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Fire, fine sediment, and fractional ground cover: Representation of fire in the Cape York – Great Barrier Reef water quality model

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Abstract: While there has been a long history of fires in northern Australia, including Indigenous burning for land management, Cape York has been experiencing an increase in extensive, intense, late dry season wildfires. Increases in 'megafires', globally, is being driven by increases in extremes under a changing climate. Wildfires can impact water quality through increased erosion risk, changed flow dynamics, and an increase in nutrient exports including carbon. The challenge for Cape York land managers is to use knowledge-based fire management to minimise wildfire occurrence, reduce carbon emissions, maintain biodiversity, and land condition. With targets set for water quality draining from the Cape York region to the Great Barrier Reef, focus has turned to how fire impacts ground cover dynamics, erosion processes, and water quality in the region. This paper aims to answer two questions; whether there are detectable changes in ground cover data because of fire and whether changes to erosion rates due to burning are represented in water quality models. A desktop assessment has been undertaken using the available spatial data, including remotely sensed ground cover data to evaluate the representation of known fire scars. Erosion rates were assessed using the Cape York water quality model over a specific study area and time-period to determine what impact, if any, fires have on fine sediment generation. This study concluded that fire scars are represented in the ground cover data which are used in the calculation of hillslope erosion in the Cape York water quality model. The main trends in ground cover change due to fire are represented in the model, however finer details about the duration and timing of cover change were beyond the scope of this study. It was determined that the key variables in determining the potential magnitude of soil loss are the timing and extent of low ground cover relative to the duration, timing, and intensity of post-fire rainfall. The highest water quality risk is associated with low ground cover, steep terrain, erodible soils, and high intensity rainfall. A future improvement for representing fire scars in the water quality models may be achieved through the incorporation of higher spatial and temporal resolution satellite imagery (e.g., using Sentinel derived products compared to Landsat).

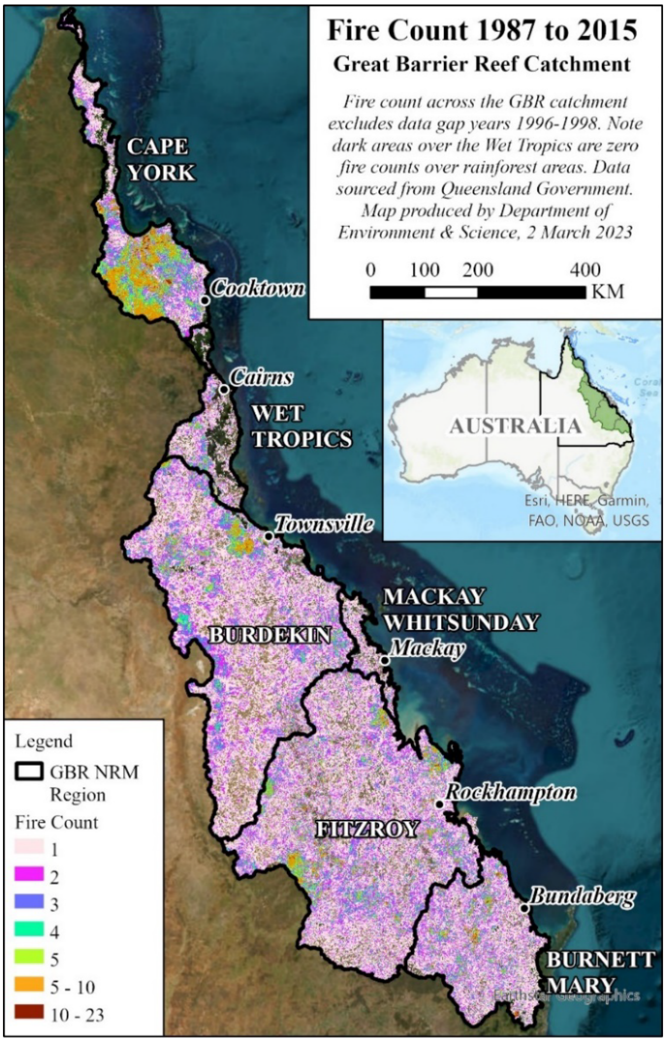

Figure 1. Fire count across the GBR

Keywords: *Water quality modelling, fine sediment, fire, remote sensing, fractional ground cover*

1. INTRODUCTION

Fire is an intrinsic feature of tropical savanna landscapes. There has been a long history of fires in northern Australia, from naturally occurring fires pre-human habitation (i.e., initiated by lightning strikes); to evidence of anthropogenic fires some 50,000 years ago by Aboriginal implementation of "fire stick practices" which increased fire frequency, producing a mosaic of burnt and unburnt land, often during June to October; to the more recent European history where the fire regime has again shifted, with future impacts predicted under a changing climate as a result of more extreme events (flooding, droughts, heatwaves, and storms) (Philip, 2017; Townsend & Douglas, 2000). The impact of fire on water quality is complex, and highly episodic at the catchment scale, with the hydrological response impacted by factors such as: fire severity, frequency, and spatial extent of burning; interval between burning and subsequent runoff; climate, especially rainfall intensity; fuel load; and catchment characteristics (ground cover, land use, slope, soils, vegetation type, composition and structure and regrowth) (Johnston & Maher, 2022; Townsend & Douglas, 2000).

Water quality models are used across the Great Barrier Reef catchment area (GBRCA) to estimate sediment and nutrient loads discharging to the GBR lagoon (McCloskey et al., 2021). These models represent hillslope, streambank, and gully erosion processes, at a daily timestep, using input datasets such as rainfall, evapotranspiration, various soil parameters, land use, and ground cover. The models are built to report on the progress towards the GBR water quality targets because of improved management practice (McCloskey et al., 2021). A frequently asked question is whether the GBR water quality models capture the impact of fires (Cape York NRM, 2020; Standley, 2019), be they naturally occurring or because of land and fire management practices. It is hypothesized that the key model input that represents fire in the GBR water quality models (in lieu of a model specifically adapted for fire) is the remotely sensed seasonal ground cover dataset, used to represent the cover factor (C-factor) in the calculation of hillslope erosion via the Revised Universal Soil Loss Equation (RUSLE). Land cover change is the most widely applied water quality model adaptation to represent fire impacts (Basso et al., 2022).

In this paper the following two research questions have been addressed: (i) whether there are detectable changes in ground cover due to fire and (ii) if those changes due to burning are reflected in the water quality model erosion rates.

2. METHOD

Discussions with Cape York (CY) stakeholders highlighted areas in the region that could be useful in a desktop assessment of whether fire scars are represented in the GBR water quality models. Land managers are keen to understand the link between on-ground works/management and water quality impacts. Selection of a case study location was also guided by an assessment of fire count across the GBR. Monthly fire scar mapping produced from Landsat 5, 7 and 8 satellite imagery was sourced for the period 1987 to 2016 inclusive (Collett, 2021), and this mapping was used to determine a fire count per pixel (30m) across the GBR catchment (Figure 1).

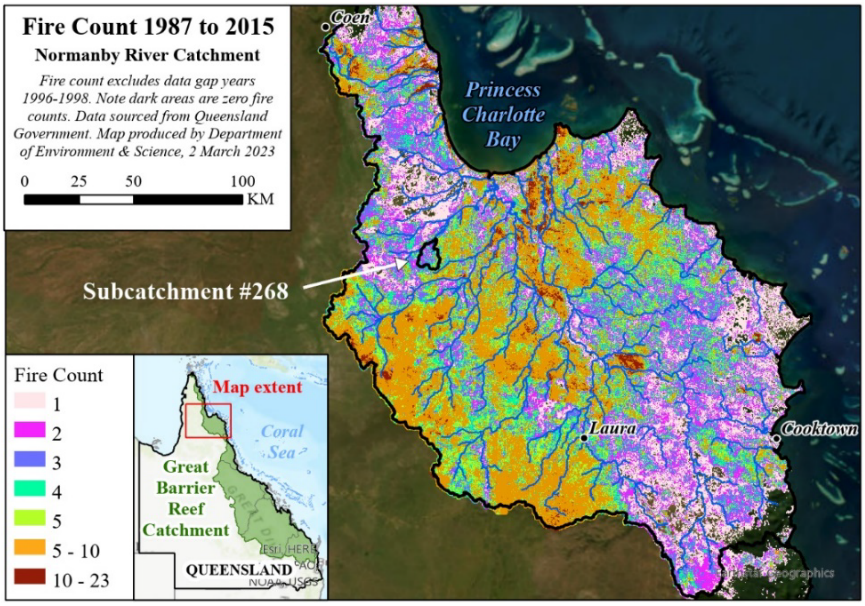

Figure 2. Fire count from 1987 to 2015 across the Normanby catchment, Cape York

An average total fire count was calculated over each GBR river basin for the 28-year period from 1987 to 2015 (excluding 1996-1998 due to data gaps). The Normanby basin had the highest average total fire count of 4.6 fires with a maximum fire count of 22. The fire count data clearly demonstrated that the Normanby catchment in CY is a hot spot for fires in the GBRCA, and subcatchment (SC #268) was selected from this region as the case study area (Figure 2). The subcatchment was arbitrarily selected to test the representation of fire; the area was checked to ensure fire scar data was clearly identifiable and fractional cover data coverage was relatively gap-free. Located in the northwest of the Normanby basin, the selected study area covers the catchment of Eighteen Mile Creek, a minor tributary of the North Kennedy River which discharges into Princess Charlotte Bay and the GBR lagoon.

The CY GBR Dynamic SedNet model is one of six models used to calculate fine sediment and nutrient export into the GBR lagoon. Fine sediment generation and export is calculated for each subcatchment and land use within the model. In the Normanby basin the dominant land uses are conservation (52.3%) and grazing (46.5%) with all other land uses being less than 1% of the total area (McCloskey et al., 2021). Detailed assessment of the representation of fire scars in the CY model was done by tracking the data for the nominated subcatchment SC #268 through the model, from fire scar representation in the ground cover data through to the modelled sediment estimates for each land use.

Ground cover is represented in the GBR Dynamic SedNet water quality models as the cover factor (C-factor) in the RUSLE calculation of hillslope erosion (McCloskey et al., 2021).

Hillslope erosion is calculated using the RUSLE equation:

$$A = K \text{ x } LS \text{ x } C \text{ x } R \text{ x } P \qquad (1)$$

where A is the annual soil loss due to erosion [t/ha/yr]; K the soil erodibility factor; LS the topographic factor derived from slope length and gradient; C the cover and management factor; R the rainfall erosivity factor; and P the erosion control practice factor.

Hillslope erosion is calculated at a 30m pixel resolution by multiplying the static factors of soil erodibility and topography (KLS) by each seasonal ground cover dataset (Figure 3). Soil erodibility is adjusted to allow for rock cover. The seasonal time-series KLSC dataset is spatially averaged by land use (model functional unit) (Figure 3a) before being multiplied against daily rainfall erosivity (R). The fine sediment proportion of the load is then calculated as the clay-silt fraction of the load. The proportion of sediment entering the stream is calculated using the Hill Slope Delivery Ratio (HSDR) which varies in CY from 3% to 5%.

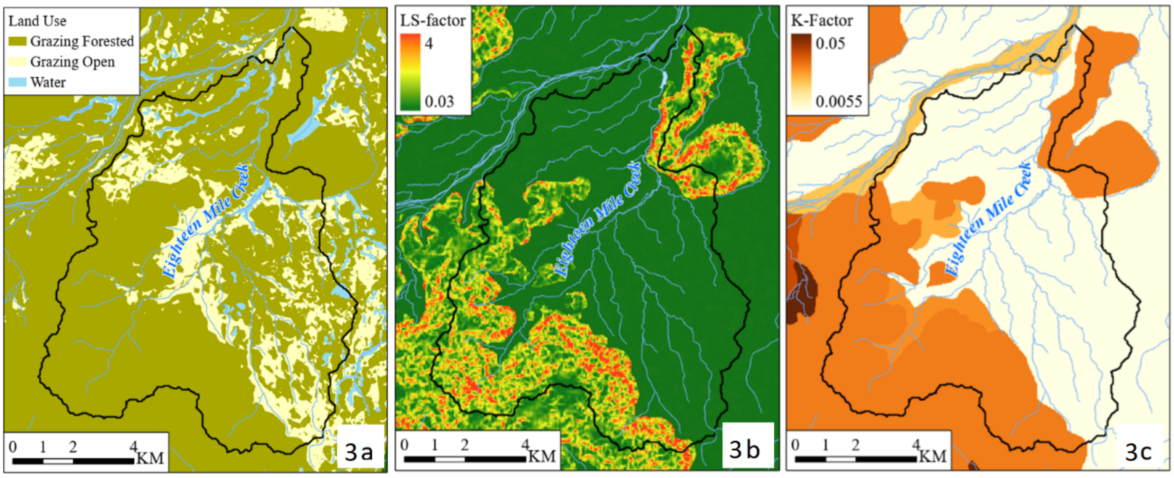

Figure 3. CY SC #268: (a) land use, (b) slope length and gradient (LS-factor), (c) soil erodibility (K-factor)

The C-factor time-series (1987 to 2018) dataset is created using the bare ground fraction from the seasonal fractional ground cover dataset (TERN, 2022) that is generated from time-series Landsat satellite imagery. The bare ground fraction is converted to a cover metric to better fit satellite-derived ground cover to manually observed ground cover which was the basis for the C-factor derivation (Rosewell, 1993; Trevithick & Scarth, 2013). C-factor rule masks are used to determine where the seasonal fractional cover data is utilized across the GBR; in CY a static C-factor value of 0.001 is assigned to densely vegetated areas with a foliage projective cover (FPC) of more than 60%, otherwise Rosewell's equation (Rosewell, 1993) is used to assign a variable C-factor value according to seasonal bare ground cover fraction (McCloskey et al., 2021).

Fractional cover data quality and coverage are limited spatially and temporally by Landsat satellite imagery due to overpass frequency, cloud and cloud shadow and scan line corrector (SLC) failure (Landsat 7). The satellite return period of 16 days limits the opportunity to capture variations in ground cover due to fire given vegetation cover can 'green up' within days depending on site conditions and the timing, duration, and intensity of follow up rainfall. Also, CY is particularly prone to cloud cover which is a significant limitation particularly during the wet season over coastal areas and rugged mountainous terrain where optical remotely sensed imagery such as that captured by Landsat sensors may be obscured by cloud and cloud shadow for many weeks. More than half of seasonal fractional cover data (1987-2015) over the Normanby had some limitations due to cloud cover or data gaps. Total cloud amount is measured by estimating the cloud cover fraction in eighths or oktas. Average annual cloud cover at 9am over the Normanby catchment is 3 to 4 oktas, with peak average cloud coverage of 5 oktas in February (Bureau of Meteorology, 2023) which is high compared to most other areas of the GBRCA. The SLC-off issue caused data loss and gaps in Landsat7 imagery after the end of May 2003 (US Geological Survey (USGS), 2023). Despite the limitations Landsat is freely available and is the longest running satellite imagery program offering coverage from 1987 providing valuable data coverage.

To create one seasonal fractional cover layer a medoid (a multi-dimensional median) pixel value is used where there are three or more valid observations(Flood, 2013). A valid observation is where the pixel has not been masked due to cloud, cloud shadow or water. If less than three images are available, pixel-based patch data (i.e., a single date from a valid observation) is used to fill gaps (Trevithick et al., 2014). When no patch data is available, a moving average of surrounding cells from the entire time-series is used. Across the Normanby, the number of seasons represented by patched fractional cover data (prior to application of moving average) over the period 1987 to 2018 ranged from 108 seasons of data in the northwest to 119 seasons of data in the southwest. The southwest also had the highest proportion of gap-free coverage at 98%, compared to 95% in the north and 92% in the southeast. The southeast of the Normanby is a hilly coastal area that is more likely to have cloud cover due to the influence of the dominant moist southeast trade winds.

Comparison of monthly fire scar mapping against the ground cover data provides an indication of how well fire scars are represented in the C-factor before, during and after fire events. Fire scar mapping is useful to confirm low cover areas are due to fire as decreases in ground cover may be due to factors other than fire, such as ephemeral lakes or drought, and areas of consistently low cover may be due to tidal flats, scalds or other degraded areas, rock cover, sand, and/or naturally sparse vegetation. Small patches of consistently low ground cover in the trial subcatchment area were due to sparse vegetation cover associated with *Melaleuca saligna* low open woodland.

3. RESULTS

A large fire event in spring (November) of 2015 over subcatchment SC #268 was tracked in detail through the CY model. The fire covered most of the subcatchment, with a small area on the western boundary burned earlier in the season in June 2015 (Figure 4). The average bare ground over the subcatchment increased after the November 2015 fire from 10% to 26% (Figure 5). Post-fire ground cover increased again following the summer wet season with bare ground cover dropping back to 11%.

The RUSLE KLS-factor, based on soil and terrain, is static so any change in the combined KLSC-factor will be due to variation in the seasonal C-factor data. The summer 2015-2016 decrease in ground cover (Figure 5) due to fire is clearly shown as an increase in the combined KLSC-factor value (Figure 6). Higher KLSC-factors will produce a larger predicted sediment load, and when combined with the summer 2015-2016 rainfall (Figure 7) via the R-factor as shown by the increased sediment load predicted for 2016 (Figure 8) over the forested grazing areas.

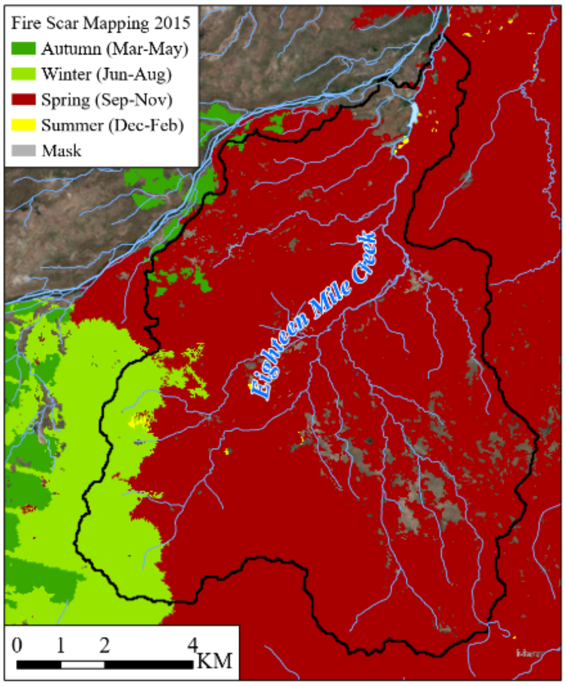

Figure 4. CY SC #268 fire scar mapping, 2015–2016

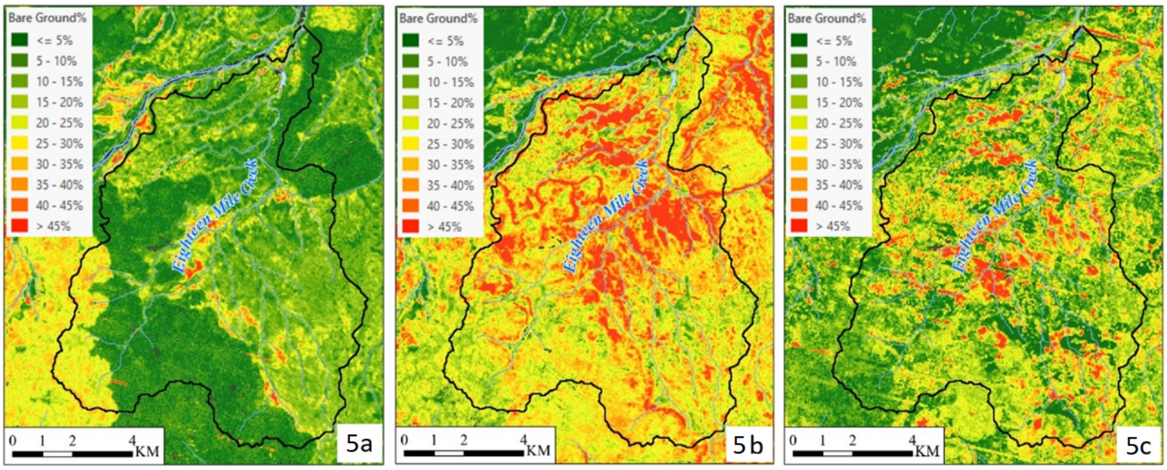

Figure 5. Patched seasonal bare ground cover, CY SC #268: (a) spring 2015, (b) summer 2015–2016, (c) autumn 2016

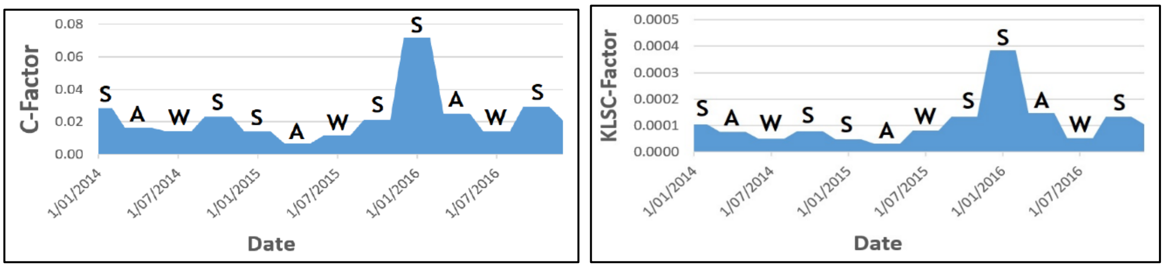

Figure 6. CY SC #268 RUSLE values for forested grazing (seasons labelled): (a) C-Factor (left), (b) combined KLSC-Factor (right)

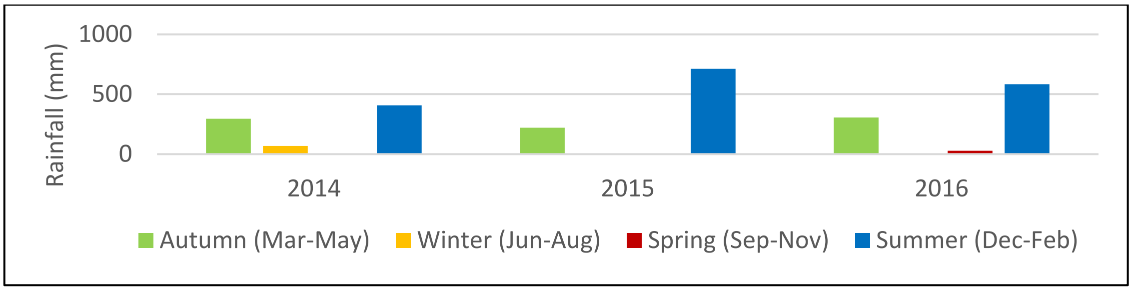

Figure 7. Rainfall at Laura, CY (station 028000)

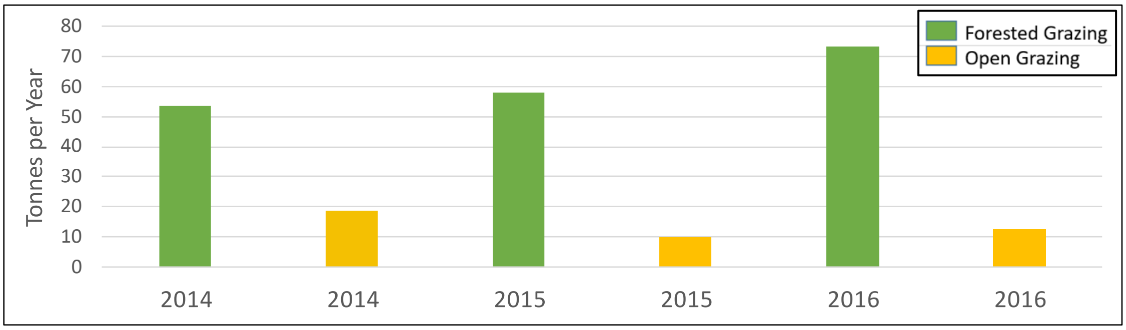

Figure 8. CY SC #268 hillslope fine sediment estimates

5. DISCUSSION

When compared to the forested grazing areas, the open grazing areas (Figure 3) are predominantly located on flatter terrain with low slope length and gradient (LS factor) and less erodible soils (K factor) which is reflected in the lower predicted sediment loads for open grazing (Figure 8), despite also being burned. The higher sediment load for forested grazing in 2016 is due to the increase in bare ground cover and rainfall (713mm) over summer of 2015-16 (Dec-Feb) occurring over landscapes with steeper terrain and more erodible soils.

Successful detection of burnt areas will depend on timing of the burn and how long the burnt area persists in relation to the quality and quantity of successful satellite image capture over the fire scar area. It is expected that the fractional cover will inherently bias towards capture of larger higher-intensity fires that occur over extended dry periods with less cloud cover and create larger more defined burn scars that generally take longer to regenerate. The use of patched seasonal bare ground cover that selects a medoid value from the seasonal composite excludes outliers so sediment loads may be under-estimated over patched data periods unless the burnt area persists through the season.

Fractional ground cover data may not detect ground cover change where there have been cool low-intensity fires, as small and/or fragmented patch burns that only the impact the understorey will leave the canopy intact. This issue is particularly relevant to higher tree cover areas, particularly those above 60% FPC, where a ground cover correction is not applied. This type of low-intensity patch burning is the objective of CY land managers (Queensland Parks and Wildlife Service, 2012) that aim for early dry-season burns to maintain healthy ecosystems, assist vegetation regeneration, and manage fuel loads to reduce the risk of late dry-season high-intensity wildfires, thereby also reducing the risk of erosion by maintaining healthy ground cover. In most cases it is expected that low intensity burns will benefit and promote ground cover in CY, however undetected low levels of ground cover that persist for a prolonged period and are obscured by tree canopy would cause an under-estimation of erosion risk. These areas may occur due to extended dry periods following burning and/or grazing impacts.

According to the water quality models the highest erosion risk occurred when low ground cover coincided with other erosion risk factors including higher intensity rainfall, more erodible soil, and steeper terrain. The timing and extent of low ground cover relative to the duration, timing and intensity of the post-fire rainfall were the key variables in determining the potential magnitude of soil loss.

6. CONCLUSION

Visual assessment confirmed that in CY fire scars are well-represented in the fractional ground cover data, which is derived from satellite imagery. This data is used to represent the spatial and temporal variability of ground cover when calculating fine sediment load hillslope estimates in GBR water quality models. The timing, extent and location of fires, in combination with the duration, timing and intensity of post-fire rainfall, are key factors influencing how much fine sediment is lost.

Although low intensity, early dry season burns are less likely to be captured in the ground cover change data, it is the representation of high intensity fire scars that are critical because if these areas are not well-represented, they are likely to result in larger discrepancies in predicted sediment loss due to a more sustained period of low ground cover. Given the satellite data limitations including overpass frequency, cloud cover and SLC-off issues, recent introduction of the use of Sentinel-2 satellite with higher spatial and temporal resolution is expected to improve the representation of fire in the models by providing more valid observations in seasonal data. Future work may include the quantitative assessment of single-date Sentinel-2 fractional ground cover data comparing the nearest pre and post burn imagery dates to help inform about the magnitude of change caused by fire and the rate of regeneration. Fire scar mapping which now uses Sentinel-2 imagery has had a method improvement following substantial research (Queensland Government, 2023) and now relies on change in the bare ground fraction as the basis for detecting fire, demonstrating the suitability of using bare fraction for representation of fires.

Post-fire rainfall intensity is a key factor in the generation of soil erosion and although daily rainfall data is used, there is a paucity of climate data stations in CY to inform climate interpolation which is an area for potential future improvement.

Australian bush-fire frequency is increasing significantly (Dutta et al., 2016). The more hazardous conditions are not only amplifying conditions suitable for wildfire, but also reducing the window of time suitable for conducting fuel reduction burns. Even though burning practices may change and improve, as climate change pressures increase it is likely to become more difficult to maintain healthy landscapes with the same level of investment. Improved understanding and representation of fire in the GBR water quality models will assist in tracking this change over time, helping to inform future investment and management efforts.

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