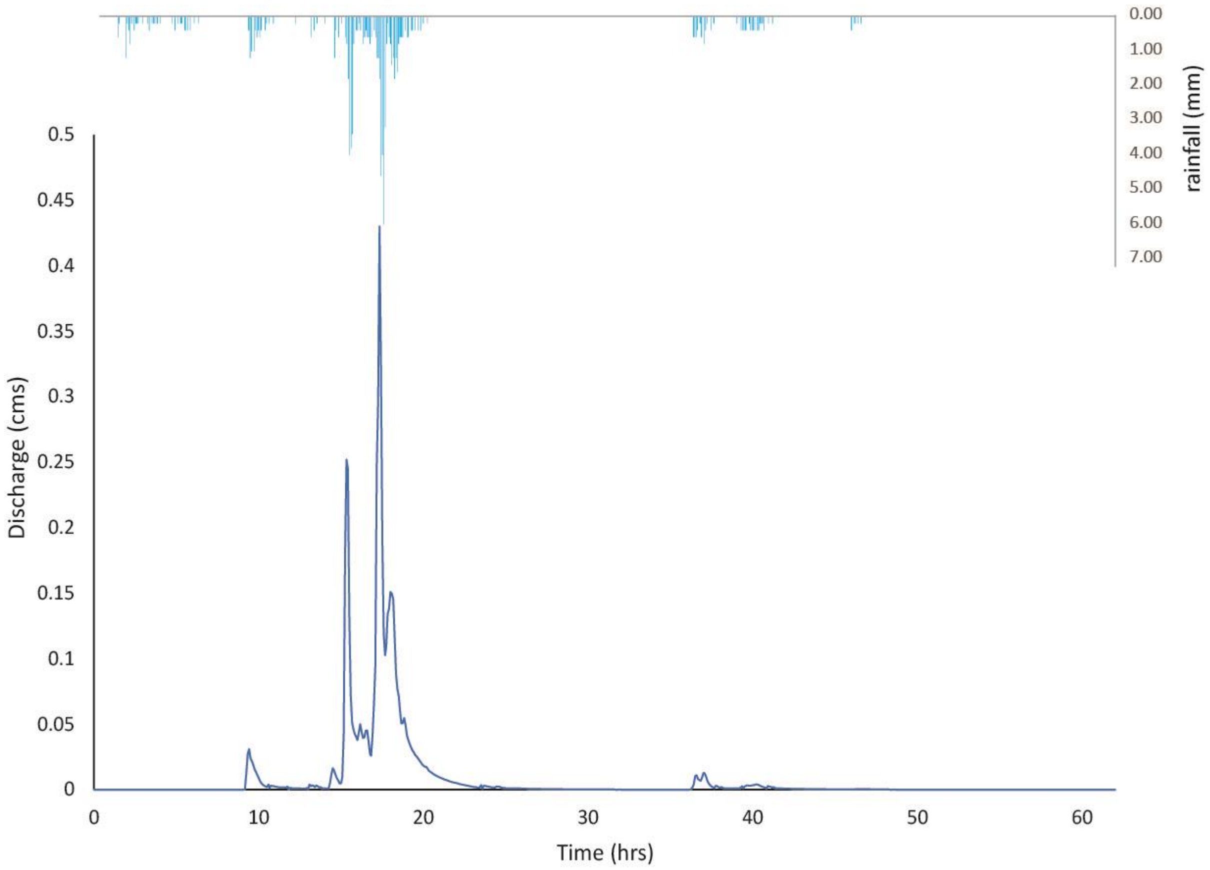


Figure 34: Modelled hydrograph for Event 6 at Treatment 4.

Data availability:

- Results of these models are available in the spreadsheet included with this report.
    - File name: TUFLOW_Results_StormEvents_22_AUG_2022.xlsx
- TUFLOW model files are available by request from Justin Stout.
    - Email: justin.stout@canterbury.ac.nz

Appendix 3 Calculation of the total nutrient inputs to the gullies from the amendments

Amendment weights were calculated from volume applied and bulk density. The bulk density of the coarse and fine aggregate was determined by filling a 5-litre plastic bucket with aggregate and weighing the contents. The bulk density of bagasse was obtained from a literature search. The volume of amendment was calculated from the layer depth and surface area given in the Schedule of Quantities in various reports. For hay, the amount applied was calculated from the number of bales, bale weight and dry matter content.

Error analysis was carried out by assigning standard deviations to each of the quantities in the calculations using educated guesses and propagating these errors through the calculations using the following formula where Δx and Δy are standard deviations:

Addition and Subtraction: z = x + y   or   z = x – y

$$Dz = \sqrt{(\Delta x)^2 + (\Delta y)^2}$$

Multiplication and Division: z = x y or z = x/y

$$\frac{\Delta z}{z} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2}$$

The calculated weights of imported amendments are given in *Table 23*. Using the weights in *Table 23* the weight of total nutrients imported to each gully in the amendments used during remediation was calculated and are listed in Table 24. The total nutrients imported to the gullies represent the total pool of additional nutrients that may be available to contribute to export from the gullies during runoff events.

Table 23. Calculated weight of imported amendments added to the gullies during remediation

Site	Sub-Areas	Amendment layers from bottom to top[A]	Depth of Layer (mm)		Surface Area (m2)			Volume Applied (calculated)	Volume Applied (Reports)		Bulk Density of amendment (kg/m^3)			Weight of amendment applied for imported amendments.			
			Value	**SD[C]**	**Value**	**SD[D]**	**Ref.**	**(m^3)**	**(m^3)**	**Ref.**	**Value**	**SD**	**Ref.**	**(kg)**	**SD**	**(tonne)**	**SD**
T1	Bed	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm.			1505	75	E							2709	192	2.71	0.19
		Graded rock bed (50-150mm size)	100	20	1505	75	E	150.5	151	E	1111	10	H	167206	34503	167.21	34.50
	Batter	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm.			5,674	284	E							10213	722	10.21	0.72
		Layer of crushed aggregate (<50mm size) on 75% of the batter surface area.	200	20	5,674	284	E	851.1	851	E	1475	10	I	1255630	140641	1255.63	140.64
		Layer of topsoil on 25% of batter surface area. Used topsoil scavenged during reshaping.	200		5,674	284	E	283.7	284	E							
		Blanket mulching with Rhodes grass hay. Allocated 45 bales (450kg, 8' x4 'x 3') to batters based on surface area. Used an estimate of 85% DM[B]. (SD-No of bales = 2, SD-Wt of bale = 45kg, SD-Dry wt fraction = 0.05)			5,674	284	E							17213	2138	17	2.14
		Hand seeding of site (~20kg /ha) using exotic perennial grass species including Tolga Rhodes and Sabi grass. (SD-Seeding Rate= 1 kg/ha).			5,674	284	E							11	1	0.01	0.0008
		Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm.			3765	188	E							6777	479	6.78	0.48
		Layer of crushed aggregate (<50mm size) on 75% of the batter surface area.	100		3765	188	E				1475	10	I	416588	21020	416.59	21.02
	Up-slope Area (Scarp)	Layer of topsoil assumed to have been scavenged from gully during reshaping.	100		3,765	188	E	376.5	377	E							
		Blanket mulching with Rhodes grass hay. Allocated 30 bales (450kg, 8' x4 'x 3') to batters based on surface area. Used an estimate of 85% DM[B]. (SD-No of bales = 2, SD-Wt of bale = 45kg, SD-Dry wt fraction = 0.05).			3,765	188	E							11475	1535	11.48	1.54
		Hand seeding of site at (~20kg /ha) using exotic perennial grass species including Tolga Rhodes and Sabi grass. (SD-Seeding Rate= 1 kg/ha).			3,765	188	E							7.53	1	0.008	0.0005
	Catchment	Fenced for managed stock access															
		Diversion bund to intercept catchment flows															
	Total				10,944	341											

Site	Sub-Areas	Amendment layers from bottom to top[A]	Depth of Layer (mm)		Surface Area (m2)			Volume Applied (calculated)	Volume Applied (Reports)		Bulk Density of amendment (kg/m^3)			Weight of amendment applied for imported amendments.			
			Value	**SD[C]**	**Value**	**SD[D]**	**Ref.**	**(m^3)**	**(m^3)**	**Ref.**	**Value**	**SD**	**Ref.**	**(kg)**	**SD**	**(tonne)**	**SD**
T4	Bed	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm.	150		3547	177	E							6385	451	6.38	0.45
		Graded rock bed (50-150mm size)	100		3547	177	E	354.7	355	E	1111	10	H	394072	20020	394.07	20.02
	Batter	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm.	150		14329	716	E							25792	1824	25.79	1.82
		Layer of crushed aggregate (<50mm size) on 75% of the batter surface area.	200	20	14329	716	E	2865.8	2,149	E	1475	10	I	3170941	355173	3170.94	355.17
		Layer of topsoil on 25% of batter surface area. Used topsoil scavenged during reshaping.	200		14329	716	E	716.45	716	E							
		Blanket mulching with Rhodes grass hay. Allocated 112 bales (450kg, volume = 8'x4'x3') to batters based on surface area. Used an estimate of 85% DM[B]. (SD-No of bales = 2, SD-Wt of bale = 45kg, SD-Dry wt fraction = 0.05).			14329	716	E							42840	5217	21	5
		Hay bunds on the contour - on northeast batter only.															
		Hand seeding of site on two separate occasions each at (~20kg/ha) using exotic perennial grass species including Tolga Rhodes and Sabi grass			14329	716	E							57	4	0.057	0.004
	Up-Slope Area (Scarp)	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm			5,216	261	E										
		Layer of crushed aggregate (<50mm size) on 75% of the batter surface area.	100		5,216	261	E				1475	10	I	577138	29121	577.14	29.12
		Layer of topsoil assumed to have been scavenged from gully during reshaping.	100		5,216	261	E	521.6	522	E				9389	2402	7.65	2
		Blanket mulching with Rhodes grass hay. Allocated 41 bales (450kg, 8'x4'x 3') to batters based on surface area. Used an estimate of 85% DM[B]. (SD-No of bales = 2, SD-Wt of bale = 45kg, SD-Dry wt fraction = 0.05).												15683	2402	7.65	2
		Hand seeding of site on two separate occasions each at (~20kg /ha) using exotic perennial grass species including Tolga Rhodes and Sabi grass			5,216	261	E							21	1	0.021	0.001
	Catchment treatments	Fenced for managed stock access															
		Diversion bund to intercept catchment flows															
	Total				23,092	783											

Site	**Sub-Areas**	**Amendment layers from bottom to top^{A}**	**Depth of Layer (mm)**		**Surface Area (m2)**			**Volume Applied (calculated)**	**Volume Applied (Reports)**		**Bulk Density of amendment (kg/m^3)**			**Weight of amendment applied for imported amendments.**			
			Value	**SD^{C}**	**Value**	**SD^{D}**	**Ref.**	**(m^3)**	**(m^3)**	**Ref.**	**Value**	**SD**	**Ref.**	**(kg)**	**SD**	**(tonne)**	**SD**
Control	Bed	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm. Not mentioned in Report 2 but assumed to have been done.			1575	79	F							2835	200	2.84	0.20
		Graded rock bed (50-150mm size)	100		1575	79	F	157.5	158	F	1111	10	H	174983	8890	174.98	8.89
	Batter	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm.			18275	914	F							32895	2326	32.90	2.33
		Layer of crushed aggregate (<50mm size)	100	20	18275	914	F	1827.5	1828	F	1475	10	I	2696115	556119	2696	556.12
		Layer of imported topsoil	100	20	18275	914	F	1827.5	1828	F	1100	10	J	2010250	414826	2010	414.83
		Blanket mulching with bagasse	75	20	18275	914	F	1370.6	1371	Calculated from depth and area	120	10	K	164475	46682	164	47
		Rock checks on batters at upstream end of design. (SD-Volume = 10%)							36		1111	10	H	39996	4016	40	4
	Up-slope Area (Scarp)	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm.			7818	391	F							14072	995	14.07	1.00
		Layer of crushed aggregate (<50mm size)	50	20	7818	391	F	390.9	391	F	1475	10	I	576696	232506	577	232.51
		Layer of imported topsoil	50		7818	391	F	390.9	391	F	1100		J	429990	21500	430	21.50
		Hay bunds on the contour made from Rhodes Grass hay round bales. Drone photos suggest that 32 round bales were used. Used a dry wt of 255kg (average of 4x4 and 5x4 round bales)[B] (SD-No of bales = 2, SD-Dry Wt of bale = 45kg).												8160	1528	8	2
	Total				27668	997											

Site	Sub-Areas	Amendment layers from bottom to top[A]	Depth of Layer (mm)		Surface Area (m2)			Volume Applied (calculated)	Volume Applied (Reports)		Bulk Density of amendment (kg/m^3)			Weight of amendment applied for imported amendments.			
			Value	SD[C]	Value	SD[D]	Ref.	(m^3)	(m^3)	Ref.	Value	SD	Ref.	(kg)	SD	(tonne)	SD
Gully 13	Bed	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm. Not mentioned in Report 2 but assumed to have been done.			6748	337	G							12146	859	12.15	0.86
		Graded rock bed (50-150mm size)	100		6748	337	G	674.8	As required	G	1111	10	H	749703	38088	749.70	38.09
		2 elevated rock sills. Assumed to be 50-150 mm quarry rock. (SD-Volume = 10%)							148	G	1111		H	164428	16443	164	16
		Rock Check Dams. Assumed to be 50-150 mm quarry rock. (SD-Volume = 10%)							147	G	1111		H	163317	16332	163	16
	Batter	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm.	150		25186		G							45335	2267	45	2.27
		Layer of crushed aggregate (<50mm size)	100	20	25186	1,259	G	2518.6	2518	G	1475	10	I	3715696	766424	3716	766.42
		Layer of imported topsoil	100		25186	1,259	G	2518.6	2518	G	1100		J	2770460	138523	2770	138.52
		Blanket mulching with bagasse	75	20	25186	1,259	G	1889.0	1889	G	120	10	K	226674	64335	227	64
	Up-slope Area (Scarp)	Gypsum (18t/ha, SD: 0.9) incorporated to a depth of 150mm.			11535	577	G							20763	1468	21	1.47
		Layer of crushed aggregate (<50mm size)	50	20	11535	577	G	576.8	577	G	1475	10	I	850881	343049	851	343.05
		Layer of imported topsoil	50	20	11535	577	G	576.8	577	G	1100		J	634425	255745	634	255.74
		Hay bunds on the contour made from forage sorghum round bales. Drone photos suggest that 58 round bales were used. Used a dry wt of 255kg (average of 4x4 and 5x4 round bales)[B].(SD-No of bales = 2, SD-Dry Wt of bale = 45kg).												14790	2667	15	3
	Total				43469	1426											

[A] See Table 1 for more details.

[B] https://www.feedinglivestock.vic.gov.au/2019/05/02/bale-weights/

[C] It is assumed that the SD of the depth is the same regardless of the depth.

[D] The surface area measurements were taken from the Schedule of Quantities of various reports. Theses\ areas were obtained with drones and should be very accurate. However, the overall accuracy would be dependent on how closely there were adhered to during gully remediation. I'm assuming a coefficient of variation of 5%.

[E] Appendix A Schedule of Quantities in Report 3

[F] Item 1 Gully Remediation Northern Control Gully in Appendix A - Schedule of Quantities of Report 2

[G] Item 3 Gully Remediation Gully 13 in Appendix A – Schedule of Quantities of Report 3

[H] Average measured BD of samples taken from T1, T4 and Control.

[I] Measured on a sample taken from the fine aggregate mound at Gully 13

[J] BD of the surface layer of a typical Black Vertosol (APSoil 54) selected from CSIRO APSoils found in Qld. Same soil used for APSIM modelling,

[K] Generally accepted value of BD from a literature review

Report 2 – Damon Tefler (2020). 2020 GBRF Reef Trust Partnership Stage 1: Phase 3 Gully Remediation Works - Strathalbyn Station. Technical Specification and design Detail. Prepared by Damon Tefler (Fruition Environmental Pty Ltd), checked and approved by Rock-it Science Pty Ltd and issued to Greening Australia Ltd.
File Name: 200429_Strathalbyn_Gully_Project_2020_Phase3_Tech_and_Design_SpecFINALDRAFT.pdf

Report 3 - Nicklin Evans (2017). Technical Specification: Strathalbyn Gully Project Phase 1. Prepared by Nicklin Evans (Alluvium Consulting) for Damon Telfer (Rock-it Science Pty Ltd). Revision 2.
File Name: P217003_R01_v3_Strathalbyn_Gully_Project_Phase_1_DD_Technical_Spec_final.pdf

Table 24. Calculated weight of total nutrients added to the gullies from imported amendments. A colour ramp has been used to rank the nutrient weight values within each site with red the highest.

Site	Imported Amendment	Weight of Imported Amendment				Total Nutrient content of amendment							Nutrients added to gully with amendment					
		(kg)	SD	(t)	SD	Sampling Time	Dumas N or 2M KCL ext. NH$_4$ & NO$_3$^{A} (%N)		Dumas TOC^B (%)		Kjeldahl P^C (%)		N (kg N)		TOC (kg C)		Kjeldahl P (kg P)	
						(Days since works)	Value	SD^D	Value	SD^D	Value	SD^D	Value	Cal. SD	Value	Cal. SD	Value	Cal. SD
T1	Gypsum	19699	888	197	1													
	Graded Rock Bed (50-100mm)	167206	34503	167	35	1079	0.000193	NA	NA	NA	NA	NA	0.323	NA	NA	NA	NA	NA
	Crushed Aggregate (<50mm)	2088807	146790	2088	146	1079	0.00179	0.000	0.198	0.010	0.028	0.001	22.509	3	2486	305	351.6	43
	Rhodes Grass Hay (Blanket Mulching)	28305	2633	29	3	1079	1.81	0.045	45	1.137	0.120	0.019	511.38	49	12869	1239	33.87	6
	Grass Seed	19	0.96	0.019	0.001													
T4	Gypsum	41566	1993	42	2													
	Graded Rock Bed (50-100mm)	394072	20020	394	20	891	0.000159	NA	NA	NA	NA	NA	0.6262	NA	NA	NA	NA	NA
	Crushed Aggregate (<50mm)	3748079	356365	3748	356	891	0.00179	0.000	0.198	0.010	0.028	0.001	67.191	7	7421	797	1049	113
	Rhodes Grass Hay (Blanket Mulching)	58523	2775	28	3	891	1.13	0.028	42	1.043	0.113	0.049	661.3	35	24423	1309	66.13	29
	Grass Seed	78	4	0	0													
Control	Gypsum	49802	2538	50	3													
	Graded Rock Bed & Rock Checks (50-100mm)	214979	9755	215	10	98	0.000177	NA	NA	NA	NA	NA	0.3798	NA	NA	NA	NA	NA
	Crushed Aggregate (<50mm)	3272811	602766	3273	603	98	0.00179	0.002	0.198	0.010	0.028	0.001	58.671	60	6480	1237	916.4	175
	Topsoil	2440240	415383	2440	415	98	0.053	0.003	0.897	0.045	0.042	0.002	1301.5	231	21889	3883	1025	182
	Bagasse (Blanket mulching)	164475	46682	164	47	98	0.233	0.006	23.933	0.598	0.014	0.006	383.78	109	39364	11216	22.75	12

Site	Imported Amendment	Weight of Imported Amendment				Total Nutrient content of amendment							Nutrients added to gully with amendment					
		(kg)	SD	(t)	SD	Sampling Time	Dumas N or 2M KCL ext. NH_4 & NO_3[A] (%N)		Dumas TOC[B] (%)		Kjeldahl P[C] (%)		N (kg N)		TOC (kg C)		Kjeldahl P (kg P)	
						(Days since works)	Value	SD[D]	Value	SD[D]	Value	SD[D]	Value	Cal. SD	Value	Cal. SD	Value	Cal. SD
	Rhodes Grass Hay (Hay bunds)	8160	1528	8	2	98	0.703	0.018	44.733	1.118	0.15	0.04	57.392	11	3650	689	12.48	4
Gully 13	Gypsum	78244	2834	78	3													
	Graded Rock Bed & Rock Check Dam & Rock Sills (50-100mm)	1077448	44584	1077	45	98	0.000352	NA	NA	NA	NA	NA	3.789	NA	NA	NA	NA	NA
	Crushed Aggregate (<50mm)	4566577	839696	4567	840	98	0.00179	0.000	0.198	0.010	0.005	0.000	81.864	16	9042	1723	248.7	47
	Topsoil	3404885	290851	3405	291	98	0.057	0.003	1.080	0.054	0.044	0.002	1929.4	191	36773	3640	1498	148
	Bagasse (Blanket mulching)	226674	64335	227	64	98	0.263	0.007	30.067	0.752	0.01	0.01	596.91	170	68153	19418	30.6	16
	Forage Sorghum Hay (Hay bunds)	14790	2667	15	3	98	0.780	0.020	44.500	1.113	0.184	0.04	115.36	21	6582	1198	27.21	7

[A] For the organic amendments, the values are the average Dumas N concentrations found in samples taken from the gullies on 7/12/2020. For the rock and aggregate samples, the values are KCL ext. NH_4 & NO_3 concentrations found in samples taken from the gullies on 7/12/2020

[B] Average TOC concentration found in samples taken from the gullies on 7/12/2020

[C] Average Kjeldahl P concentration found in samples taken from the gullies on 7/12/2020