CSIRO PUBLISHING

RESEARCH NOTE
https://doi.org/10.1071/WF22046

International Journal of WILDLAND FIRE
International Association of Wildland Fire

Rivers up in smoke: impacts of Australia's 2019–2020 megafires on riparian systems

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Received: 4 March 2022
Accepted: 20 May 2022
Published: 16 June 2022

Cite this:
Fryirs KA *et al.* (2022)
International Journal of Wildland Fire
31(7), 720–727. doi:10.1071/WF22046

ABSTRACT

Background. Increasing occurrence of megafires and wildfires is threatening the integrity of many natural systems and sustainability of the ecosystem services they provide. For example, the 2019–2020 Australian fires were one of the costliest natural disasters in the country's recorded history. **Aims.** This study aims to analyse the extent and severity of the fires on riparian systems across coastal catchments of New South Wales. We open a discussion about whether megafires and wildfires are creating novel riparian ecosystems and if prescribed and cultural burns should be used as a riparian vegetation management technique. **Key results.** Of the 81 304 km of stream analysed, ~29% (23 266 km) were impacted by extreme or high-severity burning, with vegetation canopy completely consumed, or completely scorched and partially consumed. A further 21% (17 138 km) experienced moderate to low-severity burning, with partial canopy scorching or understorey burning. Such widespread, synchronous burning of riparian systems is unprecedented. **Conclusion and implications.** Riparian management strategies must evolve to mitigate against future catastrophic fires that are becoming more frequent and severe under climate change. Research needs to establish the extent to which Australian riparian ecosystems are adapted to fire, the regimes and customs of cultural burning in these zones, and how to use such burning in riparian management.

Keywords: bushfire, climate change, cultural burning, geomorphology, novel ecosystem, riparian ecology, river management, wildfire.

Introduction

In the United Nations Decade of Ecosystem Restoration and under the United Nations Sustainable Development Goals (SDGs) of Clean Water and Sanitation, and Life on Land, freshwater ecosystems are considered a high priority for development and application of sustainable management principles and practices. Additionally, SDG 13 on Climate Action has a target to 'strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries'. However, the extent and severity of recent megafires (fires that are >40 500 ha and/or have an unusually large impact on people and the environment) and wildfires (wild, uncontrolled fire; synonymous with the term bushfire in Australia) that have occurred in Australia, California, parts of Europe, south-east Asia and South America have highlighted the significant risk that changes in the world's climate and increasing occurrence of droughts coupled with hot, dry weather are having on the integrity and viability of the world's ecosystems.

The environmental impacts of the 'Black Summer' fires of 2019–2020 in Australia may never be fully known or quantified (Read and Denniss 2020). Over a 7-month period, fires burned more than 12.6 million ha (126 000 km^2) of bushland, resulting in the loss of ~1 billion animals (Dickman 2020; Phillips and Nogrady 2020), 34 human lives and more than 3000 homes. Smoke from the fires created an algal bloom larger than Australia in the Southern Ocean (Tang *et al.* 2021). In the state of New South Wales (NSW), an area the size of 22% of the United Kingdom was burned, totalling some 5.4 million ha (54 000 km^2), or 7% of the State (DPIE (Department of Planning, Industry and Environment) 2020*a*, 2020*b*).

Nearly every catchment in coastal NSW suffered, as fires burned into wetter environments that anecdotally 'do not normally burn', including riparian systems (Meddens *et al.* 2018; Lewis 2020).

Natural and human-ignited fire is not uncommon in the Australian landscape (Russell-Smith *et al.* 2007; Bradstock 2010; Bradstock *et al.* 2012). Prior to European colonisation, Aboriginal and Torres Straight Island peoples applied 'stewardship by fire' for millennia (Bowman 1998). Indigenous and natural burns were low-severity, frequent and patchy, typically only occurring under certain climatic conditions (Williams *et al.* 2015). Aboriginal burn regimes created conditions where fire-adapted flora and fauna thrived and burning kept fuel loads low (Robinson *et al.* 2016). However, to what extent riparian systems were burned and with what regime is unknown (Enright and Thomas 2008). Nevertheless, it is unlikely that ubiquitous, widespread and severe burning like 2019–2020 has occurred before (Black and Mooney 2006; Mooney *et al.* 2011; Graves *et al.* 2019).

The aims of this research note are:

(1) To analyse and document the spatial extent and severity of megafire and wildfire impact on riverine and riparian systems across every coastal catchment of NSW during the 2019–2020 summer.
(2) To open a discussion about whether severe burning is contributing to the creation of novel riparian ecosystems, and whether cultural and/or prescribed burning could be used as a riparian vegetation management technique to mitigate against future catastrophic fires.

The methods used in this study are outlined in Supplementary Table S1. The Open Access Fire Extent and Severity Mapping (FESM) 2019–2020 dataset used defines four burn severity classes as: (1) *Extreme*, canopy was completely consumed; (2) *High*, canopy was completely scorched and partially consumed; (3) *Moderate*, canopy was partially scorched; and (4) *Low*, understorey was burnt and canopy was unburnt (DPIE 2020*a*).

Regional setting

There are 19 main catchments in coastal NSW covering an area of 181 599 km^2 (Fig. 1). In general, these catchments contain headwater source zones on short tableland settings above 1200 m above sea level (asl) and contain river and wetland systems classed as laterally unconfined with discontinuous channels (Fryirs *et al.* 2021*a*). Most catchments then fall over a steep escarpment and through confined gorge country before reaching extensive areas of rolling and hilly terrain in partly confined valleys (Fryirs *et al.* 2021*a*). Only larger catchments have a short lowland plain with alluvial, laterally unconfined continuous channel rivers (Fryirs *et al.* 2021*a*).

Climate and fire conditions during the 2019–2020 summer

During the fires, NSW had been suffering a major drought since mid-2017 (DPIE 2020*c*). This followed the Millennium Drought from 2001 to 2010. The 2019–2020 summer experienced above-average temperatures with several days of extreme fire risk culminating in multiple 'catastrophic' fire warnings. Across Australia in 2019, rainfall was the lowest on record, with rainfall 62% below average (BoM 2021). Many weather stations in NSW recorded their warmest January day on record on 4 or 5 January 2020 (BoM 2021), with Sydney's western suburbs registering their hottest day on record at 48.9°C (120.0°F) on 4 January (BoM 2021). Air pollution levels produced by smoke were above benchmarks for poor air quality on 134 days (74% of spring–summer days 2019–2020) across NSW (Bowman *et al.* 2020*a*; DPIE 2020*d*).

The fire season started on the North Coast of NSW in early September 2019 (Fig. 1). By November, areas on the central coast of NSW (Fig. 1) surrounding Sydney were impacted. On 12 November 2019, Sydney experienced its first-ever 'catastrophic' fire day. In early January 2020, Sydney and its ~5.3 million people were cut off by road in all directions. The Gospers Mountain fire north-west of Sydney was arguably the biggest wildfire in Australian history (SMH 2019; Nolan *et al.* 2021). On 30 December 2019, weather conditions drastically deteriorated on the south coast of NSW (Fig. 1), triggering evacuation orders for thousands of residents and tourists. In the new year, fire extended to the coast and made world headlines with scenes of people and wildlife seeking the safety of beaches and the ocean. On 10 February 2020, the NSW Rural Fire Service declared many of the fires extinguished after an intense low-pressure cell moved over eastern Australia. Over a 48-h period, 419 mm (16.5 in.) of rain fell at Katoomba in the Blue Mountains west of Sydney (BoM 2021). By 4 March 2020, all fires in NSW had been extinguished.

Results

Burned catchments

Overall, 30% of the total area of coastal catchments was burned, equating to ~55 074 km^2 (Fig. 1*a*, Supplementary Table S2). The spatial extent of burning was most severe on the south coast (52% of total area burned), followed by the north coast (30%) and central coast (23%) (Supplementary Table S2).

On the south coast, 17% of the region experienced an extreme burn severity, and 14% a high severity burn, together accounting for 9108 km^2 of the total 15 312 km^2 burned (Supplementary Table S3). A further 10 and 11% experienced a low and moderate-severity burn, respectively

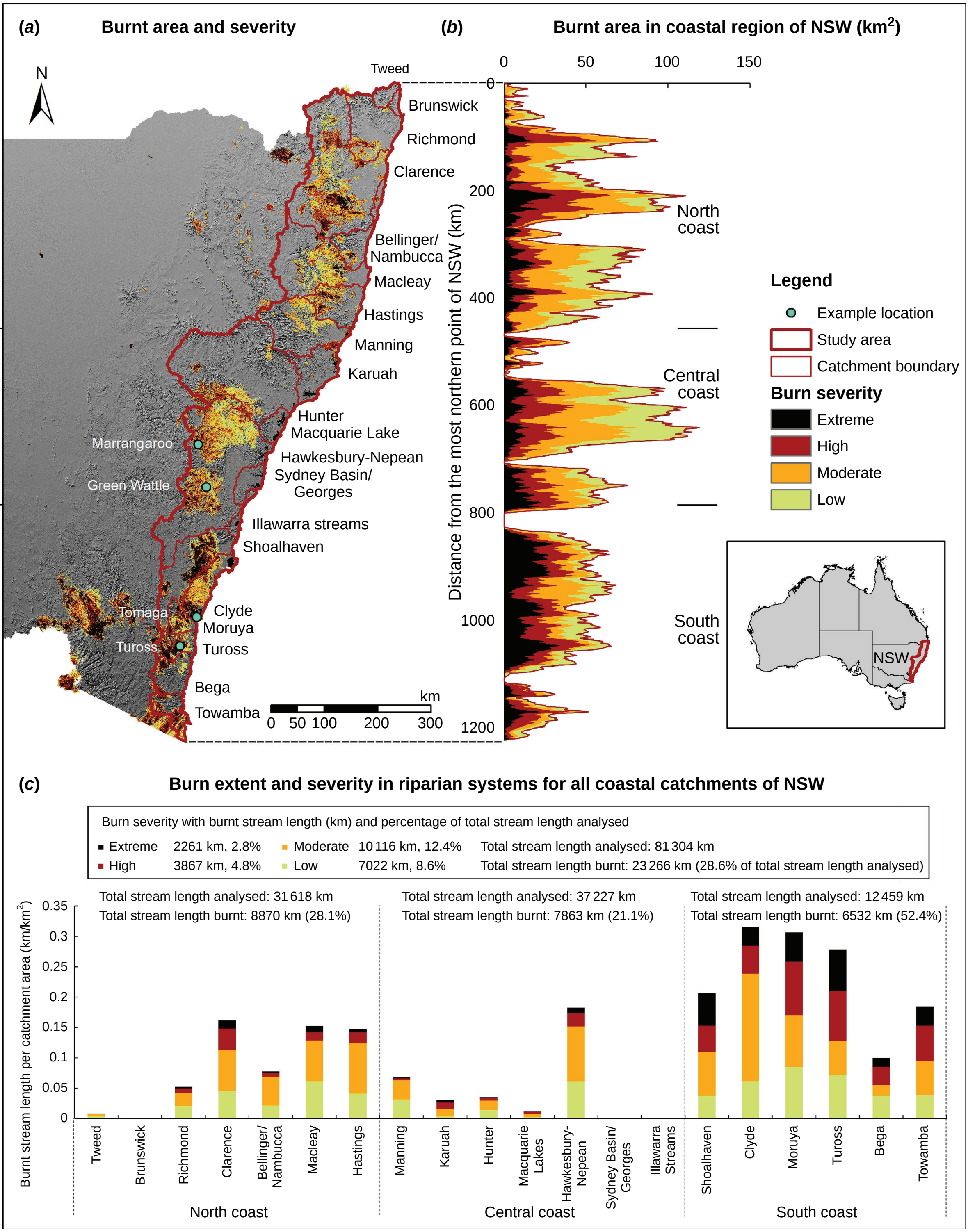

Fig. 1. Spatial extent and severity of burning in coastal catchments and riparian systems (stream length) of NSW during the 2019–2020 bushfire season.

(Supplementary Table S3). The burned area extended from headwaters to the ocean in many places (Fig. 1*a*), peaking at 67.9 km^2 of latitude distance (see Step 4 of methods in Supplementary Table S1) across the Tuross and Moruya catchments (Fig. 1*b*). The Tuross was the most severely affected catchment, with 74% of its total area burned (51% at extreme or high severity; Supplementary Tables S2, S3).

On the north coast, 30% of the region was burned, totalling 19 860 km^2. A larger area experienced a low or moderate-severity burn (8 and 11%, respectively) than a high or extreme-severity burn (7 and 4%, respectively; Supplementary Table S3). Burning was concentrated in the central parts of catchments, and peaked at 110.9 km^2 of latitude distance across the Clarence catchment (Fig. 1*b*). Over 30% of the Clarence, Macleay and Hastings catchments were burned (Fig. 1*a*) with between 9 and 15% at high or extreme severity (Supplementary Tables S2, S3).

On the central coast, 23% of the region was burned (19 900 km^2) (Supplementary Table S2), with over 15% experiencing low or moderate-severity burns (Supplementary Table S3). Extreme burning was concentrated in the Blue Mountains World Heritage Area (Fig. 1*a*; Fryirs *et al.* 2021*b*). The Hawkesbury–Nepean catchment was most severely affected, with over 40% of total area burned (Supplementary Table S2), and over 15% at high or extreme severity (Supplementary Table S3). The burn area peaked at 119.1 km^2 of latitude distance across this catchment (Fig. 1*b*).

Burned riparian zones

Across all coastal catchments, a total of 81 304 km of stream length was analysed. A staggering 23 266 km was burned, equating to ~29% of streamlines (Fig. 1*c*, Supplementary Table S4). Over 7% of stream length (6128 km) burned at an extreme or high severity and 21% (17 138 km) at a moderate or low severity.

The south coast was most impacted, with 52% of total stream length burned (6533 km) and over 20% at high to extreme severity (Fig. 1*c*, Supplementary Table S4). The Clyde, Moruya and Tuross catchments had the highest percentage of stream length burned at 74, 67 and 70%, respectively (3244 km) (Supplementary Table S4). Furthermore, 18, 30 and 38% of stream length in these catchments was affected by a high or extreme-severity burn (Supplementary Table S5). The Shoalhaven had 2224 km (45%) of stream length affected, the highest in the region, and a high or extreme severity burn occurred along 21% of stream length (Supplementary Table S5).

On the north coast, 28% of total stream length was burned (8870 km) (Fig. 1*c*, Supplementary Table S4). Low to moderate-severity burning affected 21% of stream length and extreme severity 7% (Supplementary Table S5). The Clarence, Macleay and Hastings catchments had the highest percentage of total stream length burned at 33, 34 and 34%, respectively (Supplementary Table S4). These are some of the largest catchments in coastal NSW, making the affected stream length 8021 km (Supplementary Table S4), with 1946 km impacted by a high or extreme-severity burning (Supplementary Table S5).

On the central coast, 21% of total stream length was burned (7863 km) (Fig. 1*c*, Supplementary Table S4) with just over 3% affected by a high or extreme-severity burn (Supplementary Table S4). In this region, the Hawkesbury–Nepean catchment was the most impacted with nearly 40%, or 5825 km, of total stream length burned (Supplementary Table S4) and 7% experiencing a high or extreme-severity burn (988 km) (Supplementary Table S5). The Manning catchment was impacted with nearly 20% of total stream length burned (Supplementary Table S4).

Burned river types

The most heavily impacted rivers were in confined, bedrock valley settings (Fryirs *et al.* 2021*a*), totalling 14 622 km of stream length, or 38% of stream length burned (Figs 2, 3, Supplementary Table S6). Of these, 11% experienced a high or extreme burn severity and ~28% a low or moderate-severity burn (Supplementary Table S7). Surprisingly, laterally unconfined rivers with discontinuous channels that normally contain wet or saturated ground were the next most impacted (Figs 2, 3), accounting for 18% of stream length burned and 1075 km (Supplementary Table S6). Nearly half of these rivers were affected by a high to extreme burn (Supplementary Table S7). This impact was heaviest in the Temperate Highland Peat Swamps on Sandstone (THPSS) in the Blue Mountains west of Sydney (see Fryirs *et al.* 2021*b*). Approximately 17%, or 3585 km, of stream length burned along partly confined rivers with discontinuous floodplain pockets (Figs 2, 3, Supplementary Table S6). Most of this burning was low to moderate severity (Supplementary Table S7). Laterally unconfined rivers with continuous channels were the least affected, accounting for 7% of total stream length burned (Figs 2, 3, Supplementary Table S6).

Discussion

Novel ecosystems? Implications for riparian management

Fire is an important disturbance agent in many landscapes and fire impacts are often acutely felt by both terrestrial and aquatic ecosystems (Bowman *et al.* 2009). Riparian zones act as an ecotone between aquatic and terrestrial ecosystems with different moisture regimes, microclimates and denser vegetation structures (Pettit and Naiman 2007). Owing to these conditions, fires in riparian ecosystems tend to occur at lower frequencies and severities than in terrestrial areas (Douglas *et al.* 2016). Yet the implications of severe fire on the geomorphic, vegetative and hydrological structure and function of rivers are largely unknown (Bixby *et al.* 2015). For coastal rivers of NSW, the impact of the 2019–2020 fires on riparian vegetation ranged from a heavily impacted 'moonscape' to a patchwork mosaic of burned and unburned areas (Figs 2, 3). Short-term impacts of sediment erosion and runoff on water quality have been significant (EPA 2020; DPIE 2020*b*, 2021*b*). However, medium- and long-term

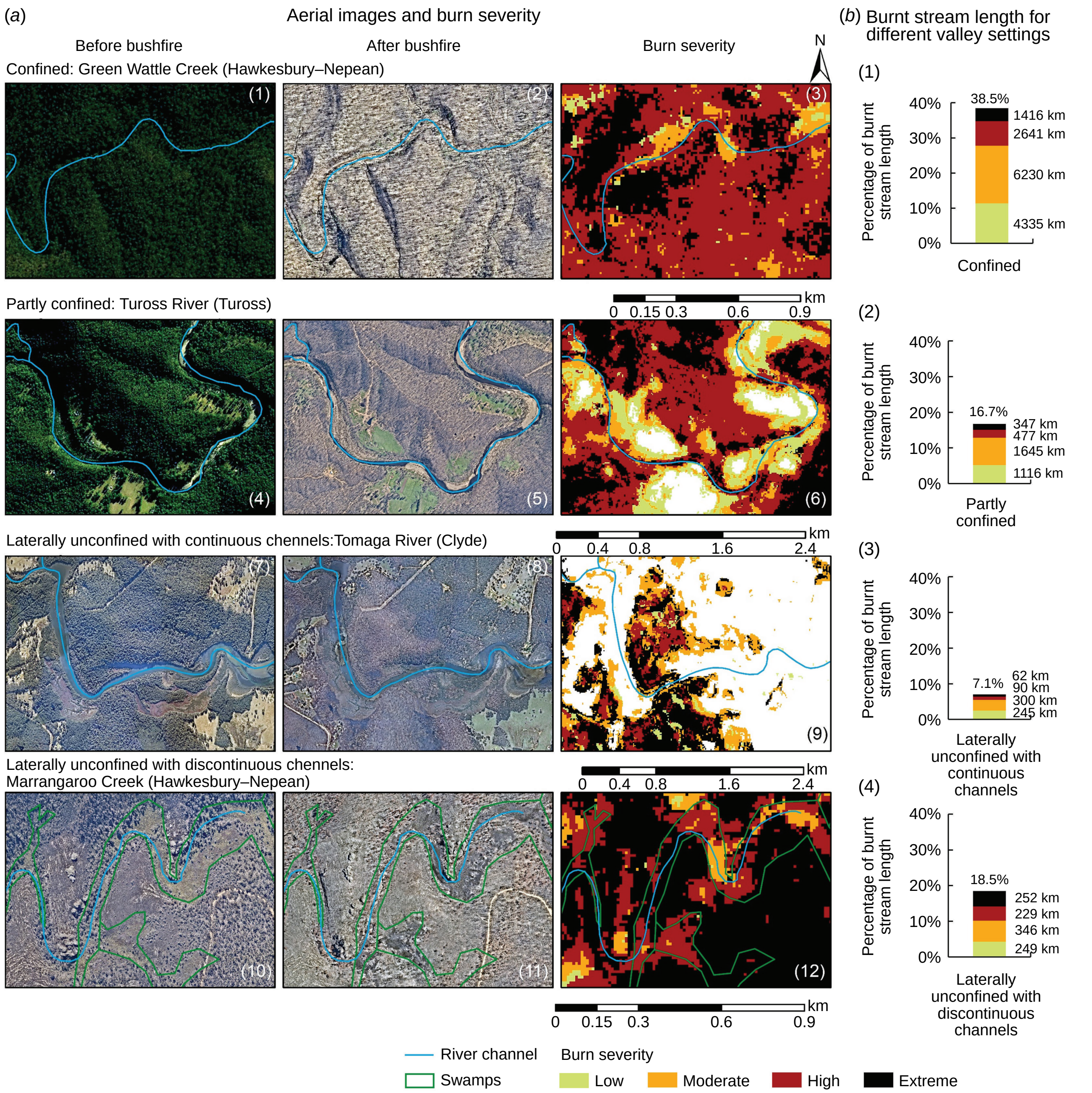

Fig. 2. Representative examples of confined, partly confined, laterally unconfined with continuous channels and laterally unconfined with discontinuous channels river types before and after the 2019–2020 bushfires, and the severity of burning experienced.

effects on sediment supply and transport, biogeochemical cycling and aquatic ecology will take years or decades to manifest (Verkaik *et al.* 2013; Bixby *et al.* 2015; DPIE 2021*b*).

The severity and impact of the 2019–2020 fires may mean some 'original' riparian ecosystems have been lost and replaced with new, novel ecosystems (cf. Hobbs *et al.* 2009). A combination of drought coupled with severe fires may cause terrestrialisation of riparian zones in some systems (Pettit and Naiman 2007; Douglas *et al.* 2016; Tran *et al.* 2020). Under climate change, summers are becoming hotter and drier, the fire season is becoming longer, and wildfires more frequent and more intense in many parts of Australia (Tran *et al.* 2020; IPCC 2021). Drought and extreme temperatures contribute to the dryness of the landscape, which makes rainforest and riverine vegetation more prone to combustion (Abram *et al.* 2021). These conditions can prevent certain fire-sensitive species from growing to maturity and reproducing, leading to irreversible changes in riparian ecosystem structure (Gallagher *et al.* 2021).

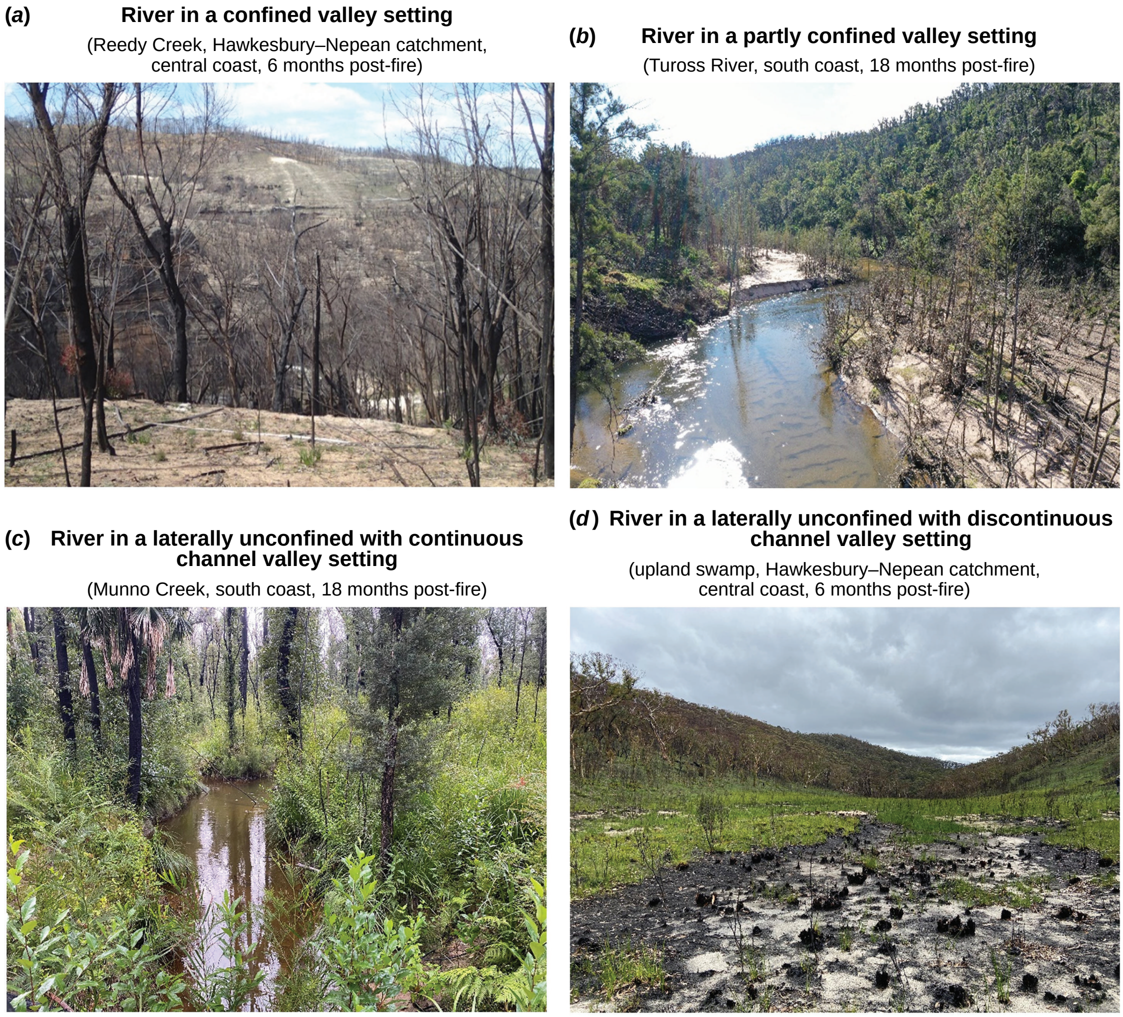

Fig. 3. On-ground examples of riparian systems impacted by different burn severity. Source of photos: the authors.

What does the occurrence of severe and more frequent fires mean for the future of riverine and riparian management in these systems? Since European colonisation, many river systems in NSW have been heavily impacted by anthropogenic disturbance (e.g. Brierley *et al.* 1999, 2005; Fryirs *et al.* 2013, 2018). Arguably, most riparian zones in the Anthropocene are already novel ecosystems with species in new combinations and abundances (Catford *et al.* 2013; Morse *et al.* 2014; Bowman *et al.* 2020*b*). These ecosystems tend to have a high presence of invasive weeds in both the extant vegetation and seed bank stores (O'Donnell *et al.* 2016; Fryirs *et al.* 2018) that can make them more flammable, fire-prone and likely to act as fire corridors under extreme conditions (cf. Verkaik *et al.* 2013). Additionally, a history of land management and forestry that encourages fire suppression and exclusion and use of riverine vegetation as fuel breaks, together with cycles of extreme wet and drought conditions, may also contribute to the creation of novel ecosystems that burn with greater severity (Dwire and Kauffman 2003; Lindenmayer *et al.* 2020). Therefore, many novel or degraded riparian ecosystems may benefit from some burning as part of environmental management practice to reduce the fuel load caused by invasive exotic species and to improve biodiversity (Bowman *et al.* 2020*b*; Cochrane and Bowman 2021). Additionally, prescribed and cultural burning may lower fire severity on moister riparian zones (Andersen *et al.* 2005; King *et al.* 2013; Douglas *et al.* 2016; Lewis 2020; Steffensen 2020).

Future research and considerations

The 2019–2020 fires have inflamed debate about when and how to use prescribed and cultural burning as an environmental management technique, yet this conversation has not extended into discussions about rivers and riparian zone management and recovery. Further research is needed to establish the extent to which riparian ecosystems in Australia are adapted to natural and human-induced fire

(Le Breton *et al*. 2020), the regimes and customs of cultural burning in these zones prior to European colonisation (Robinson *et al*. 2016; Bowman and French 2019; Steffensen 2020; Cochrane and Bowman 2021), and whether prescribed and/or cultural burning should be trialled and added to the river managers' toolkit alongside a range of other nature-based solutions to protect or rehabilitate the integrity of Australia's riparian landscapes. It is now urgent that lessons are learnt from the 2019–2020 megafires and that adjustments are made to riverine and riparian management practice to mitigate against inevitable future catastrophic wildfire events and prevent further loss of vital riverine and riparian ecosystems.

Supplementary material

Supplementary material is available online.

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Data availability. The data used in this study are publicly available. The Fire Extent and Severity Mapping (FESM) were retrieved from DPIE (2020*a*). The NSW River Styles dataset is available at DPIE (2021*a*) and the Catchment Boundaries of New South Wales are available at DPIE (2018). The full set of results by catchment, burn severity and river type class is located in Supplementary Tables S1–S6.

Conflicts of interest. The authors declare no conflicts of interest.

Declaration of funding. This work was funded by an ARC Linkage grant (LP190100314) led by KF.

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