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Quantifying Fine Sediment Erosion From Unsealed Roads Draining to the Great Barrier Reef Before and After Applying Best Management Practices

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Abstract
Unsealed roads and their construction and maintenance are a direct anthropogenic source of sediment in river catchments. Maintenance practices use graders to form the road crown, add gravel material, reshape table and diversion drains, and remove vegetation from batters. Repeat high-resolution terrestrial laser scanning (TLS) was used to quantify unsealed road erosion at six road segments (2.5 ha) over two years each with average rainfall to assess (1) baseline erosion from status quo maintenance, and (2) changes in erosion by applying Best Management Practices (BMPs) to reduce fine sediment delivered to the Great Barrier Reef (GBR). Baseline erosion rates were 132 t/ha/yr locally of all size classes and 38 t/ha/yr < 20 µm to GBR, higher than natural catchment rates (<2 t/ha/yr). Suspended sediment concentrations (<20 µm) were 10 times higher downstream of the road crossings compared to upstream. BMPs implemented in the second year included no grading disturbance of drains and batters for grass recovery, woody vegetation control with herbicide, drain rock lining or grade control structures, rock mulching steep batters, rock chutes at gully heads, and rock mattress floodways. Normalised by a control segment, vegetation recovery on batters and drains resulted in the lowest reduction in erosion (22%), compared to the addition of rock mulch and check dams (42–43%) and more frequent water diversion (69%). Wholistic management funding for road condition and safety; vegetation and weed spread; sheet, rill and gully erosion; and GBR pollution should be treated as a complete package by Federal, State, and Local governments.

Keywords Road erosion · Terrestrial laser scanning · Best Management Practices · Erosion control · Marine pollution · Government funding

Introduction

Globally, roads and road development have a major impact on catchments, rivers, and ecosystems (Laurance et al. 2014; Yu et al. 2024). There are > 40 million km's of road globally, with >15 million km unpaved (CIA 2021), with numbers rapidly increasing. In Queensland, Australia, there are 66,000 km of paved and 110,000 km of unpaved roads (ABS 2008). This is a gross underestimate as private roads, tracks and fence lines are not included (e.g., Spencer et al. 2016; Shellberg et al. 2025).

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Unsealed roads and their construction and maintenance are the ultimate anthropogenic source of sediment in catchments. This source of sediment did not exist before human development. The persistent bare soil of unsealed roads and their batters and drains provides a large area for rainfall-runoff induced soil erosion to deliver sediment to stream networks and coastal ecosystems such as coral reefs (Ramos-Scharrón et al. 2024). Unsealed roads alter water runoff processes and create overland flow (Ziegler and Giambelluca 1997), rapidly route and deliver water to the stream network (Montgomery 1994), and extend channel networks through gullying and stream piracy (Wemple et al. 1996). Due to these hydrologic and geomorphic impacts, roads increase coarse and fine sediment supply to the stream network (Reid and Dunne 1984) and increase gully frequency (Croke and Mockler 2001).

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Introduction

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In Australian catchments draining to the Great Barrier Reef (GBR), local Shire Councils typically manage the unsealed formed road network of gazetted roads. Across rural Councils, a majority of road funding comes from the Australian Government Disaster Recovery Funding Arrangements (DRFA) and Queensland Reconstruction Authority (QRA), especially in disaster-prone areas with monsoonal rainfall or cyclone impacts in most years. Roadworks typically form and reshape the road crown, add gravel material, install and re-cut table drains and cutoff (diversion) drains, and remove all vegetation (grass and trees) along road batters and verges. The result is a bare earth (14-18 m wide) road corridor at the start of each wet season (Figure 1). DRFA criteria stipulates that only like-for-like repairs can be made to bring the road back to pre-disaster condition, with no upgrades or betterments regardless of cost effectiveness or long-term sustainability issues (QRA 2018). Any road betterments (culverts, floodways, bitumen sealing) need to come from other limited funding streams. Erosion control measures or weed spread and management issues are often externalised, with minimal funding or guidance to control these during annual maintenance.

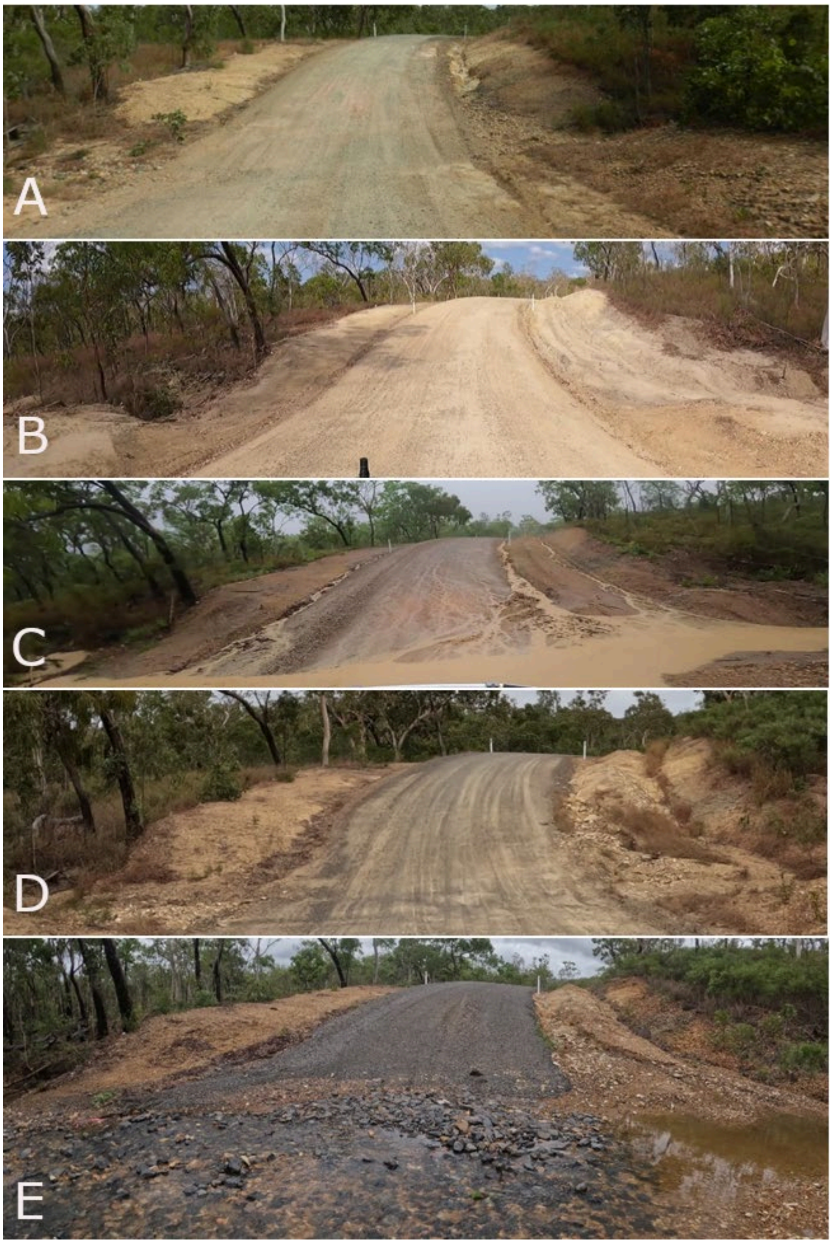

Figure 1 An unsealed road in July 2021 (A), Nov 2021 after DRFA works (B), Dec 2021 during a minor storm (C), June 2023 after an average wet season (D), and Dec 2023 after cyclone Jasper (E) showing the cyclic nature of maintenance and erosion

Erosion rates and water quality impacts from unsealed formed roads in catchments draining to the GBR have not been well quantified across the large variation of spatial and temporal variability. Gleeson (2012) measured suspended sediment concentrations (SSC) 2 to 4 orders of magnitude higher in streams downstream of unsealed road crossings compared to upstream grazing land. Claussen and Telfer (2021) measured high SSCs > 3000 mg/L < 20 µm in road drains during early wet season rainfall-runoff events. Johnson et al. (2024) measured SSCs between 100 to 5000 mg/L in unsealed road table drains, and sediment loads of 1 to 12 tonnes/ha/year.

Roads have been an essential historic component of catchment sediment budgets that quantify natural and anthropogenic sources of sediment to river systems (Reid et al. 1981).

Process-based models of road erosion, calibrated to local data, have been developed to better incorporate roads into larger sediment budgets (Luce and Cundy 1994; Fu et al. 2010). Unfortunately, sediment budgets in GBR catchments have not included formed unsealed roads or unformed primitive tracks (McCloskey et al. 2021), despite the large extent of bare ground associated with roads (ABS 2008; Spencer et al. 2016).

Terrestrial laser scanning (TLS) has become an important tool to measure erosion changes using high-resolution digital elevation models (DEMs). Temporal scans can be subtracted to create a DEM of Difference (DoD) and quantify erosion and deposition. Repeat TLS measurements of detailed gully erosion change have been illuminating to erosion process understanding (Goodwin et al. 2016; Li et al. 2023). TLS scanning of unsealed road surfaces has been used for asset degradation assessment (Akgul et al. 2017) as well as erosion quantification (Cao et al. 2021).

The objective of this study was to use terrestrial laser scanning (TLS) to quantify unsealed road erosion over time at multiple road segments and stream crossings. It was hypothesised that 1) unsealed roads, batters and drains are a significant source of anthropogenic sediment to local streams and the GBR Lagoon compared to upstream background catchments, and 2) that correctly applied Best Management Practices (BMPs) can reduce this erosion by changing management practices and funding arrangements. The impetus of this work is how to reduce anthropogenic fine sediment loads (<20 µm) delivered to the GBR from catchment sources, as measured and modelled (McCloskey et al. 2021). Load reduction targets range from 10% to 25% (catchment dependent) of anthropogenic fine sediment loads by 2025 (State of Queensland, 2018). After climate change, "*poor water quality from land-based delivery of fine sediments and other pollutants is a major threat to freshwater, coastal and inshore marine ecosystems of the GBR*" (Waterhouse et al. 2024).

Methods

Study Area and Road Segments

The study area is in the Annan Catchment in southeast Cape York Peninsula (CYP) draining to the northern GBR. The unsealed Oaky Creek Road was selected as a study area near Cooktown (Figure 2). This road traverse patches of dispersive sodic soils along stream crossings with variable alluvium, colluvium and weathered bedrock of the Hodgkinson Formation (weak meta-sediment, mostly slates, siltstone, mudstone). These dispersive soils are prone to high erosion rates and gullying. They are representative of unsealed roads across CYP (Spencer et al. 2016). Six (6) road segments were selected across a range of road slopes and conditions. All segments were centred on a stream crossing, extending on average 150 m on either side along approaches from road crest to road crest. Segment lengths averaged 270 m, but had a range of 172 to 420 m.

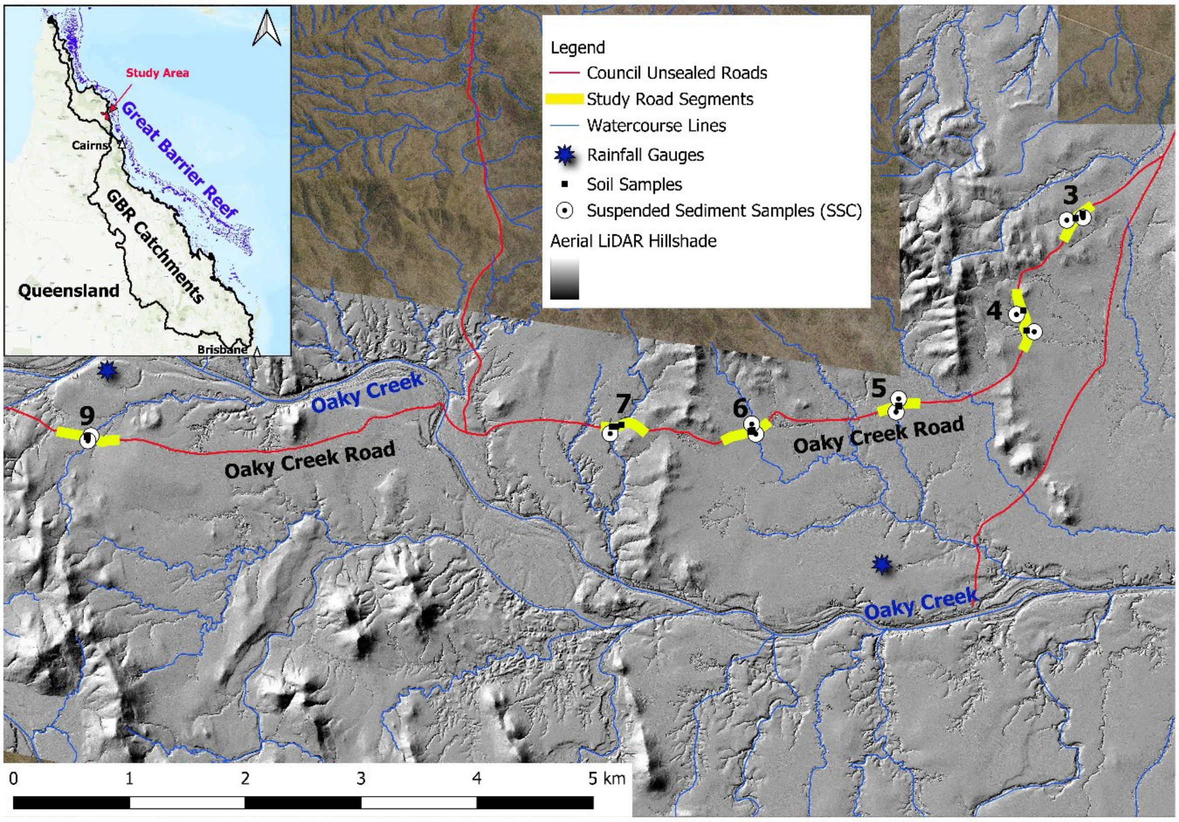

Figure 2 Map of study area with airborne LiDAR hillshade data

Study Design

This study used a before-after, control-impact (BACI) study design to assess erosion volumes and tonnage over two wet seasons via TLS at six different segments (3,4,5,6,7,9).

1. Status quo machinery disturbance at six segments (2021-2022, before),
   a. Segments 3, 4, 5, 6, 7, 9 (Figure 2)
2. Treatments with BMPs to reduce erosion at selected segments (2022-2023, after),
   a. Segment 9 (passive vegetation management only)
   b. Segments 3, 4, 5, 6 (rock + passive vegetation treatment)
3. Control segment with status quo machinery disturbance (2021-2024, control).
   a. Segment 7 (control)

During the first year (2021-2022), the study was unknown to the maintenance grading operator, with business-as-usual grading in October 2021. Erosion rates measured over the wet season Nov-2021 to June 2022 were only the result of rainfall-runoff and local traffic. In August-2022, road segments 3, 4, 5, 6, 9 were signed as exclusion areas, with instructions not to grade the drains or batters, and only grade the road running surface shoulder to shoulder with no gravel spill into drains. The control segment 7 was unmarked and unknown to the operator, and experienced business-as-usual full grading of the road surface, batters, and drains in September 2022.

Best Management Practices (BMPs) for erosion control along unsealed roads were drafted by collaboration between local engineers and geomorphologists (Klye et al. 2024; 2025). These BMPs were applied in October 2022 to road segments 3, 4, 5, 6, 9 to achieve hypothesised erosion reduction results. A different operator installed the BMPs, with the instructions and guidance to use methods and tools not historically funded under the current QRA (2018) regime (such as rock and herbicide), but following road industry best practice for Queensland (QTMR 2021; 2023). Subsequently, erosion rates were measured over the next wet season Nov-2022 to June 2023. BMPs applied included:

- Reduced grading disturbance of soils in drains and cut batters,
- Passive vegetation recovery following reduced disturbance,
- Broadleaf herbicide spraying of woody weeds (tree suckers), and targeted herbicide spraying of invasive annual grasses,
- Drain grade control structures or rock lining at erosion hotspots,
- Rock mulching or armouring of steep batters at erosion hotspots,
- Rock chutes at gully heads at drain outlets,
- Rock mattress bed-level stream crossings.

Terrestrial Laser Scanning

TLS surveys were conducted via stationary ground surveys at each of the 6 road segments. TLS data were collected using a tripod mounted Riegl VZ-400i or VZ-600i scanner, with high accuracy, high precision ranging. The point density of each scan position was 27,700 points per m^2, but each surface was typically scanned from 4 positions making the point density much higher. Approximately 50 to 80 scan positions consistent over time were surveyed at each ~300 m long road segment, with spacing and positioning ensuring good coverage and beam angle.

All segments were scanned before (November-2021) and after (June-2022) the first wet season (WY 2022, water year from Nov to June). Segments were re-scanned before (November-2022) and after (June-2023) the second wet season (WY 2023) as a focused analysis of BMP treatment and control segments.

Scanned point cloud data were combined in RiSCAN Pro and aligned with repeat scan data collected after the wet season and multiple years. Alignment to fixed objects was used for initial and repeat comparisons. Ground control points (n = 4 to 6 per segment) were installed using star pickets driven deep, with 100 mm diameter plastic pipe surrounding them, encased in concrete, with reflector tape. Tree bases, stable road signs, and concrete floodways were also used as fixed object datums. Absolute geolocation was conducted using an average of GPS readings from each scanner over the period of the scan project.

Aligned point clouds were down-sampled to a 1 mm grid. This initial ground model was generated using a polynomial surface fit. Below ground points were removed (e.g., reflections in water bodies). Ground points were identified using a Progressive Morphological Filtering Algorithm. An elevation grid digital elevation model (DEM) was generated at 10 mm resolution, using a smoothed inverse distance squared nearest neighbours algorithm on the ground points.

For each wet season period, the first DEM (Nov) was subtracted from the second DEM (June) to quantify change and create a DEM of Difference (DoD). The DoD quantifies the volumetric change (negative or positive) between successive topographic surveys by integrating the cell-by-cell change for each pixel. These data were aggregated up into change volumes for individual road elements or road segments described below.

A vertical minimum level of detection (LoD) was applied to the DoD data to account for measurement errors and separate true from false change. This is especially important for very small widespread changes below the threshold for detection (Wheaton et al. 2010; Goodwin et al. 2016). The vertical LoD was estimated from the overall root mean square error (RMSE) of scan-to-scan registration to concrete floodway surfaces and ground control points that had zero change over time.

Road Element Analysis

The DEMs and DoDs of each road segment were classified into different geomorphic units or elements. The term Road Element is used to describe the different components of an unsealed road system. A geographic information system (GIS) was used to delineate Road Elements into discrete polygons based on their function in the road system, location, catchment area, and similar slope (Figure 3). A given road segment had multiple elements of the same type. Road element polygons were used to clip the volumetric change DoD and calculate the volumetric change in each road element.

- **Road Surface** (running surface shoulder-to-shoulder)
- **Table Drain** (drain channel flowing next to edge of road)
- **Cutoff Drain** (diversion drain channel flowing away from road)
- **Cut Batter** (batter slope above table drain cut by a grader)
- **Drain Batter** (batter slope above cutoff drain)
- **Creek Crossing** (stream bed < 15 m along creek; immediate disturbed road crossing)
- **Diversion Tracks** (used during concrete floodway construction).

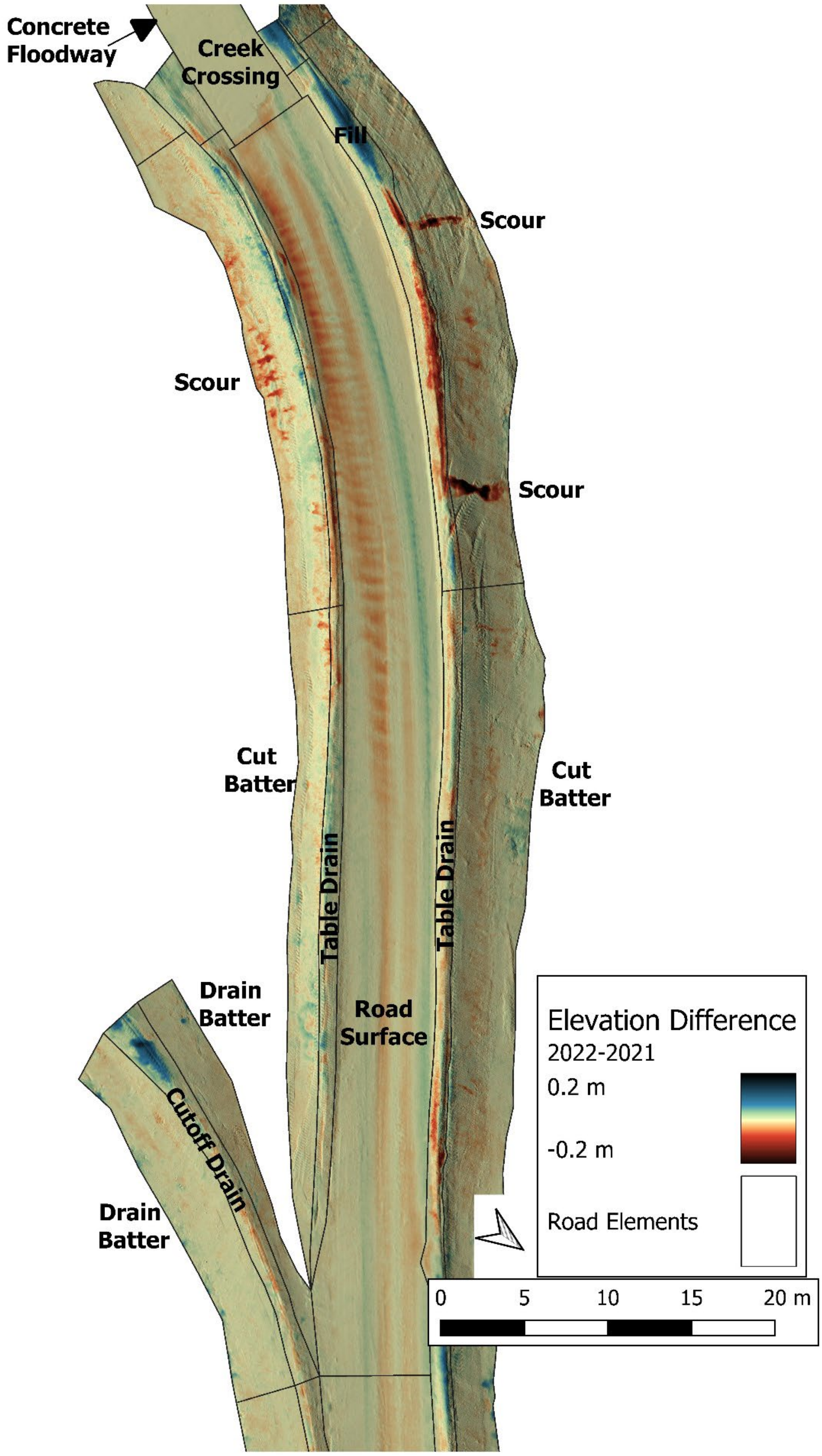

Figure 3 Road element units and TLS DoD erosion change along part of Segment 3 in WY 2022

Soil Samples
Soil samples (n=25) were collected at representative road elements (Figure 2). Soil parameters included bulk density, particle size distribution, and exchangeable sodium percentage. Average values were applied to each element across the study area.

Bulk density samples were collected using 5 cm deep steel rings, 3.5 cm diameter, that were tapped into the soil surface and carefully dug out and capped. Samples were oven dried and weighted to 0.1 g to measure the dry bulk density (g/cm^3).

Particle size distribution was measured using laser diffraction particle size analysis using a Mastersizer 3000LV with samples pre-treated with hydrogen peroxide and sodium hexametaphosphate. The percentage of the sample < 20 µm (very fine silt and clay) was the key metric used for its influence on the GBR (McCloskey et al. 2021).

Exchangeable sodium, magnesium, potassium, and calcium (cmol+/kg) were measured using alcoholic ammonium chloride method (15C1) of Rayment & Lyons (2011). The exchangeable sodium percentage was measured as the cation concentration divided by the total effective cation exchange capacity.

Sediment Delivery Ratios
The particle size of sediment eroded from road elements has a strong influence on its connectivity to drains, streams, and ultimately the GBR. Particles < 20 µm (very fine silt and clay) are easily transported and remain suspended after erosion, and are the size of concern for this study and the GBR (McCloskey et al. 2021). Coarser sediment > 20 µm (coarse silt, sand, gravel) are transported and deposited at the local to sub-catchment scale, and can influence the road network, the local stream system, and river estuary, but not the GBR. This coarser sediment > 20 µm was excluded from the analysis as explained below.

A drain sediment delivery ratio (DSDR) was used to conservatively factor in some fine sediment (< 20 µm) deposition, between the drain outlet (or end) and a stream or gully channel. Paired SSC < 20 µm samples along discrete flow paths from the road drain and downstream stream confluence were collected manually at the same time during rainfall events. The SSC ratios were used to categorize DSDRs and potential deposition of fine sediment of different distances, and validate earlier guides (Wilkinson et al. 2024). These fine SDRs were expected to be greater than those documented for coarser sediments (> 100 µm) in mountain environments (Ketcheson and Megahan 1996).

The river sediment delivery ratio (RSDR) is the fraction of fine sediment that is delivered to the river mouth after being transported into a fluvial channel from an erosion process.

A RSDR for fine sediment < 20 µm was modelled as 0.93 by McCloskey et al. (2021) for the lower Oaky-Annan catchment.

Sediment Erosion and Load Estimation
The DEM of Difference (DoD) data from TLS were used to calculate the volume of degradation (scour) erosion of a given pixel (values < the negative LoD), the erosion volume sum for a given road element, and sum of volume less than the negative LoD for the road segment. Bulk density data were used to convert erosion volume to tonnes. Soil particle size fractions < 20 µm varing by road element, and the RSDR, were used to calculate erosion of fine sediment relevant to the GBR (McCloskey et al. 2021; Wilkinson et al. 2022).

The deposition (aggradation or fill) of coarser sediment > 20 µm (coarse silt, sand, gravel, cobble) was not included in the analysis of the TLS DoD. The deposition greater than the positive LoD measured in the DoD represented either movement of coarser sediment > 20 µm, such as loose road aggregate or sand from the road surface, or grass vegetation growth after the wet season. TLS scanning cannot penetrate very dense grass vegetation. For these mostly de-vegetated road batters, the underlying erosion below sparse grass patches was deemed to be negligible compared to bare surface erosion. The total erosion of sediment < 20 µm from dispersible soils is thus a minimum exported to the stream network and GBR.

Statistical Analysis of Road Element Unit Erosion Rates
A Before After Impact Control (BACI) study design was utilised to compare changes in unit erosion rates (kg/m²/yr < 20 µm to GBR) at individual road elements in control and treatment segments. Unique polygons for the subset of treated types were classified as 1) cutoff drain, 2) table drain, 3) drain batter and 4) cut batter. Treatments were classified as A) machine grading, B) no grading, C) rock mulching, and D) rock check dams. Three Generalized Linear Mixed Models (GLMMs) (Foster and Bravington 2013, Pardini et al., 2018, Bolker et al., 2009) assessed treatment effectiveness at different scales: (1) overall treatment vs. control, (2) treatment type, and (3) segment-specific analysis.

BACI effects were estimated from GLMMs using a gamma error distribution for continuous, positive, and right-skewed data, and a log-link function fitted by maximum likelihood with Laplace approximation. All models included random intercepts for geounit type. The primary model (1) included random slopes for the control and treatment effects enabling effects to vary across road element types. The overall BACI effect was calculated as the difference-indifferences between treatment and control: $\frac{AfterImpact/BeforeImpact}{AfterControl/BeforeControl}$, which quantifies the additional erosion reduction achieved by treatments beyond natural fluctuations expected by chance. BACI effects were estimated on a log scale and reported as back-transformed ratios. Values less than 1 indicate greater reductions in erosion at treatment sites relative to the control segment or site, while values greater than 1 indicate greater reductions at control sites. Models were run in the R (v4.5.1, “Great Square Root”) using the lme4 package (v1.1–37) (Bates et al., 2015) to fit GLMM's. Marginal means and contrasts were estimated with the emmeans package (v1.11.2).

Suspended Sediment Concentration and Rainfall Monitoring

Suspended sediment concentration (SSC) samples were collected as a supplementary dataset at paired sites above and below road stream crossings. Upstream sites were above the influence of the road and drains (background conditions), and downstream sites below the confluences of drains (impact conditions). SSC sampling occurred during wet season rainfall events at road segments 3, 4, 5, 6, 7 (Figure 2). Rising stage samplers (RSS) were used to collect SSC during the rising stage of flow events (Colby 1961). Each RSS intake was positioned 200 to 300 mm above the bed in shallow streams and bottles were exchanged after significant flow events. Laboratory analysis followed the full-bottle evaporation method with a 63 µm sieve split (ASTM 2002). On a subset of samples, laser diffraction was used to measure average 20/63 µm size ratios, which were used to scale data to < 20 µm at unique sites.

Continuous rainfall data were collected at two locations (west, east) along the Oaky Road network and compared to longer-term data at the Cooktown Airport 8 km away (Figure 2). Tipping bucket rain gauges (TB3) with 0.2 mm per tip were used along with event loggers. Event, hourly, daily, and annual rainfall totals, intensity, and erosivity were calculated using the Rainfall Intensity Summarization Tool (RIST) (USDA 2019).

Results

Terrestrial Laser Scanning

The vertical RMSE calculated at concrete floodways from scan-to-scan over two different years varied between 0.0009 m to 0.0060 m per segment, based on analysis of 440,900 pixels, with an overall RMSE of 0.0026 m. The vertical RMSE calculated at ground control points ranged from 0.0001 to 0.0058 m with a higher overall RMSE of 0.0035 m. These values were within ranges of the overall vertical RMSE found in other high resolution TLS studies (<1 to 14 mm; Li et al. 2023; Goodwin et al. 2016). For the DoD analysis, a minimum level of detection (LoD) threshold of 5 mm was applied to all road segments (Figure 4).

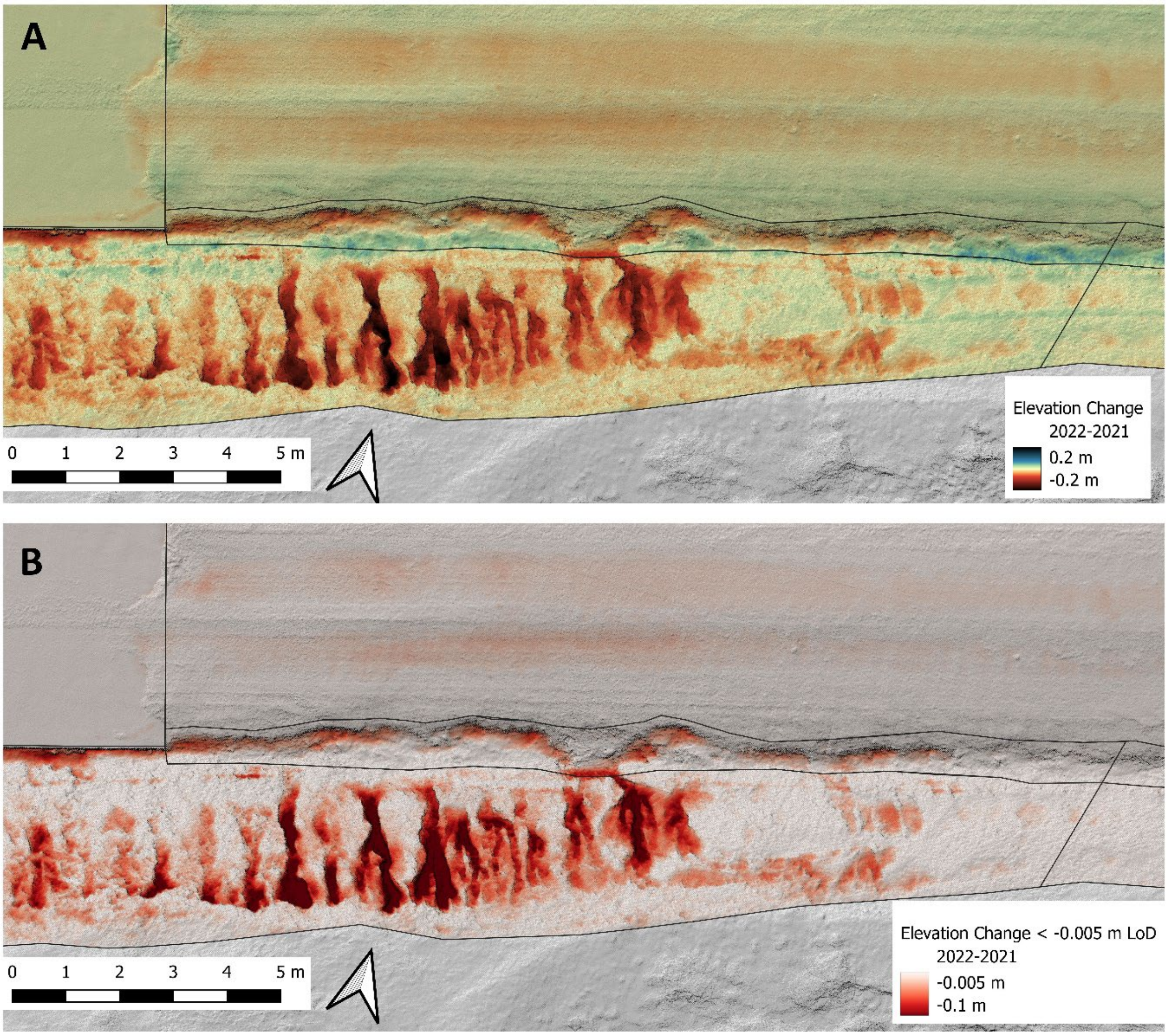

Figure 4 Elevation change at Segment 5 from 2022-2021 showing A) erosion and deposition within ± 0.2 m, and B) erosion less than the applied LoD of -0.005 m

TLS data from the first wet season (WY 2022) represented the baseline conditions of the status quo maintenance regime under full machine grading of all road elements. TLS data from the treatment year (WY 2023) are then compared to assess changes due to BMPs.

Erosion (scour) varied spatially by road element, slope, and soil type, with erosion typically increasing toward deeper road cuts near stream crossings (Figure 3). Deeper areas of concentrated scour were observed at hotspots of erosion, such as steep cutoff drains, steep cut batters with extensive rilling, and zones of concentrated flow in table drains (Figure 3; Figure 5).

Road surface elements (n=34) of all segments had an average scour of -5.4 mm of vertical loss calculated as the total erosion volume divided by the total area (Figure 5). Localised deep scour was typically around -60 mm. This is a low traffic road compared to other main gravel arteries in the region. Road batter and drain elements had greater average scour for cut batters (-6.0 mm, n=93), table drains (-10.7 mm, n= 83), and cutoff drains (-8.3 mm, n=31). Diversion tracks used during concrete floodway construction (-12.8 mm, n=6) and creek crossings (-79.8 mm, n=9) had deeper average scour from smaller areas. Localised deep scour on cut batters was typically around -30 mm, commonly seen in pedestals around rock fragments. Due to the large area covered by TLS road elements (24,813 m^2 across 307 road elements and 6 road segments), these average scour values are relatively low due to millions of pixels with minor changes but deeper than the LoD (88,498,281 out of 248,131,550 pixels < - 5 mm, or 36%, in WY 2022).

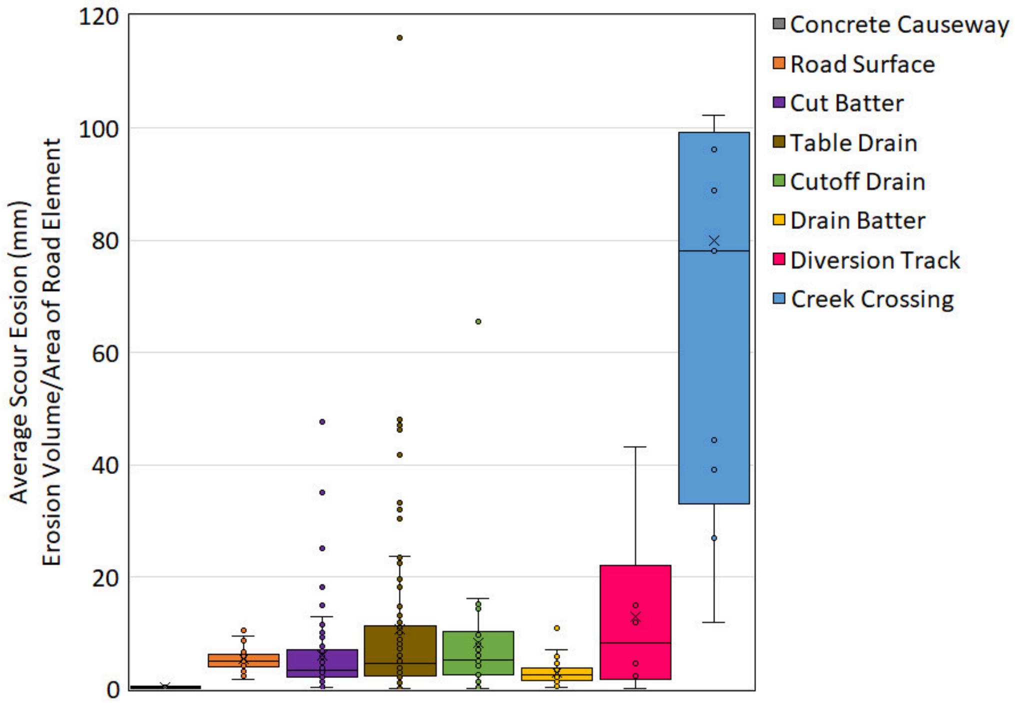

Figure 5 Average vertical scour erosion of road elements (WY 2022)

Soil Data

Soil sample bulk densities ranged from 1.60 to 2.17 g/cm^3 (n = 25). The highest average bulk densities were from imported compacted road base (2.00 g/cm^3) followed by local outcrops of weathered bedrock (1.94 g/cm^3). Soils of gully walls (1.84 g/cm^3) and cutoff drains (1.84 g/cm^3) were also high, with cut batters slightly lower (1.80 g/cm^3).

Soils had high levels of exchangeable magnesium and sodium, and low values of calcium or potassium, typical of dispersive soils. Exchangeable sodium percentage ranged from 6.2 to 25.0% (n=16) and varied on average between cut batters (11%), cutoff drains (13.1%) and gully walls (14.1%). Values of 10 to 15 ESP are defined as moderately sodic (Naidu et al. 1995).

Particle size distribution samples (n=25) had a range of 15.3 to 78.4% of sediment < 20 µm (very fine silt and clay). The highest individual values were associated with alluvial slopes at stream crossings, and lowest with weathered bedrock. Imported road base on average had the lowest levels of fine sediment < 20 µm (mean 24.3%, range 19 to 32%). Cut batters

(44.7%), cutoff drains (44.6%), and gully walls (42.9%) all had relatively similar percent fines < 20 µm on average.

Drain Sediment Delivery Ratios

Paired field measurements of the ratio of SSC < 20 µm at the drain and stream confluence versus flow distance indicated a declining trend in DSDR with distance ($DSDR_{<20}$ = -0.00267 *metres + 1.00; r^2=0.76; n=11). These field data were used to support five classes of DSDR based on distance from the road drain to stream channel.

- 1.00: for road elements and drains that drain directly to stream channels
- 0.90: for drain outlets < 50 m from stream or gully channels
- 0.75: for drain outlets between 50 to 100 m from stream or gully channels
- 0.60: for drain outlets 100-200 m from stream or gully channels
- 0.25: for drain outlets > 200 m from stream or gully channels

These DSDR's are applicable to study segments centred on stream crossings with observed high connectivity of fine sediment to streams (< 75 m away) along hillslopes of 2 to 4% slope. The 0.90 DSDR most commonly applied in this study also accounts for any fine sediment < 20 µm associated with isolated sand deposits, typically < 10% by mass. Lower sediment delivery ratios could be expected along flatter landscapes over longer flow distances.

Rainfall Data

The rainfall totals at study sites during TLS survey periods for WY 2022 and WY 2023 were close to the long-term average at Cooktown (Table 1). There were no unusual or exceptional rainfall events in either year and no cyclones. The western gauge had slightly higher rainfall due to a stronger NW monsoon pattern in WY 2023. Annual rainfall erosivity totals (R-factors) followed similar trends with values typical for regional patterns in tropical northern Australia (Lu and Yu 2002).

The number of storm events (break at 6 hrs with < 1.27 mm) was less in WY 2022 than WY 2023 (Table 1). However, major events had similar occurrences, but with WY 2022 having fewer daily totals > 50 mm but more daily totals > 100 mm. During WY 2023, more events were concentrated in a shorter wetter period in late Dec and early January, which affected the event antecedent soil moisture conditions and early grass growth.

At the eastern gauge, rainfall intensities (mm/hr) were < 1 yr annual recurrence interval for all events and durations both years (BOM 2016 IFDs). At the western gauge, rainfall intensities (mm/hr) reached the 2 yr recurrence interval (10 min, 30 min durations) during 1 event in WY 2022, and almost for 1 event in WY 2023.

Table 1 Rainfall totals and erosivity factors (R) for WY 2022 to 2023

TLS Survey Period	Oaky Creek Western Rain Gauge	Oaky Creek Eastern Rain Gauge	Cooktown Airport Rain Gauge
Units	mm total Nov-June R = MJ mm $ha^{-1}hr^{-1}yr^{-1}$ # storm events # days > 50 mm # days > 100 mm	mm total Nov-June R = MJ mm $ha^{-1}hr^{-1}yr^{-1}$ # storm events # days > 50 mm # days > 100 mm	mm total Nov-June (mean 2000-2023) [range 2000-2023]
WY 2022 Nov-June Wet Season Period	1476 mm 11,620 R 103 storm events 7 days > 50 mm 2 days > 100 mm	1497 mm 12,011 R 108 storm events 8 days > 50 mm 4 days > 100 mm	1659 mm (1582 mm mean) [617 – 2582 mm range]
WY 2023 Nov-June Wet Season Period	1635 mm 13,578 R 143 storm events 10 days > 50 mm 1 days > 100 mm	1489 mm 11,150 R 119 storm events 9 days > 50 mm 1 days > 100 mm	1531 mm (1582 mm mean) [617 – 2582 mm range]

Fine Sediment Loads

<u>WY 2022 Baseline Data</u>

TLS data of volumetric erosion change (scour deeper than - 5 mm) were combined with soil bulk density, % fines < 20 µm averaged across similar road elements, variable DSDR, and the RSDR to the GBR Lagoon. The results calculated t/yr < 20 µm eroded from road elements and segments, and delivered to the GBR in WY 2022 under baseline maintenance conditions (Figure 6a), and in WY 2023 after application of BMP treatments (Figure 7).

In WY 2022, the measured erosion for six road segments was 94 t/yr < 20 µm to GBR. Unit area rates were 38 t/ha/yr < 20 µm to GBR compared to unit length rates of 58 t/km/yr < 20 µm to GBR. In comparison, there was 327 t/yr of local erosion of all particles sizes classes, which equates to 132 t/ha/yr locally, or 202 t/km/yr locally. On average for natural soil samples, 44% was fine silt and clay < 20 µm, 41% coarse silt and sand > 20 µm, and 15% gravel > 2 mm. From an overall sediment budget perspective, 29% of the sediment eroded locally was delivered to the GBR (94 t/yr), while the remaining 71% (233 t/yr) was redeposited in roads, drains, creeks, rivers, floodplains and estuaries (mostly coarse silt and fine sand).

Erosion of fine sediment < 20 µm for each road segment in WY 2022 was a function of road length and area of road disturbance, with moderate predictive power (r^2 = 0.70 to 0.73). Soil material, slope, and vegetation cover also influenced erosion variability in elements and segments. Road surface erosion varied from 15% to 30% of the total erosion of all elements (mean 21%) in WY 2022 (Figure 6a). Cut batter erosion had a more consistent range of 25%

to 30% (mean 28%). Table drains were also major sediment sources of 14% to 40% (mean 31%). Cutoff drains contributed less fine sediment of 1% to 18% of the total (mean 9%). However, gully erosion at the end of cutoff drains was not measured with TLS surveys, and is significant depending on the road segment. Local scour immediately downstream of concrete floodways (Seg 5, 6) also contributed some fine sediment, as did crossings on natural creek beds filled with road base (Seg 4,7,9) and temporary diversion tracks (Seg 5).

The average erosion per square metre (kg/m^2/yr <20 µm to GBR) for different road elements (Figure 6b) tend to downplay the role of road surfaces, which experience small vertical losses over large areas but contribute significantly to total loads (Figure 6a). Unit erosion rates for cut batters and drain batters were also less per area, due to more localised erosion across large areas. Table drains and cutoff drains had higher unit rates due to concentrated scour in small areas. Diversion tracks also had smaller areas of intense scour. Where deep scour occurred at creek crossings in relatively small areas (< 15 m along creek), the average erosion per square metre was higher for areas with crossings on natural creek beds (Seg 4,7,9) compared to immediately below concrete floodways (Seg 3,5,6). This is because imported road base (24.3% < 20 µm) was easily scoured away from the fill placed across these stream channels.

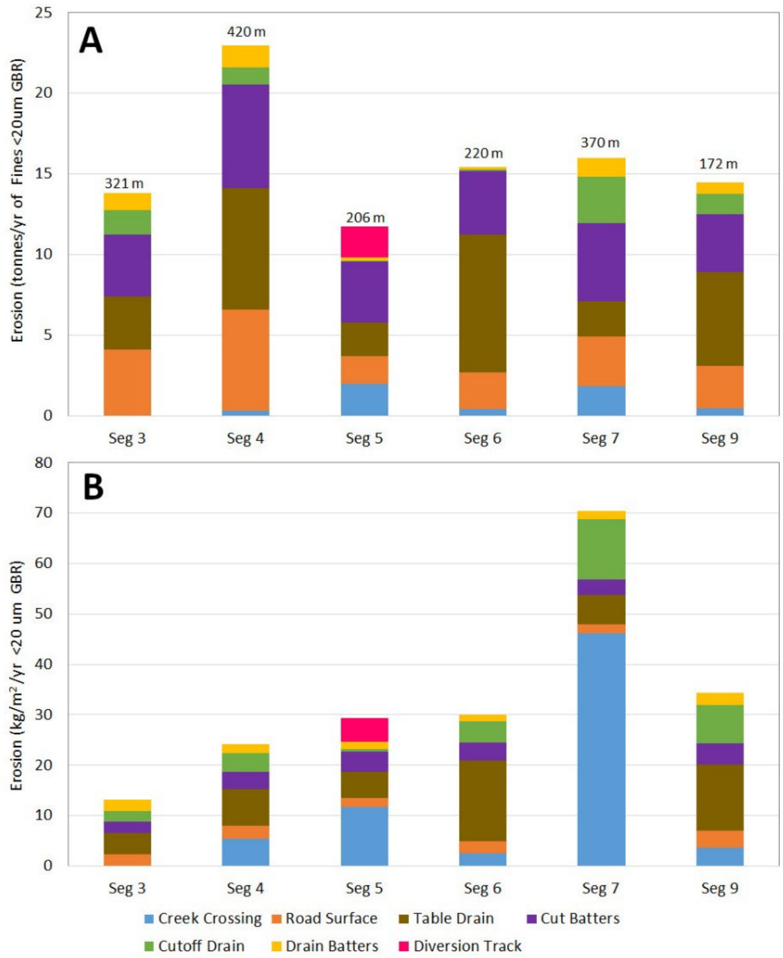

Figure 6 Segment and element erosion rates in WY 2022 before treatment showing A) erosion in t/yr < 20 µm to GBR, with segment length in meters, and B) erosion per unit area in kg/m^2/yr <20 µm to GBR

WY 2023 Data After BMP Treatment Compared to WY 2022 Baseline

In the 2022 dry season, segments 3, 4, 5, 6 and 9 were treated with various BMPs focused at erosion hotspots, while segment 7 was held as a control with no treatment. BMPs included no grading disturbance of drains and batters, passive vegetation recovery, herbicide spraying of woody weeds and invasive plants, rock mulching steep batter erosion hotspots, drain grade control structures at erosion hotspots, rock chutes at drain gully heads, and rock mattress creek crossings.

All segments experienced an overall decrease in erosion between WY 2022 and WY 2023 (Figure 7; Table 2). The smallest erosion decrease (14%) occurred at the control segment 7. Treatment segments 3,4,5,6, and 9 all had larger decreases in erosion (28-67%) than the control segment between years, indicating the sediment reduction influence of BMPs. The decrease in erosion at the control segment 7 can be attributed to rainfall differences at the eastern gauge for totals, number of large events, intensity and antecedent conditions for grass growth from smaller frequent storms (Table 1). Machine grading practices at the control segment were consistent between years, but subtle differences could have occurred.

For analysis by element, the road surfaces of segments 3,4,5,6 all had increased erosion (14 to 49%) in WY 2023 (Table 2). This was due to increased traffic and truck haulage of rock to a gully erosion control site (near Seg 6). The control segment 7 and treatment segment 9 had consistent low traffic between years and experienced minor (4% to 9%) decreases in road surface erosion (Figure 7).

Road verge elements of cut batters, drain batters, table drains, cutoff drains, and diversion tracks were the focus of BMPs treatments at erosion hotspots. Control segment 7 had the smallest erosion decrease (19%) in batter and drain elements compared to treatment segments (41 to 88%) (Figure 7; Table 2). Segment 6 had the largest reduction in verge erosion (88%), largely due to the safe water diversion of 1 km of excess drain flow, but also rock mulching cut batters. Passive vegetation recovery at segment 9 had the lowest reduction in verge erosion (41%). Larger decreases at segment 3, 4, 5 were due to rock treatments of cut batters and table drains near creek crossings (61-62%).

Normalised by the control segment change over two years and rainfall variability, passive vegetation recovery had the lowest erosion reduction (22%), compared to larger reductions where rock was used to stabilise cut batters (42 to 43%) and excess drain water diverted to safe dispersal locations (69%)(Table 2).

Table 2 Road segment fine sediment erosion rates (t/y < 20 µm to GBR) and percent reductions from WY 2022 to WY 2023 after treatment with BMPs

Parameter	Units	Water Year (Nov-Jun)	Seg 3	Seg 4	Seg 5	Seg 6	Seg 7	Seg 9
Total Fine Sediment Erosion to GBR	t/y < 20 µm GBR	2022	13.83	22.95	11.76	15.43	15.98	14.48
Treatment or Control		Oct-2022	Treatment	Treatment	Treatment	Treatment	Control	Treatment
Total Fine Sediment Erosion to GBR	t/y < 20 µm GBR	2023	9.92	14.33	7.39	5.04	13.70	9.59
% Change (+ or -) WY 2023-2022	%		-28.3	-37.6	-37.2	-67.3	-14.3	-33.8
% Change (+ or -) Normalised WY 2023-2022	%		-14.0	-23.3	-22.9	-53.1	0.0	-19.5
Road Surface & Creek Crossing Fine Sediment Erosion to GBR	t/y < 20 µm GBR	2022	4.09	6.56	3.70	2.70	4.91	3.11
Treatment or Impact		Dec-2022 After Scan	Increased Truck Haul	Increased Truck Haul	Increased Truck Haul	Increased Truck Haul	Control No Change	No Change
Road Surface & Creek Crossing Fine Sediment Erosion to GBR	t/y < 20 µm GBR	2023	6.11	7.95	4.23	3.53	4.74	2.84
% Change (+ or -) WY 2023-2022	%		49.5	21.2	14.4	30.9	-3.5	-8.7
Batter & Drain Fine Sediment Erosion to GBR	t/y < 20 µm GBR	2022	9.74	16.39	6.10	12.73	11.07	11.37
Treatment or Impact		Oct-2022	Vegetation, Rock Drain Hotspots	Vegetation, Rock Batter / Drain Hotspots	Vegetation, Rock Batter / Gully Hotspots	Vegetation, Water Diversion, Rock Hotspots	Control No Change	Vegetation Only
Batter & Drain Crossing Fine Sediment Erosion to GBR	t/y < 20 µm GBR	2023	3.81	6.38	2.30	1.50	8.97	6.74
% Change (+ or -) WY 2023-2022	%		-60.9	-61.1	-62.3	-88.1	-19.0	-40.6
% Change (+ or -) Normalised WY 2023-2022	%		-41.9	-42.1	-43.3	-69.1	0.0	-21.6

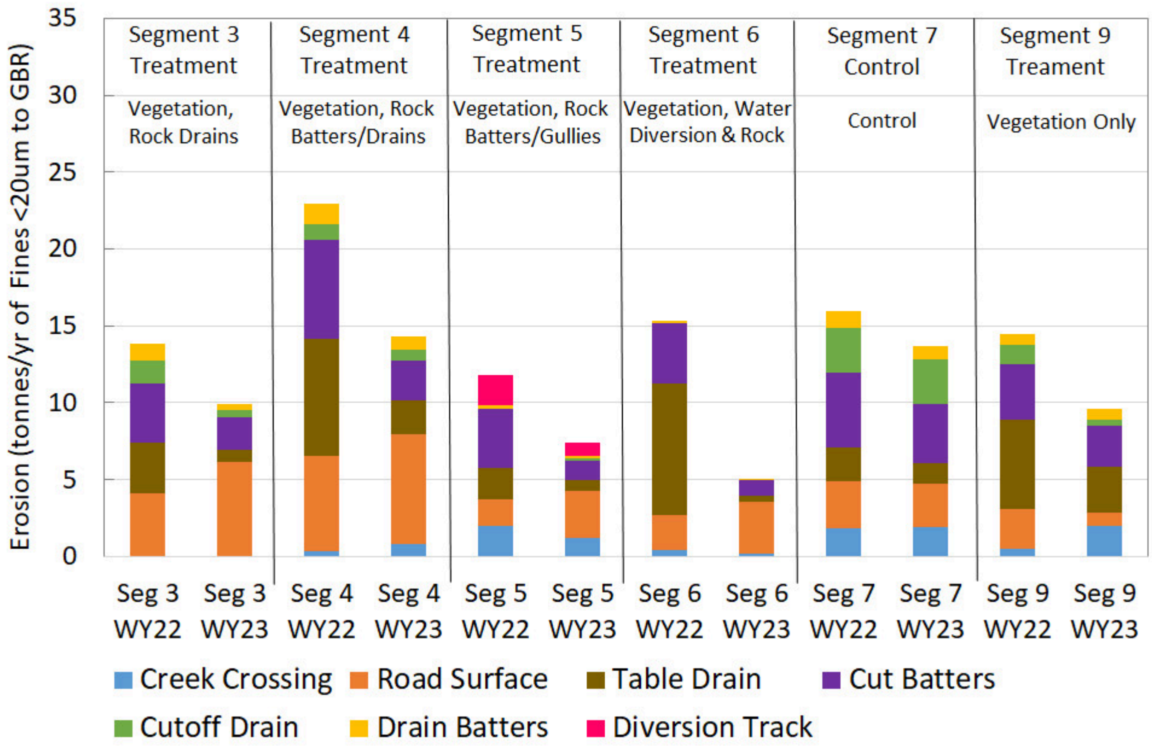

Figure 7 Segment and element erosion rates in t/yr < 20 µm to GBR before (WY 2022) and after (WY 2023) treatment with BMPs compared to the control segment 7

Statistical Analysis of Road Elements Unit Erosion Rates

Unit erosion rates (kg/m²/yr < 20 µm to GBR) at road elements (n=148 polygons) were analysed over two years at control and treatment segments using three complementary BACI GLMMs at different scales. The first analysis compared all impact (treatment) sites collectively to the single control site (Segment 7), showing a significant overall BACI interaction (rate ratio = 0.38, 95% CI: 0.23-0.62, p<0.001), corresponding to a proportional reduction of 62% (95% CI 38-77%). Control segment marginal means decreased from 1.475 (SE = 0.365) to 1.212 (SE = 0.366), while treatment segments decreased from 1.599 (SE = 0.167) to 0.356 (SE = 0.164) kg/m²/yr.

The second analysis examined specific treatment types compared to standard grading practices. Rock mulching treatment was effective in reducing erosion (rate ratio = 0.07, 95% CI: 0.04-0.13, p<0.001). In contrast, no-grade treatments showed marginal effectiveness (rate ratio = 0.65, 95% CI: 0.40-1.04, p=0.073), while check dam treatments were not significantly different from control (rate ratio = 0.76, 95% CI: 0.22-2.55, p=0.7).

The third analysis examined individual segment erosion relative to the control segment. There were significant BACI effects for segment 3 (rate ratio = 0.43, 95% CI: 0.22-0.83, p=0.012), segment 4 (rate ratio = 0.35, 95% CI: 0.20-0.61, p<0.001), segment 5 (rate ratio = 0.32, 95% CI: 0.17-0.60, p<0.001), and segment 6 (rate ratio = 0.10, 95% CI: 0.05-0.21, p<0.001), but not segment 9 (rate ratio = 0.93, 95% CI: 0.41-2.09, p=0.9). The No-Grade data distributions were influenced by some polygons not revegetating well due to harsh soil conditions, steep slopes, or the legacy of past disturbance, while other polygons responded better to passive revegetation with dense grass cover.

Suspended Sediment Concentration Monitoring

In WY 2022, paired SSC samples < 20 µm (n=70) were on average 10.3 times higher downstream of the road influence compared to upstream (Figure 8). The median SSC upstream (Seg 3, 4, 6, 7) was 113 mg/L (mean 256 mg/L) and downstream 1689 mg/L (mean 2638 mg/L). In WY 2023, paired SSC samples (n=80) were 5.5 times higher downstream than upstream. The median SSC upstream was 66 mg/L (mean 184 mg/L) and downstream 645 mg/L (mean 1086 mg/L). Reductions in SSC values were due to cumulative BMP treatments at segments 3, 4, and 6. The control segment 7 had similar SSC distributions in 2022 and 2023 (Figure 8).

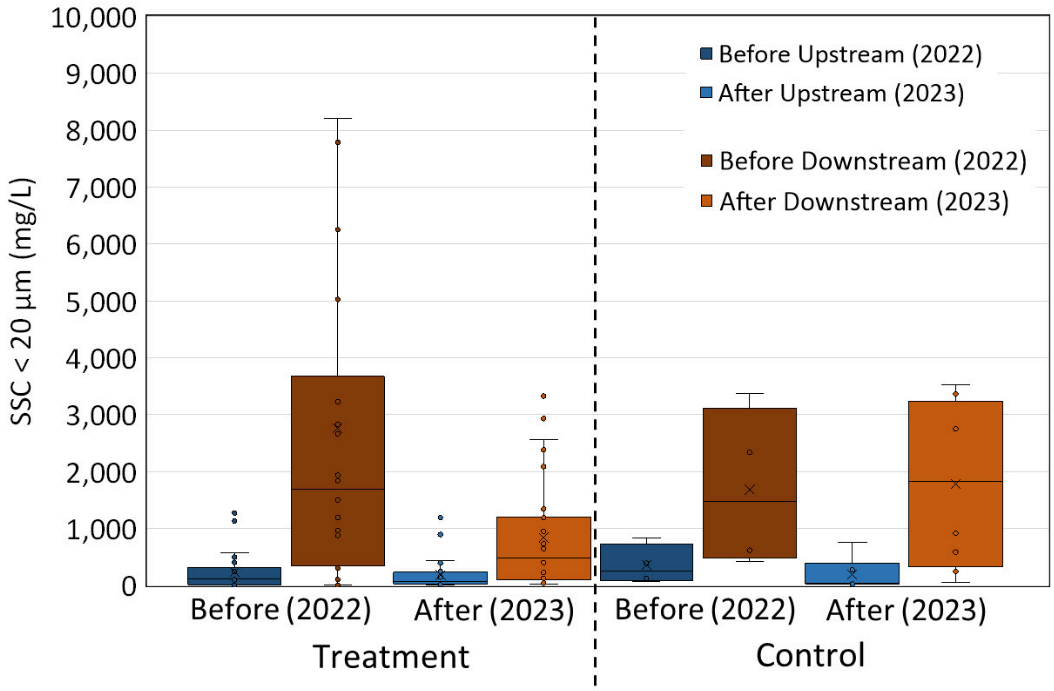

Figure 8 Box plots of suspended sediment concentration (SSC < 20 µm) in creeks upstream (blue) and downstream (brown) of road crossings at control and treatment segments

Discussion

Road Erosion Rates

High resolution TLS data along 2.5 ha of unsealed road corridor during an average rainfall year (WY 2022) measured erosion rates of 132 t/ha/yr locally of all size classes, 45 t/ha/yr < 20 µm locally, 38 t/ha/yr < 20 µm to GBR, or 58 t/km/yr < 20 µm to GBR. These erosion rates are > 30 times higher than background sheet and rill erosion rates from moderately grazed catchments in northern Australia (0.2 to 1.5 t/ha/yr; Brooks et al. 2014; Koci et al. 2020). They are also higher than global agricultural land on erodible soils with poor agricultural practices (15 t/ha/yr, Nearing et al. 2017) or sugar cane agricultural lands in GBR catchments (< 7 t/ha/yr, Visser et al. 2007). Unsealed road erosion rates vary depending on rainfall, slope, traffic, and surface material, with literature values ranging from 2.4 to 273 t/ha/yr with median values around 22 t/ha/yr for all size classes (Fu et al. 2010). Measured road erosion rates from this study (45 t/ha/yr < 20 µm local erosion) are closer to gully erosion measured in GBR catchments (Khan et al. 2023; Daley et al. 2023).

Road surfaces, cut batters and table drains contributed the most to erosion tonnage. These roads elements are the most impacted by annual grading. They will also respond the most to changes in grading practices by either alterative vegetation management (slashing or herbicide), rock mulching (armouring), or bitumen road surface sealing. The increased road surface erosion associated with increased traffic is expected (Alvis et al. 2022) and requires management approaches based on traffic conditions.

The measured 22 to 69% reductions in erosion from applied BMPs in this study are comparable to results of similar global research. Turton et al. (2009) measured 20 to 80% reductions in unsealed road erosion from the application of BMPs to road surfaces, ditches, and cutslopes, including revegetation of disturbed areas. Parsakhoo and Hosseini (2023) achieved soil loss reduction rates of 53–86% on road cut batters after applying soil conservation practices. Luce and Black (1999) found that recently cleared cutslopes and ditches generated 7 times more sediment than vegetated slopes or stable ditches. Alvis et al. (2024) found that increasing table drain roughness with rock, grass or check dams reduced sediment transport. At the regional scale, Dangle et al. (2019) modelled a reduction in erosion rates from unsealed roads near stream crossings as BMP implementation scores increased.

For this study, the cessation of the annual grading disturbance of cut batters (tillage equivalent) and replacing it with alternative vegetation management practices (slashing or herbicide as a no-till equivalent) was the easiest and cheapest way to initiate erosion reduction along unsealed roads. However, ongoing selective drain maintenance at erosion hotspots will be required in isolated areas, along with periodic road surface grading, which could partially diminish the long-term benefits of erosion reduction reported here. Diverting excess table drain water on inslope road sections via drivable dip rock crossings or culverts can significantly reduce table drain erosion, as can frequent flat-bottom diversion drains on road outslopes. Addressing gully erosion at the outlets of drains and avoiding the use of diversion tracks during floodway construction (or use of proper rehabilitation techniques) also can reduce erosion. A mix of BMP measures will be needed for major erosion reduction (Klye et al. 2024; 2025).

Climate Change Considerations

Erosion rates on exposed soils along road corridors documented in this TLS study are a direct response to rainfall intensity and cumulative rainfall erosivity (Table 1). In the tropics of Australia, the intensity of extreme rainfall at the hourly and daily scales has increased over time for larger magnitude rainfall events (Guerreiro et al. 2018; Martel et al. 2021).

Future global warming could increase the intensity and frequency of short-duration extreme rainfall events (Westra et al., 2014), with implications for increased road erosion and associated costs for road maintenance (Erlandsen et al. 2024; 2025).

The extreme rainfall of Cyclone Jasper (Dec-2023) had a major impact on the Annan Catchment (Howley et al. 2024). Study road segments held up well during 1025 mm of rain and 120-hour totals > 100 yr recurrence intervals. Erosion control BMPs were resilient and stable, including recent trials of bitumen sealing. Major damage to road infrastructure was concentrated at exposed areas of bare ground and larger creeks with major flood scour.

Sediment Abatement Costs and Economic Considerations

In Australia, the Federal Government (Reef Trust) invests in land management sectors to reduce fine sediment transported to the GBR. New credit and offset markets are emerging. On the CYP, the average sediment abatement cost paid by Reef Trust was $1624 t/y of fines < 20 µm to GBR for gully control (2015-2021). For this study, the baseline erosion rate for WY 2022 was 94 t/yr of fines < 20 µm to GBR for the six road segments (1.6 km) near stream crossings. The equivalent sediment abatement cost would be $153,000 (AUD) or $64,000/ha or $94,700/km. These costs do not include associated current or legacy gully erosion caused at the outlets of cutoff drains. In comparison, it cost the local Council government $20,000 km/yr (average 2017-2023) for grading the road surface, batters and drains on the roads in this study area. Therefore, the cost trade-offs between road maintenance and road pollution need to be carefully considered.

A detailed economic cost-benefit analysis (CBA) has been produced for this road network (21.5 km) and project segments centred on stream crossings (see Erlandsen et al. 2024; 2025). Different scenarios of road maintenance and betterment were analysed, including economic valuation of environmental impacts from unsealed road erosion. Compared to the current business-as-usual scenario, three different alternative scenarios provided better economic outcomes and society benefits (vegetation management and major erosion control applied in this study, or full bitumen sealing and betterment).

Catchment-Scale Considerations

In the Annan Catchment, there are 103 km of unsealed Council roads under similar DRFA management regimes. Photo surveys of erosion defects every 5 m have documented 147 stream crossings and 46 km of road segments centred on and well connected to stream crossings, averaging 268 m long each (Figure 9). Of these 46 kms, 32 km (69%) are located in alluvial/colluvial lithology with dispersive sub-soils and similar slopes (1 to 4%) as Oaky Creek Road sites (Figure 9). These areas represent 31% of the total unsealed road network and should be the focus of BMP implementation (Klye et al. 2024; 2025). Regionally across eastern CYP catchments, surveys documented 1511 km of Council unsealed roads and 471 km (31%) of well-connected road length at 1889 stream crossings. The scale of the road erosion problem is not isolated to these study sites.

Additional road erosion research is needed on other road segments with different lithologies, such as steeper granitic terrain in the upper catchment not represented by study sites. The remanding road network less connected to stream crossings also needs to be quantified for erosion, as do road areas with major legacy gullies from past management. This will allow for classified inclusion of road erosion data into sediment budget models (McCloskey et al. 2021).

As a minimum estimate of road erosion contribution to catchment loads, the lowest erosion rates from this study (43 t/km/yr < 20 µm to GBR) could be applied to the 32 km of road segments centred on stream crossings with alluvial/colluvial lithology. These segments could be eroding at 1300 t/yr < 20 µm to GBR with an equivalent sediment abatement cost of $2.1 million. The average annual fine sediment yield of the Annan River catchment has been empirically measured at 90,000 t/yr < 20 µm (Howley et al. 2024), with ~ 50% being anthropogenic from land disturbances (grazing, fire, gullies, roads, urban). The alluvial/colluvial subset of well-connected road crossings (1300 t/yr < 20 µm to GBR) could be around 2.8% of the anthropogenic load (45,000 t/yr < 20 µm to GBR).

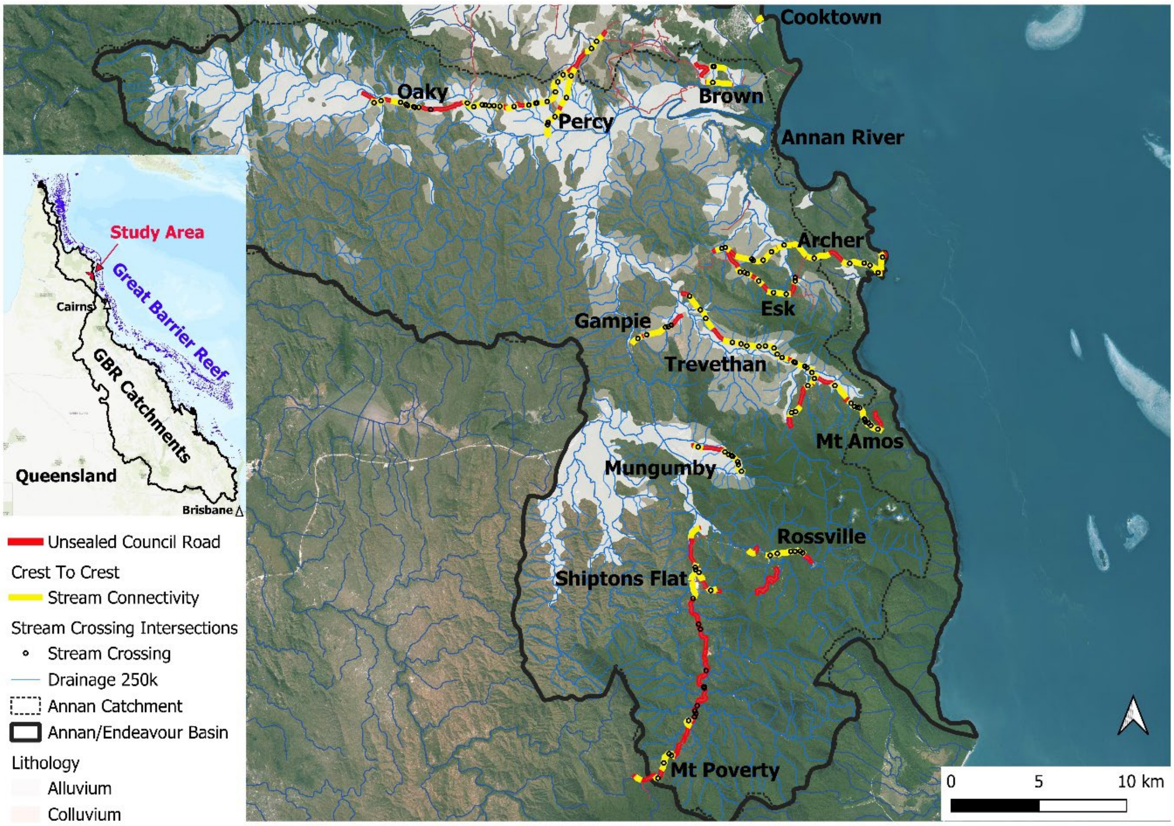

Figure 9 Council roads in the Annan River Catchment with locations of stream crossings (circles) and segments with high stream connectivity (yellow)

Funding and Legal Considerations

Local Shire Councils in Queensland generally have no specific budget for erosion control practices, despite legal requirements to not "*release stormwater run-off into waters, a roadside gutter or stormwater drainage*" (section 440ZG, EPA 1994). Similar challenges exist for Qld Biosecurity Act compliance for invasive weed management along roads. The lack of erosion prevention or control funding embedded in government maintenance programs (DRFA/QRA) means that roads are perpetually maintained in a 'high erosion risk' and 'high weed invasion risk' categories before each wet season, in an entrenched cycle of road repair. Limited betterment funding is highly competitive and used strategically at isolated sites for concrete floodways, large culverts, and occasionally bitumen upgrades.

Results highlight four cost-effective BMPs that need treatment flexibility and funding to reduce sediment pollution from unsealed roads:

1. Minimise annual grading of batters and drains to reduce costs and prevent sediment pollution, while maximising grass cover and controlling invasive weeds,
2. Avoid annually placing fine road base (24% < 20 µm) in stream crossings that flushes downstream (i.e., rock floodways preferred),
3. Selective drain maintenance only at a sub-set of erosion hotspot areas, such as local desilting with backhoe or erosion control betterments below.
4. Erosion control betterments (e.g., rock-mulching batters, check dams or rock lining in drains, bitumen dust seals, concrete or rock floodways, culverts) at erosion hotspots on 30% of road lengths well-connected to streams (Figure 9).

Wholistic funding solutions and paradigm shifts are needed for managing road condition, safety and drivability; vegetation and weed spread; road drainage; sheet, rill and gully erosion; and pollution of fine sediment to the GBR. These management challenges should be treated as a complete road package by Federal, State and local government departments working and funding together (i.e., Federal/State/Local Transport and Environment Departments). This will specifically allow Councils to better manage sensitive erosion areas with erosion control BMPs. Adopting erosion control BMP guidance will enhance environmental outcomes (sediment pollution and weed spread reduction), and achieve a win-win-win scenario for road management, community benefits, and reef protection (Klye et al. 2024; 2025; Erlandsen et al. 2024; 2025).

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Data availability

Data sets generated during the current study are available from the corresponding author on reasonable request.

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