Monitoring Fire Impacts on Ground Cover and Sediment Run-Off in a Northern GBR Catchment

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Cape York Water Partnership

The Queensland Water Modelling Network (QWMN) is an initiative of the Queensland Government that aims to improve the state's capacity to model its surface water and groundwater resources and their quality. The QWMN is led by the Department of Environment and Science with key links across industry, research and government.

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Cover Photos
Left: Hot wildfire in the late dry season, Normanby Catchment, Cape York Peninsula. John Spencer, Griffith University
Top right: Burnt alluvial (gully) hillslope in the Annan Catchment, 2021 (Jeff Shellberg)
Bottom right: Turbid water post-fire, Scrubby Creek, Annan Catchment, 2021 (Jeff Shellberg).

Executive Summary

Tropical savannah landscapes are amongst the most flammable landscapes globally, and wildfire frequency across Australia is predicted to increase with climate change. Extensive burning within a catchment can increase erosion, with potential for significant effect on water quality, including sediment and nutrient loads. Sediment load increases ranging from 1.3 to over 1000 times pre-fire loads have been measured in Australian rivers in the first year after fires. Factors that can affect the hydrologic response of catchments to fire include: (1) the frequency, timing, intensity and spatial extent of burning; (2) weather and climate, notably rainfall intensity and duration; (3) catchment characteristics including slope, soil type, vegetation type, ground-cover, and land use; (4) the time interval between burning and subsequent rainfall runoff, and (5) the presence and extent of gully, stream bank, and road or track erosion. Due to this complexity, water-related (hydrologic) impacts of fire at landscape scale are difficult to quantify and predict and thus are often overlooked in both water quality risk assessments and in sediment and nutrient load models. This knowledge gap contributes to uncertainties within modelled sediment loads from northern Great Barrier Reef (GBR) catchments, where intensive wildfires are frequent and powerful monsoon rains contribute to high rates of erosion in some areas. As a result, the risks to tropical aquatic ecosystems may be significantly underestimated.

The Cape York Peninsula (CYP) region, in the far northern GBR catchment (Queensland, Australia) comprises 42% (10,354 km^2) of total GBR reef area, 30% (11,378 km^2) of GBR seagrass area, and 23% (1,407 km^2) of GBR coastal wetland areas. Understanding the natural and anthropogenic processes controlling water quality in CYP river systems is critical to prioritise management investments and maintain healthy aquatic ecosystems for this significant region of the GBR. The impacts of severe wildfires on groundcover and adjacent riverine and estuarine turbidity and sediment loads have been opportunistically observed and recorded in CYP catchments. However, they have not yet been well quantified in a fire-focused water quality study. The Cape York Water Partnership (CYWP) have been contracted by the Queensland Government Department of Environment & Science (DES) to develop a methodology for monitoring the impact of fires on sediment run-off. The resulting *Fire, Ground Cover & Sediment Runoff Monitoring methodology* aims to:

1. Collect empirical water and sediment runoff data from at least 3 Cape York Peninsula (CYP) sub-catchments that can be used to assess and calibrate model predictions of erosion and sediment yield for a northern GBR river system under varying terrain (alluvial and hillslopes).

2. Compare the impacts of various fire types and burn intensities common in northern Australia (early dry season burn/ late dry season burn / no fire) on actual ground cover and sediment run-off at the plot (1 ha), headwater stream (5-20 ha), and sub-catchment (<10,000 ha) scale measured using stream gauging techniques (flumes, continuous turbidity, sediment samplers, and water discharge gauges).

3. Compare empirical field measurements of ground cover at the plot scale (n = 30) at the break of season (November) and quarterly associated with different fire types, burn intensities and

antecedent rainfall, with remote sensing estimates of fractional ground cover data (LandSat, Sentinel, other higher resolution data) at the same locations.

4. Ground-truth components of the SOURCE and RUSLE model inputs (and other relevant models) and conduct sensitivity analyses of different model runs to input data and sources at plot, headwater stream, and sub-catchment scale. Comparisons will include differences in slope and slope length (measured with SRTM vs. LiDAR data in hillslope and alluvial settings); catchment interpolated rainfall (R factor) compared to local annual rainfall tipping bucket measurements; soil erodibility (K factor) derived from regional soil datasets compared to local field soil sample data and actual erosion pre/post fire to calculate local soil erosivity; and the estimation of cover (C factor) from satellite spectral analysis vs field transect measurements under varying fire types and burn intensities.

The method is being developed for implementation with the Eastern Cape York Water Quality Program (ECYWQP), funded by the Great Barrier Reef Foundation (GBRF) and Reef Trust Partnership, in conjunction with ECYWQP fire management projects; however, the methods may be applied elsewhere. The methods described here focus primarily on monitoring sediment run-off, but nutrient and other impacts may also be monitored. ECYWQP fire projects are led by South Cape York Catchments, South Endeavour Trust and Yuku Baja Muliku, and aim to reduce late dry season and/or total burn area over the ECYWQP project area.

ECYWQP project sites are in south-eastern Cape York Peninsula.

Acknowledgements

Funding for the development of methods to measure the impacts of fire on ground cover and water quality (particularly sediment loads) has been provided by the Qld Department of Environment and Science’s Queensland Water Modelling Network (QWMN). The methods have been developed over the course of many discussions (and draft reviews) with Eastern Cape York Water Quality Program (ECYWQP) project teams, including Tim Hughes and Jon Witheridge of South Endeavour Trust (SET) and Denis Kelly from South Cape York Catchments (SCYC). In addition, Cape York fire management practitioners Daryl Killen and Mark Parsons (QPWS Regional Fire Coordinator) have provided advice and ideas on how best to monitor fire severity and impacts, as well as how to safely control late dry season fires for monitoring purposes. We thank Cape York ecologist Gabrielle Davidson, who is developing methods for monitoring fire impacts on wetlands, for her advice. Finally, we thank Gillian McCloskey and Angela Pollett (Qld DES) for sharing the results of their studies on remote sensing of fire scars and ground cover within the SOURCE model framework for the GBR, and Mark Silburn (Qld DES) and Ben Jarihani for their reviews and useful suggestions.

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1 Introduction and Background

Fire is a natural component of savannah landscapes as well as a resource management tool used by Indigenous and European Australians. Burning methods and timing vary depending upon the land management objective, which can include the protection of biodiversity, weed control, pasture management, carbon farming/mitigation, the control of woodland thickening and the reduction of wildfire hazard. Extensive burning within a catchment can increase erosion and may thus have a significant effect on water run-off, quality and aquatic ecosystems. Sediment and nutrient generated and exported from burnt watersheds can significantly exceed pre-fire levels.

Tropical savannah landscapes are some of the most flammable landscapes globally (Edwards *et al.* 2004), and the frequency of wildfires across Australia is predicted to increase with climate change (Dutta *et al.* 2016; Moran 2020). However, the hydrologic impacts of fire are difficult to quantify and predict, thus are often overlooked in both water quality risk assessments and in sediment and nutrient load models (Woinarski *et al.* 2007). This knowledge gap contributes to uncertainties within modelled sediment loads from northern GBR catchments, where fire impacts are frequent and extensive. As a result, the cumulative human impact and risks to tropical aquatic ecosystems may be significantly underestimated.

The Cape York Water Partnership (CYWP), in association with the Regional Advisory & Innovation Network (RAIN) Pty Ltd have been contracted by the Queensland Government Department of Environment & Science (DES) to develop a methodology for monitoring the impact of fires on ground cover and sediment run-off. This method is being developed to be implemented as part of the Eastern Cape York Water Quality Program (ECYWQP) in conjunction with ECYWQP fire management projects; however, the methods may be applied elsewhere. This work also aims to inform water quality modelling discussions and to address strategic Queensland Water Modelling Network (QWMN) water modelling-related priorities (e.g.: Botelho *et al.* 2021; Cox 2021). The methods described here focus primarily on monitoring sediment run-off, but nutrient impacts may also be monitored.

1.1 Evidence of the Impacts of Fires on Erosion and Water Quality

There is now ample evidence to show that fire, particularly intense wildfires, leads to increased rates of erosion and sediment loads in adjacent streams (Townsend & Douglas 2000; Pierson *et al.* 2008; Duggan 1994; Lane *et al.* 2006; Ayoubi *et al.* 2021). Sediment load increases ranging from 1.3 to over 1000 times pre-fire loads have been measured in Australian rivers in the first year after fires (Smith *et al.* 2011). Fires can increase erosion through several processes. The reduction in ground cover and sometimes canopy cover from fires can lead to greater raindrop impact and increased soil detachment (Pierson *et al.* 2008). The reduction in ground cover also increases surface water flow velocity, erosive capacity and transport capacity (Pierson *et al.* 2008). Fires reduce the interception capacity of vegetation, leading to increased rain splash erosion, surface flow velocity and associated erosion. Through the removal of vegetation, organic matter and microorganisms, and the addition of ash, fire can also cause changes in soil properties including porosity, soil moisture, stability, structure, and water repellency, contributing to increased water runoff rates and the initiation or acceleration of erosion (Duggan 1994; Shakesby & Doerr 2006; Ayoubi *et al.* 2021). Riparian vegetation, which often plays a significant role in reducing sediment and nutrient loss to adjacent streams, may be particularly sensitive to the impacts from hot fires (Andersen *et al.* 2005). The overall effect of these fire-related changes to soil and vegetation are increased surface water run-off and sediment yield during post-fire storm events, however the response to fire is varied and complex. Detailed reviews of the hydrological and geomorphological effects of fire are provided by Shakesby and Doer (2006), Daniel *et al.* (2008), and Pierson and Williams (2016).

Factors that can affect the hydrologic response of catchments to fire include: (1) the frequency, timing, intensity and spatial extent of burning; (2) weather and climate, notably rainfall intensity and duration; (3) catchment characteristics including slope, soil type, vegetation type, ground-cover, and land use; and (4) the time interval between burning and subsequent rainfall runoff (Townsend & Douglas 2000). The presence and extent of gully, stream bank, and road or track erosion may also be important factors. Many of these factors are relevant in the wet/dry tropical catchments of the Great Barrier Reef, where both extreme dry periods (winter, high fuel loads comprised of dead vegetation) and powerful monsoonal rains (summer) contribute to frequent hot fires and high rates of erosion in both the steeper upper catchment regions and alluvial plains dominated by highly erosive sodic soils (Howley *et al*. 2021; Brooks *et al.* 2013).

The timing or seasonality of fires is particularly important in relation to hydrologic and erosion response in tropical savannah regions and may be used as a proxy for fire severity. Early dry season (EDS/ low intensity) fires tend to burn less area and do not remove all ground cover, while late dry season (LDS/ high intensity) fires tend to both reduce canopy cover and significantly remove ground cover within the burnt area (Townsend & Douglas 2000; Lui *et al.* 2021; Perry *et al.* 2020) (*Figure 1*). In addition to the lesser impact on vegetation generally associated with fires earlier in the dry season, a longer time-period (months or years) between EDS or LDS fires and extreme monsoon or storm events allows for more ground-cover re-growth and therefore a reduced risk of erosion in response to heavy rainfall. Townsend and Douglas (2000) and Townsend et al. (2004) showed that in the Northern Australia savannah landscape, LDS fires result in significantly higher sediment loads (2.4x) in adjacent waters compared to EDS fires. In contrast, there were no significant differences in stream sediment loads following EDS fires and no fire (unburnt) in the gently undulating savanna terrain of the study area (Townsend & Douglas 2004).

While the Northern Territory studies showed the impact of LDS fires on erosion and freshwater river water quality, Barros *et al.* (2022) further found that severe fires, such as the 2019-2020 wildfires in southern Australia, can also significantly increase nutrient, metals and pyrogenic carbon concentrations in estuarine habitats (Barros *et al.* 2022). This evidence clearly shows that wildfires are a significant threat to the health of Australian freshwater and coastal ecosystems.

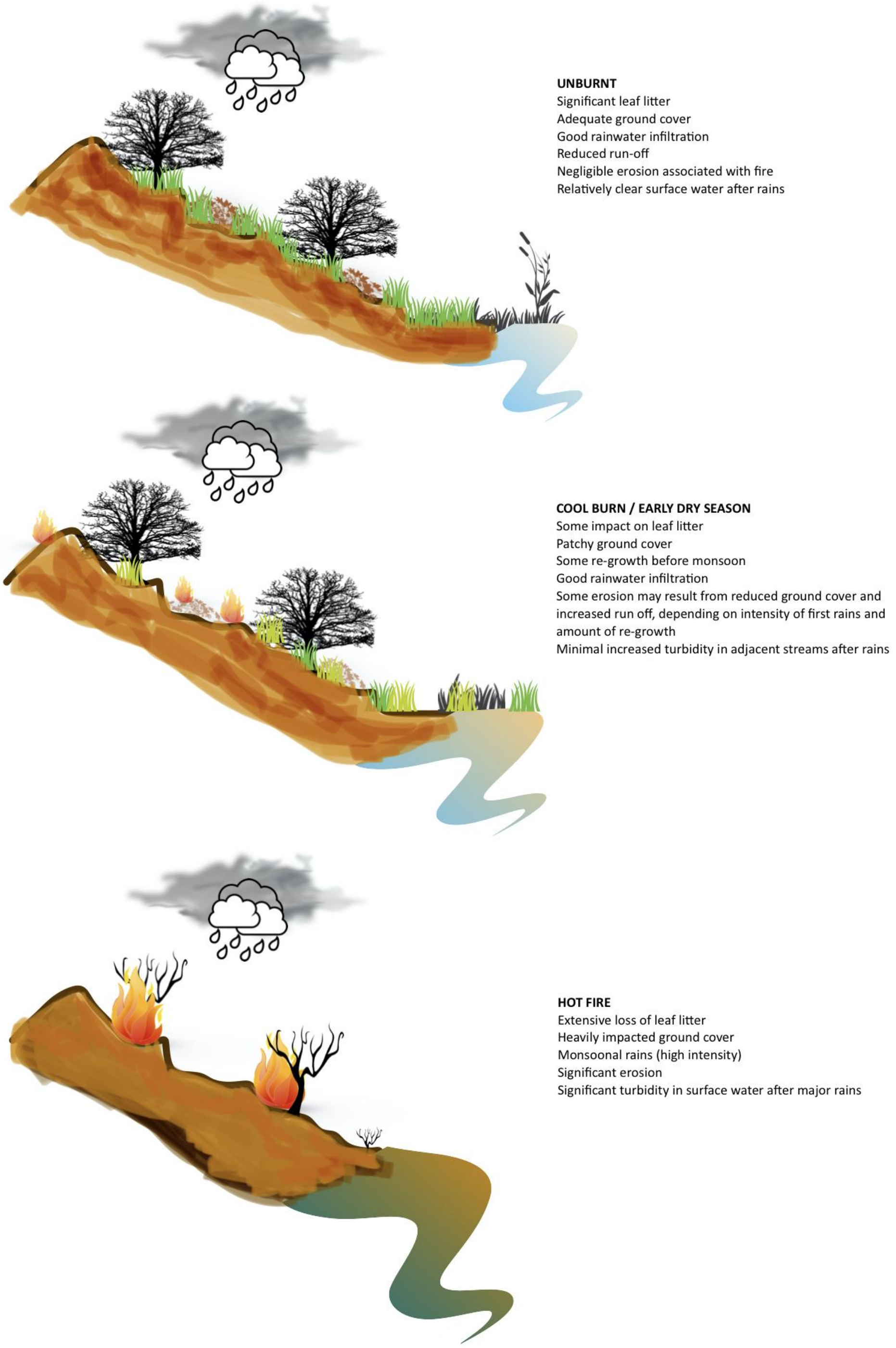

Figure 1   Schematic catchment impact typologies: unburnt, cool burn / EDS and hot fire / LDS

The impacts of severe wildfires on groundcover and adjacent riverine and estuarine turbidity and sediment loads have been opportunistically observed and recorded in Cape York Peninsula (CYP). For example, Howley *et al.* (2021) suggested that extensive wildfires contributed to elevated suspended sediment yield in the Laura River (Normanby Basin) over the 2012–13 water year. During a 5-year (on-going) study measuring sediment loads in the Annan River (southeast CYP), a late dry season (LDS) wildfire burnt over 60% (10,000 ha total) of the Scrubby Creek sub-catchment in December 2021. Extremely high turbidity (NTU >2000) and suspended sediment concentration (SSC, >3000 mg/L), as well as high carbon content, was measured in Scrubby Creek during the first wet season rains (January 2022) despite relatively low river heights (**Error! Reference source not**

found.; **Error! Reference source not found.**). As the wet season progressed and grass cover recovered, the turbidity values during large flood events were lower than the first two flushes immediately after the wildfires (**Error! Reference source not found.**). Elevated turbidity measured during first flush events compared to subsequent events is common even without fire impacts (Howley *et al.* 2021), however the "first flush" effect on adjacent sediment and carbon loads is exacerbated by the complete absence of ground cover (Figure 3). While these impacts have been recorded in CYP rivers, they have not yet been well quantified in a fire focused water quality study.

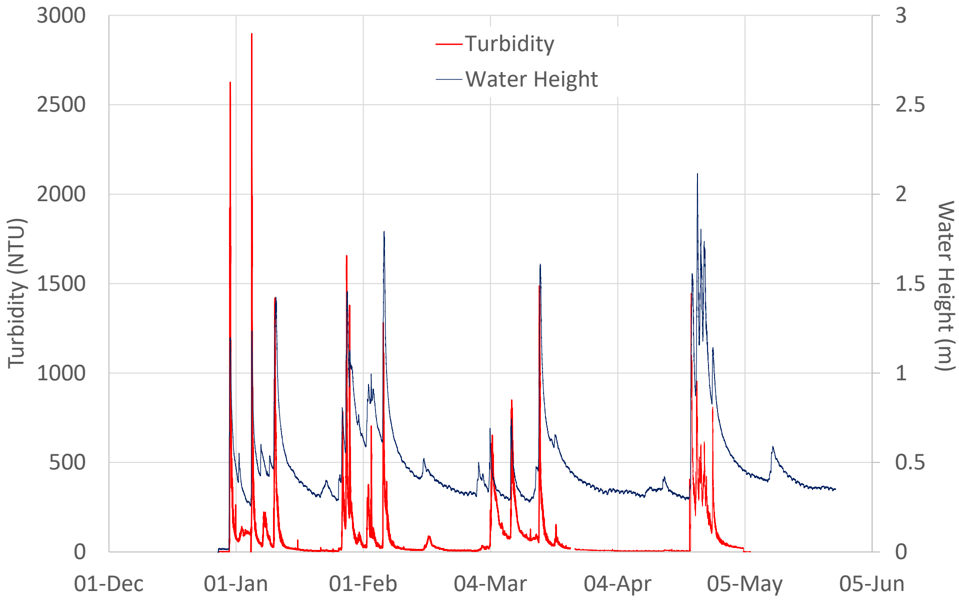

Figure 2 Continuous turbidity and water stage data at Scrubby Creek following LDS Fire in Dec-2021.

Figure 3 A burnt alluvial (gully) hillslope and turbid water post-fire in Scrubby Creek, Dec-2021.

While intense fire can increase erosion in the short-term, the long-term impacts on sediment run-off are difficult to predict. Changes in soil physical characteristics and vegetation communities, and the re-mobilisation of sediment deposited temporarily in stream channels after a fire, can produce elevated downstream sediment loads for 10 or more years after a severe fire (Neary *et al.* 2005). However, in some catchments, regrowth and depletion of mobilised sediment can reduce sediment loads back to pre-fire levels within 2 to 3 years (Hudson *et al.* 1983a; Environment ACT 2003; Corban 2012).

In addition to increased turbidity and suspended sediment loads, fires can also cause increases in nutrient concentrations in soil and water (Ilstedt *et al.* 2003; Environment ACT 2004; Corban 2012). While increased nutrient supply is often associated with sediment run-off, high intensity (hot) fires release ammonium and particulate phosphorous into the atmosphere (Qian Y Fau-Miao *et al.* 2009). The aerial deposition of smoke and ash can also result in increased phosphorous and nitrogen levels in streams (Spencer *et al.* 2003; Townsend & Douglas 2000). The impact of fires on nutrient run-off and/or deposition in adjacent streams is also variable and strongly influenced by the intensity of the fire (Townsend and Douglas 2000; Ulery *et al.* 1993; Qian Y Fau-Miao *et al.* 2009). The deposition of ash can reduce dissolved oxygen levels in adjacent rivers, which has resulted in fish kills in the ACT and Northern Territory (Environment ACT 2004; Andrew Hartwig; pers. comm. 2012).

Fire Intensity vs Severity

Fire intensity describes intensity during the fire event: (Fire Intensity is measured as the rate of energy or heat release per unit time per unit length of fire front (kW/m)
Fire intensity represents the energy released during various phases of the fire and no single metric captures all the relevant aspects of fire energy. Different metrics include reaction intensity, fireline intensity, temperature, residence time and radiant energy (Keeley 2009).

Fire severity describes severity of impact after the fire event:
Fire severity is used to describe the impact of fire on ecosystems and is usually measured by the post fire analysis of the change in above-ground biomass (Dixon & Callow 2022). However, fires can cause below-ground, understorey level and canopy level impacts that effect ecological and erosion processes differently (Knox and Clark 2016). Many variables affect fire severity including fuel loads, season (EDS, LDS, monsoon etc.), weather, topography, rate of spread and the composition of vegetation. The effect of fire on vegetation has both a horizontal (patchiness) and vertical (scorch height) component (Edwards 2011). Edwards (2009) classifies fire severity in tropical savannahs of Northern Australia as Patchy, Low, Moderate, High and Extreme (Appendix A).

This fire monitoring design will focus on an assessment of fire severity measurements as opposed to fire intensity. Measurements of fire severity (Appendix A and B) will complement the assessment of the influence of fire timing on erosion and water quality.

1.2 Modelling Sediment Erosion, Run-off and Loads

Field measurement of stream pollutant loads across the Great Barrier Reef (GBR) catchment area is challenging due to the large spatial extent, climate variability, changing land use, evolving land management practices, and cost. Consequently, modelling of sediment loads discharged from GBR rivers is often used to assess anthropogenic impacts on sediment loads associated with changes in human land use, and to determine priorities for investment in land management. Within the Australian Government and Queensland Government Paddock to Reef Program, the eWater SOURCE model is used to estimate sediment loads discharged to the GBR (McCloskey *et al.* 2021). The overarching purpose of the modelling is to assess the impact of land management changes across the GBR against the Reef 2050 Water Quality Improvement Plan's (WQIP) targets (Dougall & McCloskey 2017; McCloskey *et al.* 2014).

Modelled estimates of sediment loads and land use impacts influence priorities for future investments by the Queensland Government and the Australian Government. Cape York rivers are given a "low risk" and "low-priority" status in GBR wide risk assessments (Waterhouse *et al.* 2021). This is despite the fact that wildfires occur late in the dry season across vast areas of Cape York every year (Lui *et al.* 2021; Perry *et al.* 2020), resulting in bare ground with lower grass cover than that resulting from most grazing impacts. Underestimates, errors, or omissions in relative sediment contributions and exported loads in modelling for northern GBR rivers have been documented (Brooks *et al.* 2013; Olley *et al.* 2013; Brooks *et al.* 2014; Howley *et al.* 2016; Shellberg *et al.* 2016; Howley *et al.* 2021). Extensive local research has shown that the region is not at a low-risk of water quality impacts as may be concluded via desktop studies. It is critical that fire impacts are empirically monitored, and the accuracy of the models are evaluated, as fire may be one of the most significant drivers of variations in sediment loads in far northern GBR catchments.

While there are many models that can be used to estimate erosion, within the GBR SOURCE model, surface erosion (rill and inter-rill) is calculated using the Revised Universal Soil Loss Equation (RUSLE) at the pixel or plot scale (~100m) (Renard *et al.* 1997; Dougall & McKlosky 2017). RUSLE estimates average annual soil loss, expressed as mass per unit area per year, using factors that represent how climate, soil, topography, and land use and land management affect rill and inter-rill soil erosion caused by raindrop impact and surface water runoff. These influences are described in RUSLE with the equation:

A = R*K*L*S*C*P

where: A = average annual soil loss (t/ha/yr.) at the plot or pixel scale (100m), R = rainfall factor, K = soil erodibility factor, L = slope length factor, S = slope steepness factor, C = cover factor, and P = supporting practices factor.

The Cover factor is one of the most important factors in RUSLE because it represents the effect of land use (including fire) on vegetation cover. The SOURCE sediment load model incorporates seasonal quarterly estimates of fractional ground cover in their calculations of the RUSLE C factor, derived from 30 m Landsat data. Fire scars are represented in models by ground cover data estimated from remote sensing / satellite imagery, from quarterly 30 m Landsat, weekly 10m Sentinel-2 and daily to monthly 250 m (MODIS) data of fractional ground cover. However, there are many additional variables beyond coarse-scale ground cover estimates that can influence soil erosion and sediment loads associated with different fire types. These include 1) fire timing, intensity and extent; 2) vegetation type, grass species, and recovery potential; 3) post-fire residual vegetation, root cohesion and organic material; 4) local soil type and variability; 5) soil property modification by fire; 6) terrain and local slopes; 7) antecedent land use conditions, and 8) antecedent rainfall, timing and intensity. Therefore, directly incorporating fire impacts over time into a sediment load model can be difficult to parameterise via process-based or theoretical equations.

There is a lack of empirical data from Cape York Peninsula & GBR field sites on 1) actual ground cover following varying fire severities on different slopes and vegetation communities, and 2) soil erosion and sediment runoff at the plot (1 ha), headwater stream (5 to 20 ha) and sub-catchment (10,000 ha) scale. These data are essential to calibrate and ground truth any type of desktop model based on spatial data extrapolation and remote sensing.

There is also a lack of high-resolution spatial data on Cape York Peninsula to accurately run the RUSLE and SOURCE models at the scale that is meaningful to actual erosion processes and vegetation conditions before and after fire impacts. This could apply to each RUSLE variable including rainfall spatial variability, soil erodibility, slope and slope length, and ground cover. For example:

- *Elevation and slope*: the 30 m pixel digital elevation models (SRTM) used for slopes and slope lengths calculations do not capture most real headwater streams, local slopes, or widespread alluvial gullies on the landscape (Figure 4). Erosion processes and sediment connectivity in these streams and slopes are missed (50% of channel network length) by coarse DEMs, as are the impacts of fire on these features. High-resolution LiDAR data (0.5 to 5m pixel) is increasingly becoming available in GBR catchments, which will eventually have full coverage and drive innovation in catchment modelling (e.g., NSW already has coastal catchments with full LiDAR coverage).
- *Vegetation cover*: the 30m (Landsat) and 250m (MODIS) satellite data used by SOURCE for fractal ground cover and fire scar mapping do not capture detailed ground cover conditions and spatial complexity of burn types. This is especially the case in coastal catchments with higher woodland tree density, complex ecotones, and frequent high cloud cover. A switch to higher resolution mapping is occurring in the fire mapping industry (10 to 20 m Sentinel-2), which should also improve fractional ground cover estimates. However, concerns remain regarding the reliability of data derived from the Sentinel-2 visual bands (10m resolution). Better fire scar data may be derived from the SWIR bands (20m resolution). Higher resolution commercial data also are available for multi-spectral analysis of fractional ground cover (<6m pixel sizes), which should better estimate ground cover between and through the tree canopy.

As availability of technology improves and costs reduce, it will be imperative to transition modelling toward higher resolution datasets to drive model accuracy and parameterisation and push for innovation in science.

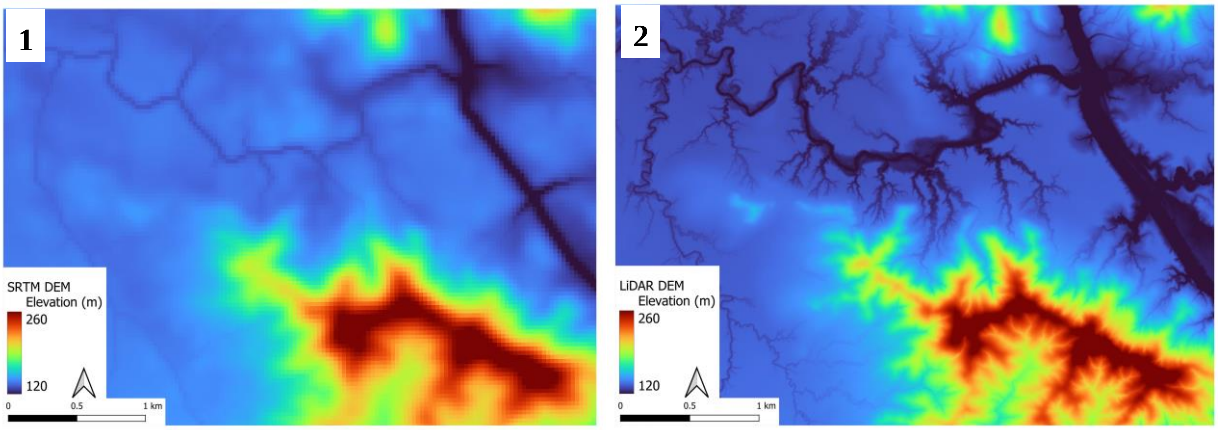

Figure 4 Resolution of digital elevation models: 1) SRTM (30m) used in SOUCE model, and 2) LiDAR (1m) data for the same areas detecting alluvial gullies and headwater streams.

1.3 ECY WQP Fire Monitoring Methodology & Pilot Study

Hydrological and geomorphological research has been limited for the remote northern GBR catchments of Cape York Peninsula (Cape York). Most estimates of river sediment and nutrient loads in this region are based on modelling with known limitations and which has: underestimated loads for some rivers by up to 50% in an average year (Brooks *et al.* 2013; McCloskey *et al.* 2014; Howley *et al.* 2016; Shellberg *et al.* 2016; McCloskey *et al.* 2021; Howley *et al.* 2021); overestimated erosion from rocky hillslopes (Brooks *et al.* 2014); and significantly underestimated the scale of alluvial gully and stream erosion (Olley *et al.* 2013; Brooks *et al.* 2013; Shellberg *et al.* 2013). The Cape York region comprises only 10% of the GBR land catchment area (43,000 km^2), but 42% (10,354 km^2) of total GBR reef area; 30% (11,378 km^2) of GBR seagrass area, and 23% (1,407 km^2) of GBR coastal wetland areas (Thomas & Brodie 2015). A better understanding of the natural and anthropogenic processes controlling water quality in Cape York river systems is critical to prioritise management investments and maintain healthy aquatic ecosystems for this significant region of the GBR.

CYWP is managing the Eastern Cape York Water Quality Program (ECYWQP) funded by the Great Barrier Reef Foundation (GBRF) and Reef Trust Partnership. The ECYWQP brings together local organisations in a coordinated effort to improve land management practices and deepen understanding of threats to water quality in Eastern Cape York catchments. Fire projects led by South Cape York Catchments (SCYC), South Endeavour Trust (SET) and Yuku Baja Muliku (YBM) are funded for the 2022 and 2023 fire seasons to manage fire across a wide range of properties from the Annan River to Muck River catchments, primarily to strategically burn in the early dry season (EDS) to avoid late dry season fires. The goal of the ECYWQP fire projects is to reduce late dry season fires (LDS) and/or total burn area over the project area.

While there are considerable challenges in quantifying the influence of fire on water quality, the ECYWQP provides an ideal opportunity and significant in-kind contributions to collect empirical data from a suite of sites under different fire management types over a period of two years, and potentially beyond. The field monitoring methodology described here considers the needs of a range of end-users, including scientists seeking a method to collect empirical data on the impacts of fire on water quality, modellers interested in validating sediment load estimates, and State, Federal and conservation organisations seeking evidence of value for investments in on-ground activities to improve or protect water quality. The monitoring work proposed here addresses concerns of the scientific community and land managers in Cape York, where the threat from fire to water quality and the GBR is considered a high priority (ECY WQIP 2016). In addition to complimenting the ECYWQP, these monitoring methods will build on past work in the Northern Territory (Townsend & Douglas 2000; Townsend *et al.* 2004) and more recent desktop studies by DES (Pollett 2021; McCloskey, pers. Comm. February 2022).

The Fire & Sediment Runoff Monitoring methodology detailed below aims to:

1) Collect empirical water and sediment runoff data from a Cape York sub-catchment that can be used to assess and calibrate model predictions of erosion and sediment yield for a northern GBR river system under varying fire types, terrain (alluvial and hillslope), and vegetation types.
2) Compare the impacts of various fire types and burn intensities common in northern Australia (EDS burn / LDS burn / unburnt) on actual ground cover measured along transects and sediment run-off at the plot (1 ha), headwater stream (5-20 ha), and sub-catchment (<10,000 ha) scale measured using stream gauging techniques (flumes, continuous turbidity, sediment samplers, and water discharge gauges)
3) Compare empirical field measurements of ground cover at the plot scale (1 ha, n = 30) at the break of season (November) and quarterly associated with different fire types, burn intensities and antecedent rainfall, with remote sensing estimates of fractional ground cover data (LandSat, Sentinel, other higher resolution data) at the same locations.
4) Ground-truth components of the SOURCE and RUSLE model inputs (as well as other relevant and potentially more accurate models) and conduct sensitivity analyses of different model runs to input data and sources at the plot, headwater stream, and sub-catchment scale. This will include comparisons in differences in slope and slope length as measured with SRTM vs. LiDAR data in both hillslope and alluvial settings; catchment interpolated rainfall (R factor) compared to local annual measurements with rainfall tipping buckets; soil erodibility (K factor) derived from regional soil datasets compared to local field soil sample data (texture, organics, etc) and actual erosion pre/post fire to calculate local soil erosivity; and the estimation of cover (C factor) from satellite spectral analysis compared to field transect measurements under varying fire types and burn intensities.

2 Fire and Sediment Method

2.1 Site Selection

Three options have been identified to aid in site selection:

1) Controlled monitoring focussing on spatial variations in sediment run-off from 3 sub-catchments with different fire types: Select three small sub-catchments within the same catchment for comparison of controlled fire experiments: EDS, LDS, fire exclusion. This is the method employed by Townsend & Douglas (2000).

Benefits:

- Ability to select similar sized catchments with similar vegetation type, soil type and terrain. Ideally also within the same climate influences.

Challenges/Disadvantages:

- High risk associated with controlled LDS burn; few landholders are willing to take this risk as LDS fires may get out of control and start extensive wildfires, burning into and/or across neighbouring properties. May be difficult to obtain a ‘Permit to Light Fire’ late in the dry season.

2) Opportunistic monitoring focussing on spatial variations in sediment run-off from 3 sub-catchments with different fire types: Select 2 sub-catchments in advance of the dry season for controlled EDS and fire exclusion experiments. Implement monitoring on these sites. At the end of the dry season but before the first rains, opportunistically select LDS sub-catchment site within the same catchment based on where LDS fires have occurred. These sites may be scoped based on fire frequency maps and local knowledge of areas that frequently burn late in the dry season but will not be pre-selected. Implement ground cover and sediment run-off monitoring opportunistically at these LDS sites after the fires occur.

Benefit:

- Reduced liability associated with starting a LDS fire.

Challenges/Disadvantages:

- Opportunistic LDS sites may be different vegetation, terrain, soil type, rainfall compared to EDS and fire exclusion sites. May be difficult to statistically compare the results due to the influence of these other factors.
- Timing of the end of dry season and first rains will be highly uncertain, thus there may be challenges associated with selecting LDS sites and conducting ground cover monitoring or installing water quality monitoring equipment before the rains commence.

3) Combined Control / Opportunistic Monitoring focussing on temporal variations in sediment run-off within selected sub-catchments: Select 3 small sub-catchments for monitoring over multiple fire seasons. Ideally, the selected sub-catchments would not have burnt in the year before the study begins to provide a standard starting point, and adequate fuel load for burns that occur within the study period. Within the selected sub-catchments, plan for early dry season burns some years and sites (but not all) and fire exclusion at some sites for at least some years. Include one area that has frequent LDS wildfires with the assumption that that will occur again at some point within the study period. Monitor ground cover and sediment run-off over the longer-term (3 - 5 years, ideally) to opportunistically capture the effects of varied fire types within each sub-catchment.

Benefits:

- Reduced risk and liability associated with starting a LDS fire (LDS fires that do occur will not be started by the project team).
- Ability to assess the impacts of different fire types within each site, ensuring that differences in sediment run-off are not due to site variations in vegetation, terrain, etc.

Challenges/Disadvantages:

- Impossible to predict where/when LDS fires will occur, thus risk of missing this burn type from the study (potentially necessitating a controlled LDS burn for this research).

Site Selection considerations:

An examination of long-term fire histories (EDS, LDS, time since last burn, etc) will be an important first step in understanding the starting point for monitoring. This will be particularly critical for identifying areas that are prone to LDS fires, for opportunistically capturing this fire occurrence within the study period. For a general overview of the broader historical context for fire on Cape York refer to Crowley and Garnett (2000).

Where possible, headwater measurement sites and sub-catchments should be located within areas that have been surveyed with Light Detection and Ranging (LiDAR) high resolution topography data (1 m resolution). Blocks have been surveyed in the Annan, Endeavour, Jeannie, Normanby and Stewart catchments of Cape York Peninsula (State of Queensland, CSIRO, Griffith Uni). LiDAR data will enable better assessment of terrain in terms of slope, length, and the presence of creek and gully erosion. RUSLE soil loss calculations and gully erosion models can be improved using more accurate LiDAR topography and compared to erosion estimates using coarser elevation data (30m) and models currently relied on (McCloskey *et al.* 2021).

Regional Ecosystem (RE) and Soil type maps should also be used to inform the assessment of sub-catchment homogeneity and comparability. Once the larger catchment and sub-catchment sites have been selected, RE, soil type maps, and LiDAR can be used to assess and select ground cover monitoring sites and plot scale sediment run-off sites that capture variability within the selected sub-catchment.

Option 3 for fire project site selection is recommended for the purposes of the ECYWQP. This will incorporate permanent long-term sites to monitor over time with the aim to assess the impacts of different fire types on sediment run-off from each headwater stream. Headwater catchment monitoring locations should remain relatively small, 10 to 20 ha in size, to minimise variations in terrain, vegetation, soil, rainfall, etc.

Different land types (geology, soil, vegetation combinations) will have likely very different responses of sediment run-off to fire. It is therefore recommended that there be two focus geology types for Fire Monitoring associated with the ECYWQP. 1) Hillslope sub-catchments (Hodgkinson Formation geology metasediments), and 2) Alluvial sub-catchments (Quaternary floodplains and terraces). These are the most common and widespread large geologic units in the ECYWQP coastal catchment areas that are influenced by fire, with the potential future addition of sandstone and granite escarpments.

As gully erosion is a common feature in alluvial soils in the Cape York region, it would be difficult to avoid this influence on sediment loads on the sub-catchment scale. LiDAR or gully mapping from satellite images can be used to evaluate the extent of gully erosion within potential site areas. Metrics such as the area, length and depth of gullies should be assessed to ensure that sites selected are comparable. By selecting Option 3, the influence of gully erosion will be less of an issue because the focus will be on assessing differences in sediment run-off at each site over time, associated with changes in fire timing and extent. However, in the comparison between sites, the contribution of gully erosion will need to be considered. Ideally there would be 6 headwater stream measurement sites (3 hillslope, 3 alluvial) nested within one larger sub-catchment (e.g., Figure 5), or two sets of 3 headwater stream sites each nested in an intermediate catchment, and then within a larger catchment. Under either scenario, both the spatial (hillslope vs alluvium) and temporal (changes over time at each site associated with different fire types) can be assessed. At least one site should be located in an area that is prone to regular LDS burns but where little on-ground fire management is planned. Other sites should be located in areas where active EDS burning or fire exclusion is planned.

An example of site selection for the ECYWQP could be:

Sub-Catchment: Scrubby Creek (10,341 ha) in the Annan Catchment – coincides with a sub-catchment node (SC #522; Figure 6) used in SOURCE by the Queensland Government to estimate sediment loads from the Annan River. This means the results from any sub-catchment scale monitoring can easily be compared with SOURCE results. Nested within this sub-catchment could be headwater streams (alluvial and colluvial) where more detailed gauging and plot scale data are collected.

- **Hillslope headwater stream:** 3 headwater catchments <15ha within LIDAR area
- **Alluvial headwater stream:** 3 headwater catchments < 15 ha within LiDAR area

Although the ECYWQP is only funded for 2 years, sites should be selected with the aim of continued monitoring over more than 2 years, and embedded within organisations that have the capacity to maintain the monitoring effort, ideally with additional long-term funding.

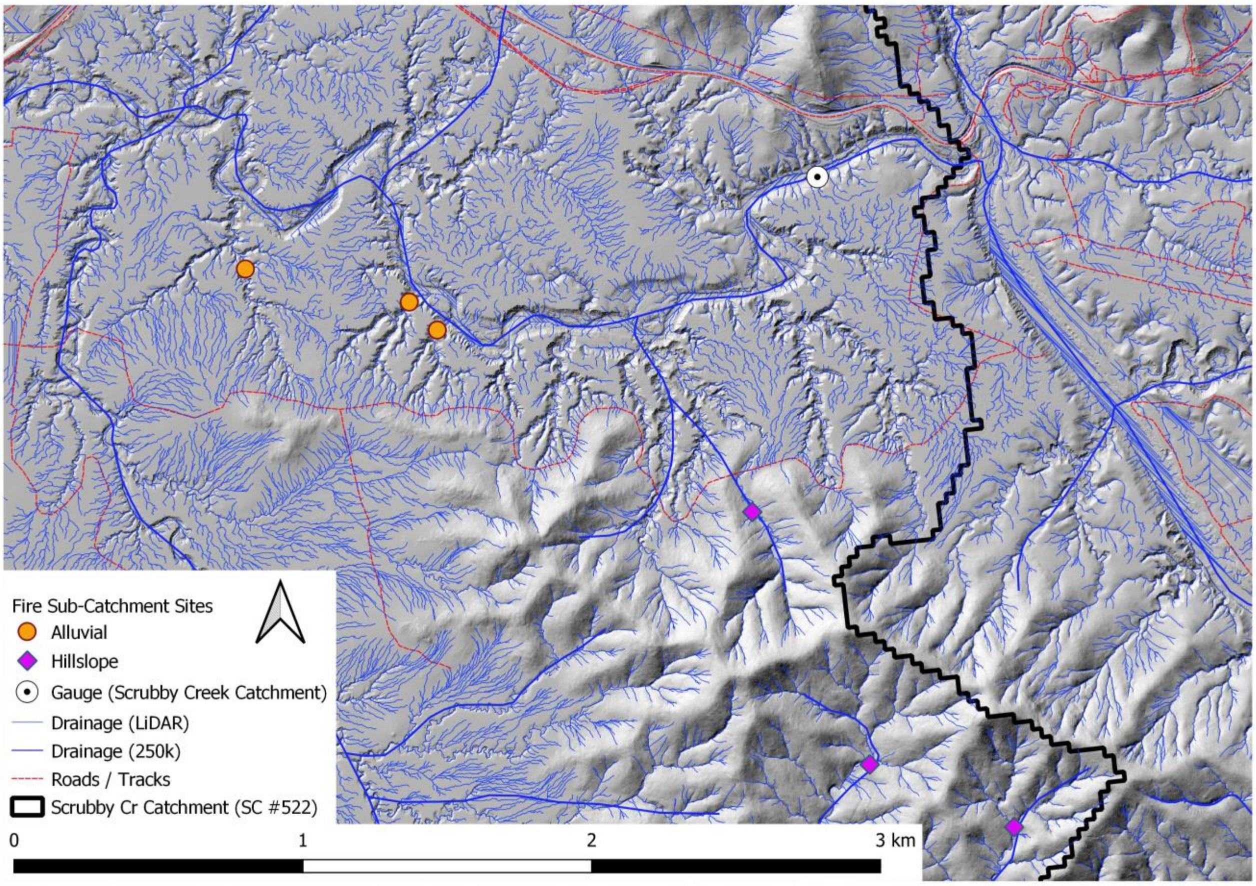

Figure 5 Lower Scrubby Creek LiDAR terrain showing potential alluvial and hillslope sub-catchment sites.

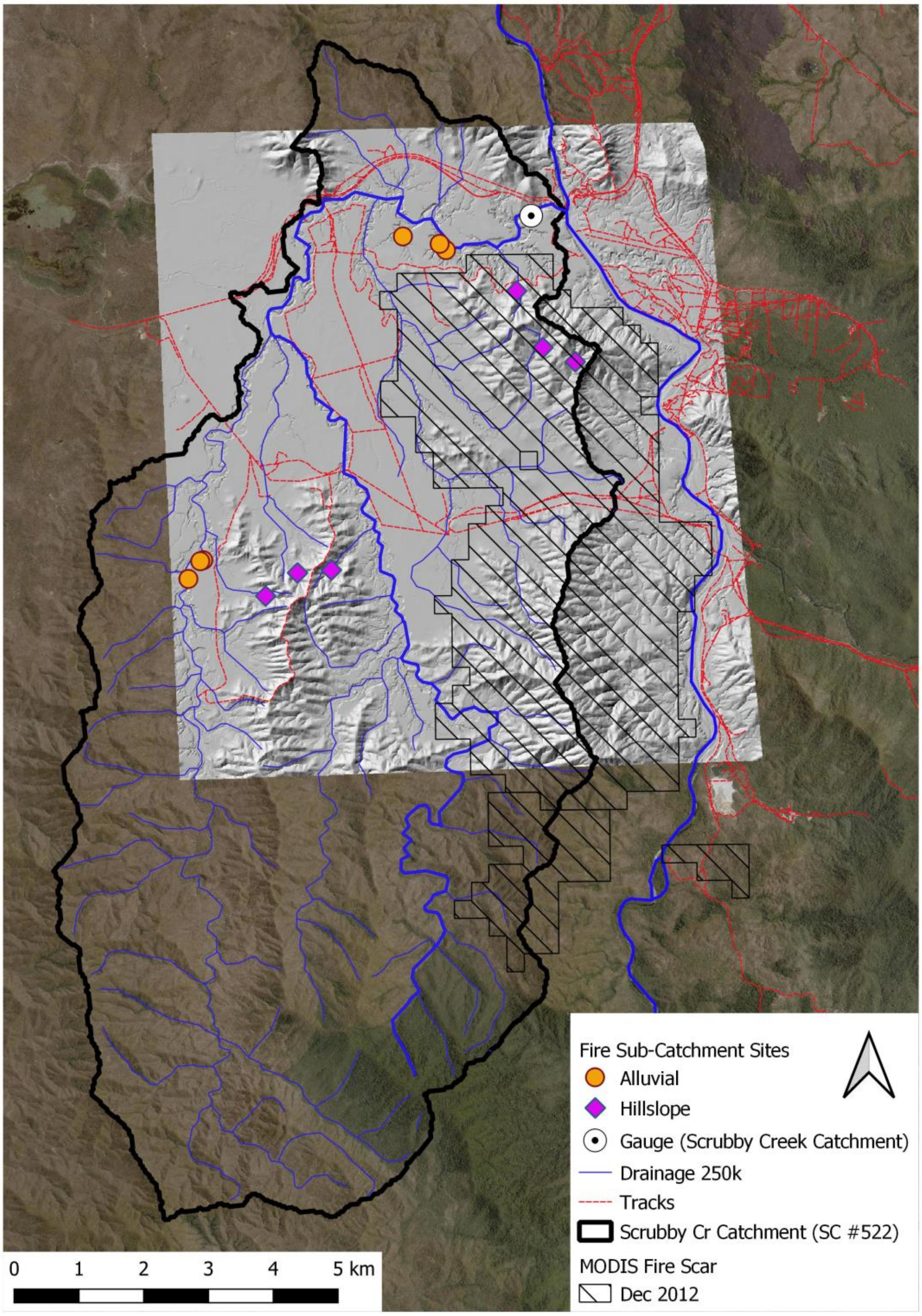

Figure 6 The Scrubby Creek sub-catchment boundary (SC #522), available LiDAR data, and multiple potential locations of nested sub-catchments for fire and water quality monitoring. Many other alternatives exist in Eastern Cape York.

2.2 Monitoring Design

For the ECYWQP Case Study, we propose a nested monitoring design where data is gathered at multiple nested scales (e.g. Figure 5; Figure 6). These include:

Sub-catchment scale (< 10,000 ha):

- Stream gauge and sediment load monitoring at catchment outlet.
- Remotely-sensed sub-catchment ground cover ground-truthed by plot scale ground cover monitoring.
- Averaged rainfall interpolated from sub-catchment rainfall measurements.
- Area, % and timing of the catchment burnt each year, based on Sentinel or other high-resolution satellite imagery. Consider including a fire severity score incorporating the burnt catchment and burnt corridor indices as per Dixon et al. 2011 (Appendix B)

Headwater stream scale (5 to 20 ha):

- Stream gauge sediment load monitoring at the outlet of the headwater catchment.
  - 3 Hillslope
  - 3 Alluvial
- Averaged ground-cover from 5+ plot sites within each headwater stream catchment, measured with 100m diameter star pattern fractional ground cover surveys.
- Rainfall based on tipping bucket measurements.
- Area, % and timing of the catchment burnt each year based on satellite imagery as per catchment scale.
- Fire severity based on on-ground measurements averaged across vegetation type.
- Gully and bank erosion mapping and severity assessments, along with vegetation assessments in erosion prone areas.

Plot Scale (1 ha):

- Fractional Ground Cover associated with star pattern fractional ground cover surveys at 5 plots (1 ha each) representing different vegetation / cover / slope / soil types within each sub-catchment (30 total)
- Plot Scale Sediment yield monitoring using flumes at one (1) hillslope or alluvial plot broadly representative of vegetation / soil / soil conditions in the small headwater stream catchments. Ideally there would be flume sites in both hillslope and alluvial sites, however additional flumes would greatly increase costs.

Assessing the influence of fire on sediment yield at multiple scales is critical to apply the findings from plot scale surveys to sub-catchment or catchment sediment loads. An inverse relationship between specific sediment yield and drainage basin area can occur when the majority of sediment is produced in headwater areas where slopes are steepest, drainage density is highest, and storage is low (Wasson 1994). Sediment deposition, as well as dilution from tributaries with lower suspended sediment concentrations, can occur in downstream areas with reduced slope gradients and well-developed flood plains (Walling and Web 1996). Alternatively, sediment yield can increase downstream in catchments that have intensive agriculture and high rainfall in the low-lying coastal zones (de Vente et al. 2007). Thus, the sediment delivery ratio for a given river system must be considered to translate the impact of fire on sediment run-off at upper catchment plots or sub-catchments to end of system sediment loads.

2.3 Monitoring Methods

2.3.1 Rainfall

Rain gauges (tipping buckets) should be located within each headwater stream catchment to accurately assess rainfall magnitude, intensity, and duration over each event and the annual total rainfall. Redundancy in rainfall gauges help avoid data loss. Annual or daily rainfall data are used to calculate the R-factor for the RUSLE Model, while local rainfall intensity data are used to correlate to erosion, water/sediment runoff, and fire severity. If the three monitored headwater catchments are not well spread across the larger catchment area (in this example Scrubby Creek), there may be need for additional tipping buckets to interpolate rainfall across the whole catchment.

2.3.2 Soil Characteristics

Soil tests and characterisation will be conducted at each vegetation plot site (n=30) as well as additional stream and gully banks within the overall headwater stream catchment. These local field soil sample data (texture, organics, etc) and actual erosion pre/post fire will be used to calculate and assign the appropriate K-factor within the RUSLE nomograph.

2.3.3 Stream gauging stations

Stream gauging stations will be located at the outlet of each nested headwater stream catchment (3 to 6) and the larger sub-catchment (1) (Figure 6). Each gauge will need to measure both water discharge and sediment concentrations in order to estimate annual (and event) suspended sediment loads. There are a wide range of options (and associated costs) for collecting these data, using various technologies and manufacturers. Here we describe methods and specific equipment considered to be relatively cost-effective and practical for the remote Cape York setting.

Discharge

Water velocity will be measured continuously using either an upward facing acoustic doppler current profiler (ADCP) and/or alternatively new technologies such as a flow camera meter (i.e. Xylem dual stereo camera). The ADCP is to be placed within the headwater stream outlets, approximately 0.1 m above the stream bed. A continuous water height (stage) recorder (pressure transducer type) will be place at the same stable cross-section to help calculate changes in water cross-sectional area over time. Velocity and area (via stage) will be used to calculate total discharge from the headwater streams and sub-catchment. These continuous discharge estimates will be checked by manual standard water discharge measurements where practical (current meter water rods) and correlated to water stage.

Sediment run-off

Stand-alone (battery operated) turbidity dataloggers are recommended to continuously (5 minutes) measure turbidity in the sub-catchment and catchment outlets. Turbidity (NTU) is measured as an indicator of SSC. Dataloggers with high turbidity range (e.g., Analyte-NEP-180-OP by Observator - up to 30,000 NTU) will be required for some sites with high concentrations, including sites with alluvial gullies. Continuous turbidity will need to be correlated to SSC periodically collected by either manually collecting SSC samples during events (bottle or DH 48 sample) or utilising an automated

ISCO pump sampler (Polyakov *et al.* 2013). Passive rising stage samplers (RSS) also can be used in a vertical array to collect SSC samples unattended but need to be changed between events. Small flow weighted pump samplers (PASS sampler; Dorien *et al.* 2018) could also be used, but these only provide time-integrated samples and an indicative average concentration for the time period. They also can miss collecting the finest suspended sediment. For this case study, we propose to utilise manual, RSS, and PASS samplers to collect SSC samples for turbidity correlation, but ISCO pump sampler would be preferred at most sites where the budget allows. Turbidity/SSC rating curves will be used along with stage/area/velocity rating curves to estimate event and annual sediment loads.

SSC samples should be collected from the same depth as the turbidity datalogger for generating the rating curve, however sampling should also be conducted across the width and depth profiles of the stream cross-section (via handheld DH-48 or otherwise) to assess variations across the stream and to estimate the average width and depth integrated SSC concentration. Depending on the analytical budget, in addition to sampling for SSC, nutrient (N & P) and carbon samples should also be collected to provide insight into the relationship between fire and nutrient run-off. Water quality parameters including pH, temperature, dissolved oxygen, and conductivity should also be measured in-situ during manual sampling events.

2.3.4 Plot-Scale Water & Sediment Run-off Measurements (Flumes)

Nested within one alluvial or hillslope headwater stream catchment will be one (1) plot (100m x 100m) where water and sediment run-off should be measured using a flume or trap. There are a wide range of designs for measuring sediment yield from a plot-scale erosion study, including instrumented Parshall flumes (Bartley *et al.* 2010a; 2014) and less expensive hillslope sediment traps designed for more difficult to access remote regions (i.e. Brooks *et al.* 2014). For the Annan River case study, we recommend Parshall flumes for accuracy.

The alluvial and/or hillslope flume site will be located downgradient from a star-pattern fractional ground cover monitoring site as per Muir et al. (2011). The site will represent typical vegetation / soil / slope conditions in the sub-catchment (as indicated by the additional vegetation plots). The aim of the flume monitoring is to capture erosion dynamics at the plot scale, compared to sediment yield at the headwater stream and sub-catchment scale (via deposition and hillslope sediment delivery ratio). Differences in sediment run-off associated with vegetation cover variations at the plot-scale over events, seasons and years (as influenced by fire type, severity, and seasonality of vegetation re-growth) will also be captured and compared. Over the years, the plot(s) would ideally be subjected to variation in fire exclusion (unburnt), EDS and LDS fire conditions, as well as seasonal growth variability. With multiple flumes (budget dependant) variations between sediment run-off measured at each flume would provide an indication of the range of erosion responses within alluvial and hillslope stream catchments to different fire types and vegetation cover. With no budget or resource constraints, multiple flume measurement plots within headwater stream catchments would document spatial variability of sediment yield associated with different vegetation types and fire severity.

2.3.5 Fractional Ground Cover Monitoring

In the GBR Source framework, Cover factor (C factor) is assessed at a seasonal timestep (four scenes per year) for the model run period via the remote sensing Fractional Cover Index product (FCI) at a 25 m grid square scale, and resampled to 30m to match the DEM.

In order to ensure consistency across monitoring projects used to ground-truth remotely sensed vegetation cover, the standard methods for measuring fractional ground cover in Queensland, as described in Muir et al. (2011), will be adopted for the ECYWQP Fire & Water Quality case study. However, the 100m transect length could be modified to cover multiple 30m x 30m Landsat pixels and ensure adequate representation of the site variability. Botanal (Tothill *et al.* 1992) pasture yield measurement methods will also be considered, to supplement vegetation cover measurements and reduce operator bias.

As described within the Monitoring Design, at least 3 but ideally 5 vegetation/ ground cover / fire severity monitoring plots will be selected for each monitored headwater stream catchment (n = 3 alluvial + 3 hillslope) within the fire and sediment run-off study (for a total of 30 ground cover plots across the study).

Ground cover measurements from each plot will be averaged across each headwater stream catchment for empirical data to compare with sediment run-off measurements. The ground cover measurements will also be used to validate remotely sensed ground cover estimates used for modelling sediment loads in SOURCE. At least one of these 100m x 100m ground cover monitoring sites will be located above the plot-scale sediment run-off flumes to measure differences in sediment run-off between vegetation types after the plots have been subjected to EDS and LDS burns. Site selection can be informed by viewing satellite imagery or aerial photography, as well as both Regional Ecosystem maps and soil maps. Ideally sites should have relatively homogeneous cover with low tree cover. Ground cover sites should be selected to represent a range of different vegetation types and cover found within the headwater stream catchment.

Timing of the ground cover surveys will be quarterly, to capture both fire seasonal variations and quarterly remote sensing of ground cover for SOURCE cover calculations.

Below is a brief description of the fractional ground cover monitoring methods, detailed in Muir *et al.* (2011).

Three 100-metre measuring tapes or transects are laid in a star-shape (Figure 7).

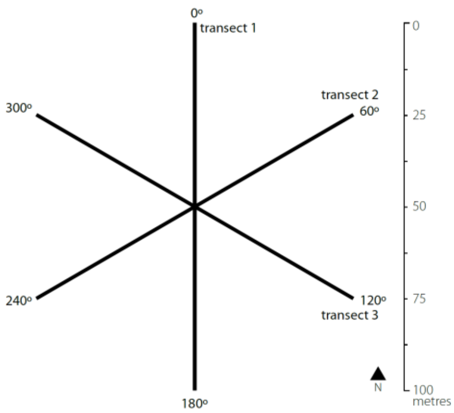

Figure 7: Star shaped transects as per Muir et al. 2011.

Observations of ground cover and woody vegetation (if present) are made every meter along the transects within a 50cm x 50cm quadrat, for a total of 300 data points at each "site". The following details are recorded within each quadrat and/or site as per Muir et al.(2011). Some simplification or minor adjustments may occur for ECYWQP Fire project monitoring:

- slope (0 to 100%), measured by clinometer, and aspect by compass
- land use
- plant growth stage
- management phase for vegetation including litter (grazed, herbicide application, etc)
- photos
- above-ground plant biomass (kg/ha) estimate using site appropriate photo references (to be developed)
- fire occurrence (see more details in fire severity measurements)
- grass cover (% by category)
- dominant vegetation species for woody plants (>2m), woody plants (<2m) and ground cover
- tree basal area if present – measured at 7 points total across the transects and averaged for the site (optical wedge prism or Haglöf Factor Gauge)
- presence and form of erosion at the site
- abundance of material deposited on the soil surface (sand/gravel/stones)
- micro-relief (smooth/mounds/depressions)
- biotic micro-relief: termite mounds, pig wallows, etc.
- soil description: soil condition, soil strength, surface cracks and soil colour (as per Munsell soil colour charts)
- cryptogram cover and colour
- rock colour, abundance and size

2.3.6 Fire Severity Measurements

While fire severity (Section 1.1) is often equated with fire timing, with early dry season associated with low severity and late dry season associated with high severity, this is not always an accurate way to assess fire severity and may not capture the range of fires that occur in the landscape. It is therefore important to incorporate fire severity measurements into the fire monitoring design. These fire severity measurements can be used to assess the impacts of fire on water quality and for future efforts to model the impacts of fire on surface water and sediment run-off.

In addition to the ground cover and other vegetation and topographical measurements included in the measurements above, observations recorded within the quadrats or general survey area specific to fire severity will include:

- Date of fire (if known)
- GPS mapping of fire area where possible to ground-truth satellite mapping
- Photos
- Fire severity measured as impacts on vegetation (as per Appendix A and Edwards, AC 2009)
    - Patchy – small trees and shrubs scorched to 2m, <80% burnt ground layer patchiness

- Low – small trees and shrubs scorched to 2m, >80% burnt ground layer patchiness
    - Moderate – scorched leaves through the mid-storey (>2 and <8m) perhaps into lower parts of the upper canopy
    - High – complete canopy scorch
    - Extreme – all foliage removed or charred
- Methods for measuring the amount of coarse fuels consumed (none, some, or all) will also be considered. Coarse fuels (>6mm diameter) are only consumed in intense (hot) fires. *However, this measurement is not possible unless there is a pre-fire fuel load availability measure, which could be difficult to obtain.*

* Based on the categories adopted by the Eastern Cape York Water Quality Program Fire Projects:
- Wet Season/ Storm Burns = January 1st (or after > 100mm rain has fallen) to April 31st.
- Early Dry Season (EDS) = April 31st to August 31st
- Late Dry Season (LDS) = Sept 1st to Dec 31st OR after > 100mm rain has fallen
- Unburnt/ Fire exclusion (FE): No fire over the previous year

Although these definitions vary across other fire programs and regions, these date ranges are considered logical within southeast Cape York according to consultations with landholders and land managers undertaking fire management.

2.4 Implementation and Costs

Implementation of the methods described here for monitoring the impacts from fire on ground cover and sediment run-off would require significant collaboration and investment. This collaboration should include experienced fire managers with knowledge of the study area, scientists experienced in the areas of hydrology, geomorphology, and potentially botany, and local landowners and/or Traditional Owners.

The cost of implementation will be highly dependent on location and number of sites, the availability of existing equipment, the involvement and roles of partner organisations and potentially links with other projects (such as existing fire management programs). A rough estimate of equipment costs alone for the ECYWQP proposed project is between $60,000 to $80,000 for 3 nested sub-catchment sites and one catchment outlet site. While the costs are substantial, improved quantification of fire-related impacts on sediment run-off is a worth-while investment. As fire is now understood to contribute significantly to GBR and other sediment loads, this influence should be accurately investigated.

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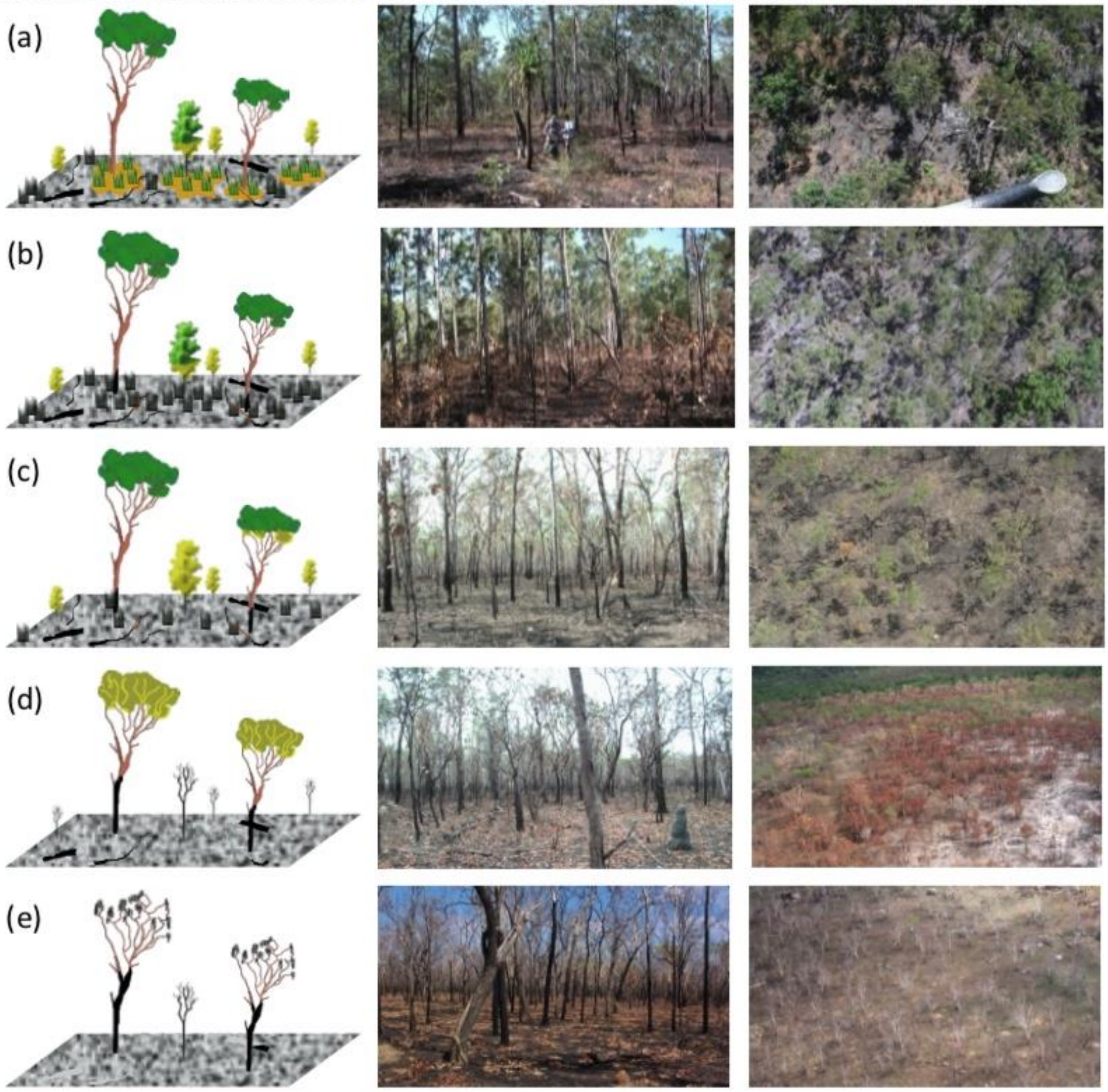
Appendix A – Fire Severity Categories

CATEGORIES OF FIRE SEVERITY IN THE TROPICAL SAVANNAS OF NORTHERN AUSTRALIA



▲ Simplified illustrations and photos of fire severity categories: (a) PATCHY, small trees and shrubs scorched to 2m, < 80% burnt ground layer patchiness; (b) LOW, small trees and shrubs scorched to 2m, > 80% burnt ground layer patchiness; (c) MODERATE, scorched leaves through the mid-storey (> 2 and < 8 m) perhaps into the lower parts of the upper canopy; (d) HIGH, complete canopy scorch and; (e) EXTREME, all foliage removed or charred.

Fire Severity categories taken from Edwards, AC. 2009

Appendix B – Burnt Catchment & Burnt Corridor Score (from Dixon et al. 2011)

The fire subindex from the Framework for the Assessment of River and Wetland Health (Dixon et al. 2011) is comprised of two components that are equally weighted (Equation 4.2): i) burnt catchment; and ii) burnt river corridor.

Equation 4.2

$$F = (BC * 0.5) + (BRC * 0.5)$$

where:
F = *fire subindex score (0-1)*
BC = *burnt catchment score*
BRC = *burnt river corridor score.*

Burnt catchment

This is a measure of the extent and frequency of fire. The index only considers fire in the late dry season and uses weightings based on the annual frequency of fire in the previous five years (Table 4.17). Repeated late dry season burning over several years reduces native vegetation cover and may result in the delivery of higher sediment, nutrient and organic loads to the river network.

Table 4.17: Weightings for frequency of fire between August–December 2005–09.

No. of years burnt	Weighting
0	0
1	0.2
2	0.4
3	0.6
4	0.8
5	1

Raster grids (100 m x 100 m) of monthly fire scars are used to calculate the frequency of fire over a five-year period. The area occupied by each frequency class is expressed as a fraction of the total area. A burnt catchment score is calculated by multiplying the fraction burnt by the frequency weightings (Equation 4.3).

Equation 4.3

$$BC = 1 - ((A_1 * w_1) + (A_2 * w_2)\ldots+\ldots(A_5 * w_5))$$

where:
BC = *burnt catchment score (0–1)*
A = *fraction of catchment burnt in each frequency class*
w = *weighting of each frequency class.*

Burnt river corridor

This is a measure of the area burnt by late-season fire within the river corridor weighted by annual frequency of fire within the past 5 years (Table 4.17). The river corridor is defined as the area extending 250 m from either side of the river channel. The burnt river corridor score is calculated using the same methods as burnt catchment score by applying Equation 4.4.

Equation 4.4

$$BRC = 1 - ((A_1 * w_1) + (A_2 * w_2) \ldots + \ldots (A_5 * w_5))$$

where:
BRC = *burnt river corridor score (0–1)*
A = *fraction of area burnt in each frequency class*
w = *weighting of each frequency class.*