



Mortality events resulting from Australia's catastrophic fires threaten aquatic biota

The size and intensity of bushfires during the 2019–2020 Australian season has been unprecedented (Nolan et al., 2020). The fires in south-eastern Australia were extraordinary in terms of the land area burnt (7.2 million ha; Figure 1); four times that of the 2019 Brazilian Amazon and 1.8 times the 2017 United States' fires (Bladon, 2018). The frequency and intensity of fires are predicted to increase over coming years as the Australian climate becomes warmer and drier (Leigh et al., 2015).

Prolonged drought conditions have resulted in water scarcity and spatially continuous dry fuel loads that have both been linked to the intensity and extent of the fires (Nolan et al., 2020). Other fire events have had catastrophic impacts on terrestrial and aquatic ecosystems (Emelko et al., 2016) and the 2019–2020 season was predicted to have negative impacts across catchments within Australia (Alexandra & Finlayson, 2020). Over 43 catchments were burnt across a diversity of landscapes, and there is the high likelihood that downstream cumulative watershed effects will result (Emelko et al., 2016). Most studies focus on localized (e.g. single catchment) impacts, such as degraded water quality (Emelko et al., 2016), direct (Lyon & O'Connor, 2008) or indirect (Bozek & Young, 1994) mortality of aquatic species, or altered food-web structure (Carvalho et al., 2019) in freshwater systems (Bixby et al., 2015). By contrast with previous fires, the scale of those in 2019–2020 challenges our current knowledge and ability to effectively manage and respond to the impacts.

Following a period of above average rainfall in the majority of the fire-impacted catchments (see Figure 1 for details), there were noticeable deaths of aquatic fauna, however, the full extent of these events remains undocumented. Rainfall records indicate abnormal events pre-fires (severe dry conditions) and post-fires (significant rainfall), related to the mortality events (Figure 1). Incidents reported in the media, state fisheries agency records and direct field observations have been used here to inform the extent of impacts to aquatic biota. Public outcry was precipitated by the incidence of large dead fish, including the threatened trout cod (*Maccullochella macquariensis*) and Murray cod (*Maccullochella peelii*; Table 1). In total, the deaths of ca. 27 species of freshwater and estuarine fish, along with four species of crustaceans, some of which are endemic, have been reported from 15 waterways and 17 locations across New South Wales (NSW) and Victoria (Vic.; Table 1). The highest number of species killed was documented in the Macleay River in northeast NSW (eight), including one event on its estuarine reach, and in the Upper Murray River region (NSW/Vic. border; also eight; Table 1). To our knowledge, this is the first record, globally, of fire events extending to, and impacting estuaries through the

mortality of obligate estuarine species (11) in seven locations across south-eastern Australia (Table 1; Figure 1).

Almost all estuarine sites with records of fish kills in this fire season were located downstream of burnt areas (Figure 1), posing previously unknown threats to these highly productive coastal systems. It is noticeable that no mortality was recorded from other burnt areas, such as the Hawkesbury-Nepean catchment, west of Sydney (Figure 1), perhaps because of the remoteness of many locations, and so a lack of reporting. The extension of the observed effects of fire to freshwater and estuarine systems is more far-reaching downstream than hitherto thought (e.g. ~54 km in the Macleay River). Inland reaches were also impacted. For instance, the Upper Murray River also had a major mortality event extending approximately 70 km downstream (Figure 1) from the burnt area, with records of both large- and small-bodied fish (e.g. Australian smelt; *Retropinna semoni*).

The processes by which fires impact freshwater ecosystems are inherently complex (Bixby et al., 2015) because they are influenced by the characteristics of the fire event (e.g. size), watershed (e.g. slopes, lentic or lotic waters) and hydrological events pre- and post-fire (e.g. drought, rainfall). Most of the fires in this 2019–2020 season burnt areas ranging from 800 to 2,000 m in elevation (Figure 1). The combination of fire severity, high elevation in the affected areas and thus steep slopes, followed by rainfall immediately after the fire, likely increased runoff and washed sediment, ash and debris to waterways (McInerney, Rees, & Joehnk, 2020). Dissolved oxygen concentration could have been rapidly depleted following increased carbon, and fell below tolerance ranges for fish and other aquatic biota. Other elements resulting from bushfires washed into waterways (e.g. nitrogen and phosphorus, methyl-mercury, burnt soils activated anions [nitrate and chloride] and cations [zinc and copper], and polycyclic aromatic hydrocarbons and polychlorinated biphenyls from ash and sediments) cannot be ruled-out as having detrimental impacts on aquatic biota (Harper et al., 2019). On the other hand, fire retardants used to extinguish fires across Australia such as Phos-Chek® D75 and WD881, which have been classified as 'practically nontoxic' and readily biodegradable in ecological toxicity tests, respectively (see Phos-Chek safety data sheets), are unlikely to cause significant or widespread mortality of adults, although the effects on aquatic invertebrates, larval and juvenile stages are unknown.

Australia's freshwater fauna is characterized by a high level of endemism and low fish diversity (Collen et al., 2014), so any loss is of great concern. Current bushfire recovery plans must include freshwater resources and urgently (a) identify immediate and

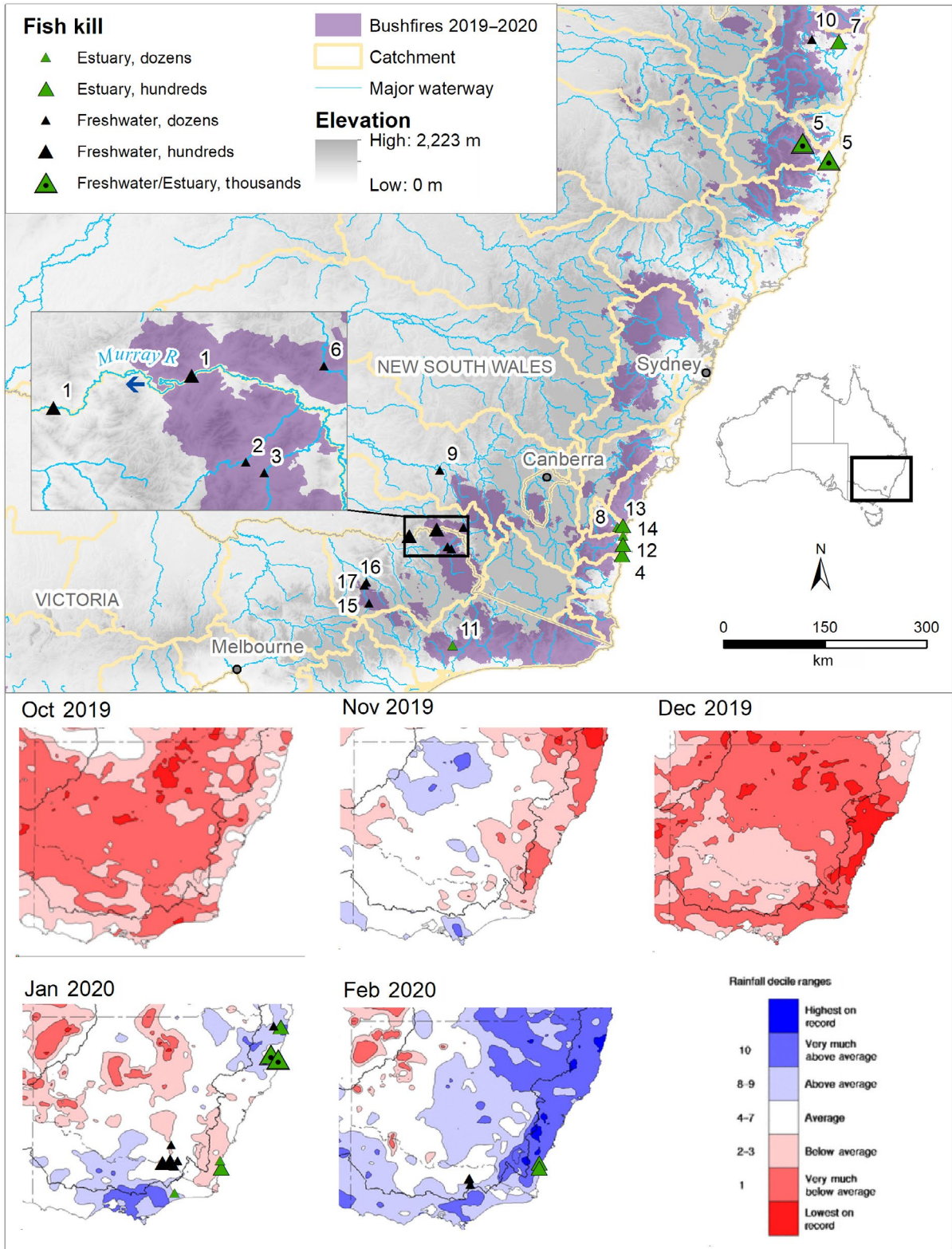


FIGURE 1 Distribution of the widespread aquatic biota mortality events in south-eastern Australia freshwater and estuarine systems associated with fire events. Numbers close to (triangles) inform the waterway/location of the mortality event (refer to Table 1). The inset on the upper Murray River (black rectangle) illustrates the extension of the mortality event to areas located downstream of the fire-affected locations. The temporal series of rainfall decile maps (October 2019–February 2020) were used to provide an indication of how the observation values for that period sit relative to the full history of record. The maps show if an observation is Average: middle bands 4–7; Below average: bands 2 and 3; Very much below average: band 1; Above average: bands 8 and 9; Very much above average: band 10. Extreme ends of the distribution are the lowest on record and highest on record, and each can also be considered within decile bands 1 and 10, respectively. Source of decile maps: Bureau of Meteorology, 2020; <http://www.bom.gov.au/climate/austmaps/about-rain-maps.shtml#deciles>

TABLE 1 List of aquatic species that have been identified during assessment of aquatic biota mortality post the 2019–2020 bushfires in south-eastern Australia, with information on the number of individuals reported ($N = 1-10$, over 10, 100's–over 1,000) origin (I, invasive; N, native), habitat (E, estuary; F, freshwater), endemism (E, endemic; NE, non-endemic) and conservation status. These species were either sampled dead in the streams or known to have been affected by bushfires according to media or States fisheries agencies' reports (Source)

Waterway	Location	Extent	Taxonomical group	Species name	Common name	Origin	Habitat	Endemism	Conservation status ^a	N	Source		
Murray River	1. Jingelic to Talmalmo, Vic.	Range location ≈ 70 km	Crustacean	<i>Euastacus armatus</i>	Murray crayfish	N	F	E	N/A	1–10	Authors direct observation. NSW Fisheries ^c		
				<i>Macrobrachium</i> sp. ^b	Freshwater prawn	N	F	E	Least concern				
				<i>Paratya</i> sp. ^b	Freshwater prawn	N	F	E	Least concern				
			Pisces			<i>Maccullochella macquariensis</i>	Trout cod	N	F	E	Endangered	100's	
						<i>Maccullochella peelii</i>	Murray cod	N	F	E	Vulnerable		
						<i>Macquaria ambigua</i>	Golden perch	N	F	E	Least concern		
						<i>Retropinna semoni</i>	Australian smelt	N	F	E	Least concern		
						<i>Perca fluviatilis</i>	Redfin perch	I	F	NE	N/A		
						<i>M. peelii</i>	Murray cod	N	F	E	Vulnerable	10's	Cameron McGregor (personal observation)
						<i>Gadopsis</i> sp.	River blackfish	N	F	E	N/A		
<i>Cyprinus carpio</i>	Common carp	I	F	NE	N/A								
Cudgewa Creek	2. Cudgewa, Vic.	Single location	Pisces	Not identified	N/A	N/A	N/A	N/A	?		Cameron McGregor (personal observation)		
Tilba Lake	4. South of Narooma, NSW	Single location	Pisces	<i>Sillago</i> sp. ^b	Sand whiting	N	E	E	N/A	100's	Newspaper article—Sydney Herald		
				<i>Girella tricuspidata</i>	Luderick	N	E	NE	N/A				
				<i>Acanthopagrus butcheri</i>	Black bream	N	E	NE	Least concern				
				<i>Platycephalus fuscus</i>	Dusky flathead	N	E	E	N/A				
				<i>Anguilla</i> sp. ^b	Eel	N	E	NE	N/A				

(Continues)

TABLE 1 (Continued)

Waterway	Location	Extent	Taxonomical group	Species name	Common name	Origin	Habitat	Endemism	Conservation status ^a	N	Source
Macleay River	5. Belbrook to Kempsey, NSW	Range location ≈ 54 km	Pisces	<i>Anguilla</i> sp. ^b	Eel	N	E	NE	N/A	1,000's	Media—The Guardian ^d and NSW Fisheries ^c
				<i>Percalates novemaculeatus</i>	Australian bass	N	F/E	E	N/A		
				<i>Aldrichetta forsteri</i> ^b	Yelloweye mullet	N	E	E	Least concern		
				<i>Trachystoma petardi</i> ^b	Freshwater mullet	N	F/E	E	Least concern		
				Unknown ^b	Herring	N	F/E	NE	Least concern		
Sportsmen Creek	6. Bogandjera Nature Reserve, NSW	Single location	Crustacean	<i>Gobiomorphus australis</i> ^b	Striped gudgeon	N	F/E	E	Least concern		
				<i>Tandanus tandanus</i> ^b	Freshwater catfish	N	F	E	Least concern		
				<i>Notesthes robusta</i> ^b	Bullrout	N	F/E	E	Least concern		
				<i>Paratya</i> sp. ^b	Freshwater prawn	N	F	E	Least concern		Luke Pearce, NSW Fisheries (personal observation) and NSW Fisheries ^c
				<i>M. peelii</i>	Murray cod	N	F	E	Vulnerable		
Sportsmen Creek	7. Sportsmen Creek, NSW	Single location	Pisces	<i>C. carpio</i>	Common carp	I	F	NE	N/A	10's	
				<i>Gambusia holbrooki</i>	Mosquito fish	I	F	NE	N/A		
				<i>Trachystoma petardi</i> ^b	Freshwater mullet	N	F/E	E	Least concern		NSW Fisheries ^c
				<i>Percalates colonorum</i>	Estuary perch	N	E	E	Least concern		
				Unknown ^b	Herring	N	F/E	NE	Least concern		
Deua River	8. Upstream of Moruya, NSW	Single location	Pisces	<i>P. novemaculeatus</i>	Australian bass	N	F/E	E	N/A	10's	NSW Fisheries ^c
				<i>Anguilla</i> sp. ^b	Eel	N	E	NE	N/A		
Tarcutta Creek	9. Windamarra Road, Borambola, NSW	Single location	Crustacean	<i>E. armatus</i>	Murray crayfish	N	F	E	N/A		
				<i>M. peelii</i>	Murray cod	N	F	E	Vulnerable		
				<i>M. ambigua</i>	Golden perch	N	F	E	Least concern		
Clarence River	10. Grafton, NSW	Single location	Pisces	<i>C. carpio</i>	Common carp	I	F	NE	N/A		
				Not identified	N/A	N/A	N/A	N/A	?	Gavin Butler, NSW Fisheries (personal communication)	

(Continues)

TABLE 1 (Continued)

Waterway	Location	Extent	Taxonomical group	Species name	Common name	Origin	Habitat	Endemism	Conservation status ^a	N	Source
Tambo River	11. Gippsland, Tambo Crossing	Single location	Pisces	<i>Anguilla</i> sp. ^b	Eel	N	E	NE	N/A	10's	ABC News ^e
Mummaga Lake	12. Dalmeny, NSW	Single location	Pisces	<i>Tetractenos hamiltoni</i>	Common Toadfish	N	E	NE	Least concern	100's	NSW Fisheries ^c
Moruya River	13. Shelly Beach, NSW	Single location	Crustacean	<i>Portunus armatus</i>	Blue swimmer crab	N	E	NE	N/A	100's	NSW Fisheries ^c
			Pisces	Unknown ^b	Flounder	N	E	NE	N/A		
				Unknown ^b	Anglerfish	N	E	NE	N/A		
				Unknown ^b	Kingfish	N	E	NE	N/A		
Tuross Lake	14. Tuross Head, NSW	Single location	Pisces	<i>T. petardi</i> ^b	Freshwater mullet	N	F/E	E	Least concern	10's	NSW Fisheries ^c
				<i>A. butcheri</i>	Black bream	N	E	NE	Least concern		
				<i>Sillago</i> sp. ^b	Sand whiting	N	E	E	N/A		
				Unknown ^b	Black fish	N	F/E	NE	N/A		
Buffalo River	15. Abbeyard, Vic.	Single location	Pisces	<i>Oncorhynchus mykiss</i>	Rainbow trout	I	F	NE	N/A	10's	Author (Katherine Doyle) and Cameron McGregor (personal observation)
	16. Nug Nug Reserve, Vic.	Single location		<i>M. peelii</i>	Murray cod	N	F	E	Vulnerable		
	17. Downstream Lake Buffalo, Vic.	Single location									

Abbreviations: ?, unknown information; N/A, not applicable; NSW, New South Wales; Vic., Victoria.

^aBased on the Australian Environmental Protection and Biodiversity Conservation (EPBC) Act List of Threatened Fauna and the IUCN Red List of Threatened Species.

^bSpecies identification uncertain.

^cNSW Fisheries Fish Kills Reports—<https://www.dpi.nsw.gov.au/fishing/habitat/threats/fish-kills>

^dThe Guardian—<https://www.theguardian.com/world/2020/jan/17/hundreds-of-thousands-of-fish-dead-in-nsw-as-bushfire-ash-washed-into-river>

^eABC News—<https://www.abc.net.au/news/2020-01-23/eels-found-dead-in-polluted-tambo-river/11893646>

long-term actions to mitigate impacts; and (b) develop medium- and long-term research plans based on sound science to advance knowledge aimed at enhancing freshwater ecosystem resilience. While immediate responses have focused on rescuing threatened fish and listing species as a national priority for urgent management, research plans still need to be developed to understand the efficacy of such actions. Management units have been prioritized based on aquatic biota and catchments at greater risk post-fire, given that such events are predicted to be more common in future. Freshwater ecosystems are recognized as the most threatened globally (Vorosmarty et al., 2010), yet fire impacts are rarely acknowledged as a threat in the scientific literature and in water management policies.

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