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Impacts of Extreme Events on Southeastern Australian Freshwater Crayfish

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ABSTRACT

Extreme events like wildfire, flooding and drought, and activities related to managing these events (fire dam, bridge and road construction and water regulation) potentially impact freshwater crayfish populations, although limited information exists. Our study analysed abundance data for four freshwater crayfish species across an 11-year period, including pre- and post-wildfire and post-flooding data, and describes the impacts of human actions on their populations in the Grampians National Park in Victoria, Australia. Wildfire and flooding were generally associated with reduced crayfish abundances for *Euastacus bispinosus*, *Cherax destructor*, *Geocharax falcata* and *Gramastacus insolitus*, but in some habitats, *C. destructor*, *G. falcata* and *G. insolitus* did not decline. A general trend of decreasing abundances for all species was evident over the study period, likely due to the landscape-scale impacts of wildfire, flooding and the shrinking of available habitat during drought. Southeastern Australia is a crayfish biodiversity hot-spot and increased frequencies of wildfire, flooding and drought are forecast for this region as climate change progresses, threatening crayfish populations. Therefore, it is important that disaster recovery management seeks to minimise additional damage to crayfish habitat availability and connectivity.

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INTRODUCTION

Crayfish are an important component of freshwater ecosystems worldwide (Lodge and Hill 1994; Momot 1995; Nyström 2002), often comprising the majority of aquatic invertebrate biomass (Huryn and Wallace 1987; Whitledge and Rabeni 1997) and playing a fundamental role in ecosystem structure and function (Reynolds and Souty-Grosset 2012). Richman et al. (In press) recently evaluated the extinction risk of the world's 590 freshwater crayfish species using IUCN Categories and Criteria, finding proportionally more threatened species in the crayfish family Parastacidae and Astacidae than in the Cambaridae. The Australian Parastacidae tend to have small highly fragmented ranges (Richman et al. In press), which has serious implications for their conservation. An estimated 65% of Australian freshwater crayfish are at risk from climate-mediated threats (Richman et al. in press). Southeastern Australia has the highest diversity of freshwater crayfish in the southern hemisphere (Crandall and Buhay 2008). The Grampians National Park (GNP) in Victoria, Australia, lies within this hot-spot and seven species of freshwater crayfish from six genera occur together in this region. These crayfish occur in a range of habitat types ranging from ephemeral (seasonally inundated with water) habitats, such as flooded vegetation and wetlands, to perennial habitats, such as streams and fire dams (clay lined water reservoirs constructed for the purpose of fighting wildfires) (Johnston and Robson 2009a). The fauna and flora of the GNP region are adapted to seasonal change to some extent (Robson et al. 2011), which makes appreciable quantities of summer rainfall a major disturbance for the biota (Hershkovitz and Gasith 2013). Currently, limited information exists about the impacts that extreme events, such as wildfire, flooding and drought, have on freshwater crayfish, in Australia or elsewhere (but see Parkyn and Collier 2004; Meyer et al. 2007; Furse et al. 2012; McCarthy et al. 2014, and references therein), but this information is required to appropriately manage and conserve these crayfish populations into the future, especially under changing climate regimes. This is because climate mediated distrbances, such as wildfire, flooding and drought may pose significant threats to crayfish, through

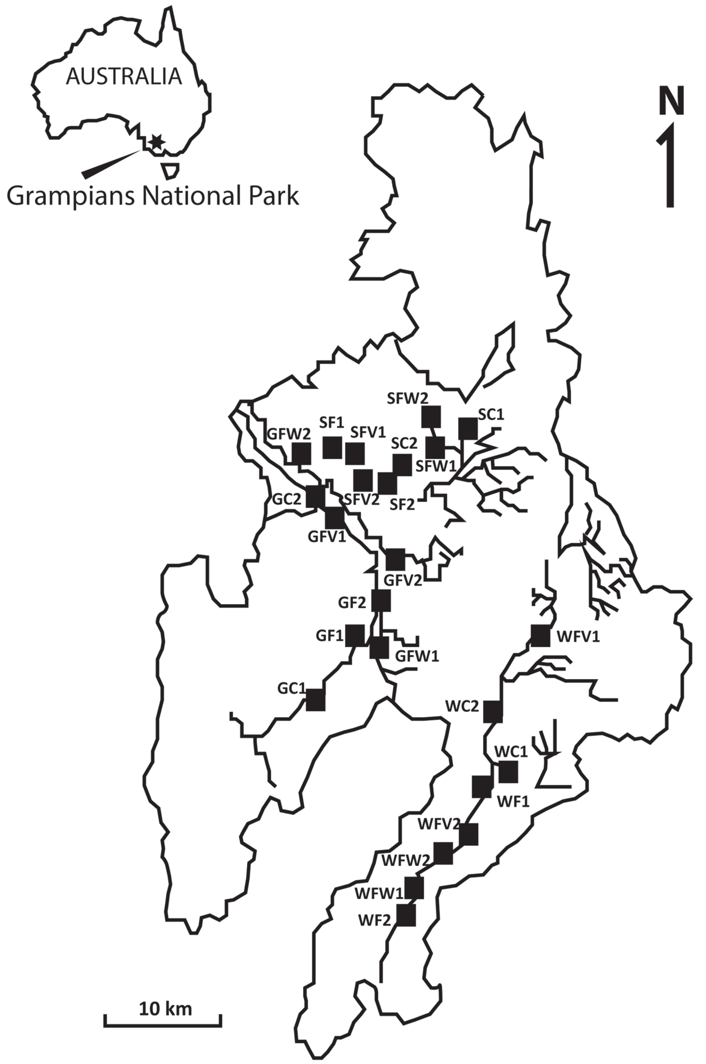

Figure 1. Map showing the location of the Grampians National Park in Australia and the study sites within this area. Wannon River catchment (W), Scrubby Creek Catchment (S), Glenelg River Catchment, fire Dam (F), flooded vegetation (FV), stream (C), floodplain wetland (FW), replicate site numbers (1) and (2).

altering habitat, which in turn may alter species distributions and the size and structure of populations through the frequency and severity of these events.

Wildfire frequency is increasing across southeastern Australia because of increased summer-autumn temperatures and decreased humidity (CSIRO 2007; Nyman et al. 2011). The GNP experienced many wildfires during the millennium drought (1999 to 2009, Bond et al. 2008), with the largest and most intense being the Mt. Lubra fire in summer 2006. In the GNP region, winter flooding occurs in average or above average rainfall years, but intense rainfall events arising from storms, may also cause large floods in the summer-autumn dry season. Intense rainfall events during the dry summer-autumn season may have a much larger impact on aquatic fauna than similar events during winter-spring (McMullen and Lytle 2012). This is because during the dry season (late summer to late autumn – January to late May) GNP soils are likely to be hydrophobic, so most rainfall runs directly into waterbodies rather than being absorbed into soils, as it is in the winter (Hershkovitz and Gasith 2013). The hydrophobicity of the soil is exacerbated by fire, increasing the run-off over land during rainfall events (DeBano 2000), so floods that arise from intense rainfall events in summer-autumn can be expected to be larger than similar events in winter-spring, especially if they follow wildfire. Therefore intense flooding occurring during the dry time of year (summer-autumn) may affect freshwater crayfish species (especially species occurring in seasonal habitats), by encouraging ‘false starts’, whereby floodwaters interrupt its aestivation period and stimulate it to emerge and continue its life cycle at a disadvantageous time.

A major flood event following wildfire occurred in the GNP in January 2011, which caused severe erosion of headwater streams and destroyed bridges and other infrastructure. The movement of substrate and woody debris during flooding also had the potential to damage or destroy crayfish burrows and shelter. This flood constituted the largest intense summer rainfall event in the GNP since records began in 1890, with between five and six times the monthly average rainfall falling in a 24 – 72 hour period (BOM 2012, 2013). The frequency of intense summer-autumn rainfall, and thus flooding events, is expected to increase across southeastern Australia with climate change (CSIRO 2007; Nyman et al. 2011) and this will potentially compound the impacts arising from flooding following drought (Verkaik et al. 2013b).

The construction/reconstruction of physical infrastructure such as fire dams, bridges and roads in wildfire and flood affected areas, is necessary to reinstate access after these events have passed. To date little information has been published on how these activities impact adjacent waterbodies or their fauna, much less any impacts on crayfish species. It is likely however, that these activities could also negatively impact crayfish populations due to the nature and level of soil disturbance required to construct such infrastructure.

This paper assesses the impacts of selected extreme events (wildfire, flooding and drought) on the distribution and abundance of four southeastern Australian freshwater crayfish species. We compare data collected in seasonal field surveys in the GNP in the two years prior to the Mt. Lubra wildfire (2003 – 2005), with data collected during the 12 months post-fire (2006 – 2007), in which 19 of 24 sites of the pre-fire sampling sites were burnt. In addition, data collected on two occasions post- 2011 intense summer flooding (spring 2012 and spring 2013) is also compared to the pre- and post-fire data, to assess the impact of flooding on crayfish populations. The sampling regime spanned an11-year period, with the pre-and post-fire sampling corresponding with the end of the millennium drought (1999 – 2009, BOM 2013). Additionally, field observations of the impacts of management actions related to post-fire and post-flood recovery (construction of new fire dams, bridge and road building and water regulation) on the crayfish of this region are discussed.

MATERIALS AND METHODS

Study Design and Freshwater Crayfish Species

The GNP is located in south-western Victoria, Australia. It comprises an area of 1672 km^2 and is minimally altered by human settlement (Jackson and Davies 1983). The Grampians Ranges are

Table 1. Total crayfish abundances at study sites for pre- and post- the 2006 Mt. Lubra fire and after the 2011 flood event (post-flood) surveys. Data presented are the total number of crayfish individuals captured over the pre-fire (eight sampling occasions between 2003 – 2005 pooled), post-fire (four sampling occasions over 12 months (2006 – 2007) pooled) and post-flood (one sampling occasion in spring 2012, plus the resampling of eight selected sites in spring 2013). Sites were no crayfish were captured on the spring 2012 post-flood sampling occasion and that were also not sampled on the spring 2013 post-flood survey are denoted 'ns'. Sites not affected by the Mt. Lubra fire (unburnt) are underlined. Wannon River catchment (W), Scrubby Creek Catchment (S), Glenelg River Catchment, fire Dam (F), flooded vegetation (FV), stream (C), floodplain wetland (FW), replicate site numbers (1) and (2).

	Cherax destructor			*Geocharax falcata*			*Gramastacus insolitus*			*Euastacus bispinosus*		
Site	Pre-fire	Post-fire	Post-flood	Pre-fire	Post-fire	Post-flood	Pre-fire	Post-fire	Post-flood	Pre-fire	Post-fire	Post-flood
WF1	14	38	3	42	8	ns	20	0	ns	0	2	ns
WF2	0	0	ns	0	0	20	0	0	ns	0	0	ns
WFV1	1	0	ns	0	7	ns	0	0	ns	0	0	ns
WFV2	0	0	ns	140	34	ns	1	0	ns	0	0	ns
WC1	1	0	0	0	4	0	0	0	0	1	8	2
WC2	0	0	7	0	0	0	0	0	0	6	14	15
WFW1	0	0	4	40	0	0	263	0	15	0	0	0
WFW2	0	0	ns	31	21	23	0	0	ns	0	0	ns
SF1	174	87	21	0	0	ns	0	0	ns	0	0	ns
SF2	326	293	3	0	0	ns	0	0	ns	0	0	ns
SFV1	1	0	0	53	26	2	68	24	12	0	0	0
SFV2	19	18	7	60	46	4	247	78	5	0	0	0
SC1	0	0	0	0	0	0	0	0	0	71	13	9
SC2	139	37	5	2	3	ns	0	0	ns	0	0	ns
SFW1	45	0	ns	23	7	ns	0	0	ns	0	0	ns
SFW2	13	121	ns	3	1	ns	0	0	ns	0	0	ns
GF1	426	184	ns	1	0	ns	0	0	ns	0	0	ns
GF2	153	191	ns	0	0	ns	0	0	ns	0	0	ns
GFV1	0	0	ns	0	0	ns	0	0	ns	0	0	ns
GFV2	2	0	ns	0	0	ns	9	0	ns	0	0	ns
GC1	5	0	0	108	58	4	57	0	0	7	2	0
GC2	17	4	7	49	58	21	391	108	31	0	0	ns
GFW1	122	32	13	0	0	ns	105	25	ns	0	0	ns
GFW2	6	23	3	27	0	22	103	0	153	0	0	0

a series of three north-south orientated ranges rising abruptly from the surrounding plains and constitute the end of the Great Dividing Range. The average annual rainfall varies from 700 mm to more than 900 mm (Jackson and Davies, 1983) with most falling in winter (June – August). July and August are the wettest and coolest months, and mid-summer to mid-autumn (January – April) are the driest and hottest (Calder, 1987). The region sampled in the current study ranged in altitude from 212 to 405 m above sea level. The surface geology predominantly comprised river alluvium (gravels, sands and clays) and swamp deposits (Geological Survey of Victoria maps 1:126,720 Spencer-Jones 1965).

Eight surveys were conducted seasonally (every three months) prior to a major fire in 2006 (known as the Mt. Lubra fire), from spring 2003 to summer 2005 as part of the lead author's PhD research (see Johnston 2008; Johnston et al. 2008; Johnston and Robson 2009a; Johnston et al. 2010). This pre-fire sampling was carried out to collect distribution and abundance data on the freshwater crayfish species: *Euastacus bispinosus* Clark, *Cherax destructor* Clark, *Geocharax falcata* Clark, *Gramastacus insolitus* Riek and *Engaeus lyelli* Clark (however, information regarding *E. lyelli* will be omitted from this paper due to insufficient sample sizes). Upon completion of this pre-fire sampling, the Mt. Lubra fire occurred, burning all but five of the sites of this original survey (See Table 1 and Figure 1). Amidst concern from GNP environmental managers, an opportunistic (and 'in kind' supported) 12-month long post-fire project was carried out by the lead author, using the same sampling methods as were used in the pre-fire sampling to allow comparison between the two data sets, allowing the impacts of the Mt. Lubra fires on GNP crayfish distribution and abundances to be assessed. This post-fire data (unpublished) consisted of four surveys conducted seasonally over the following 12 months, from autumn 2006 to summer 2007. Sampling for each of these two projects (pre-fire and post-fire) was conducted at

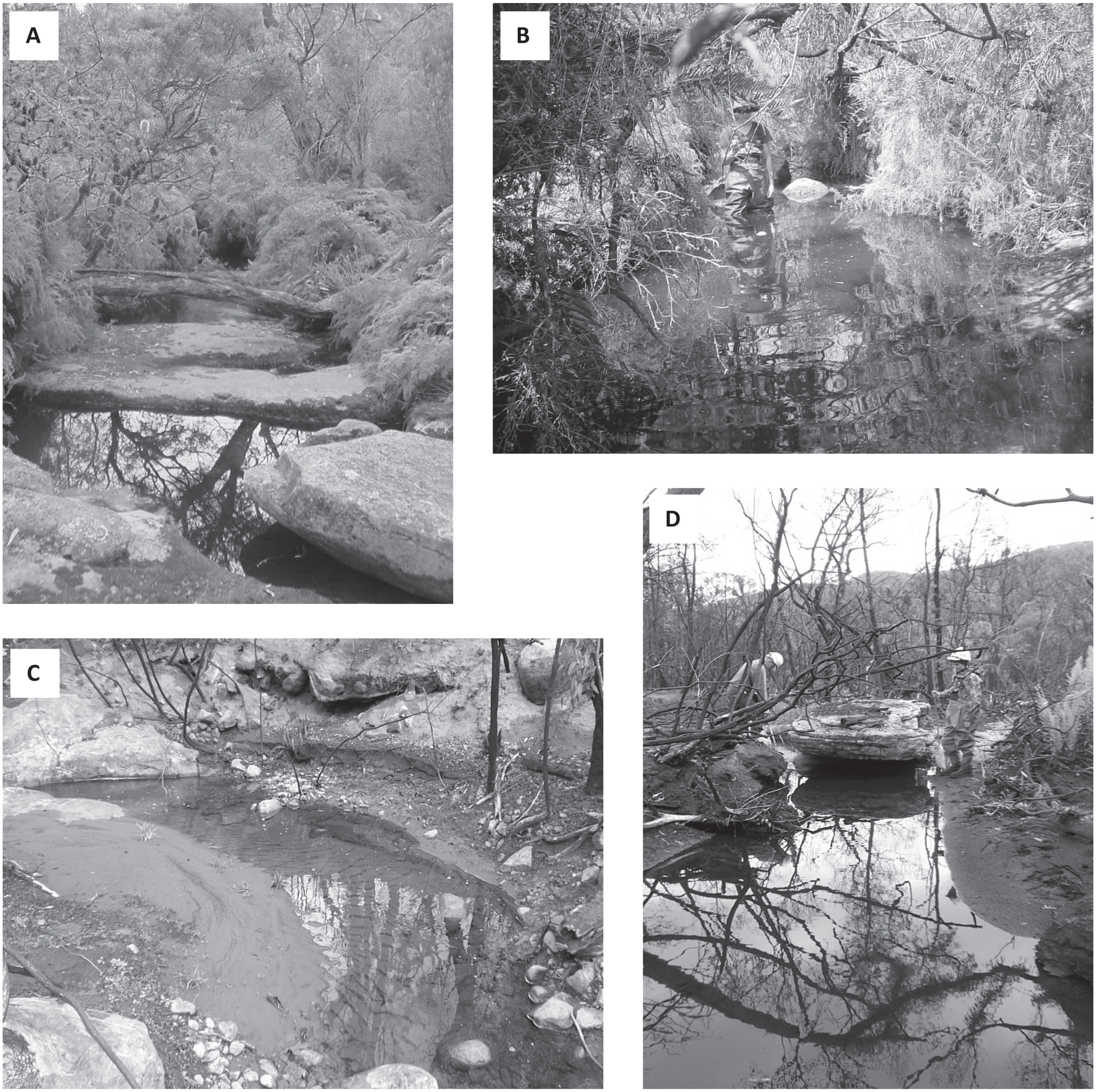

Figure 2. Photographs of site SC1 pre-fire and post-fire. A, an example of SC1 habitat pre-fire; B, run habitat at SC1 pre-fire with intact riparian zone, varying depth and undercut banks; C, a section of SC1 post-fire showing slumped banks with no undercutting and stream in filled by eroded sediment and ash to a uniform and shallow depth; D, the same section of SC1 (as shown in photo B) post-fire, with riparian vegetation removed via burning and sediment filling the channel and undercut bank area.

each of 24 sites spread across three catchments; the Wannon River catchment, the Scrubby Creek catchment and the Glenelg River catchment in the GNP (see Johnston and Robson 2009a). Within these three catchments, two replicate sites of each of four common habitat types were sampled. These habitat types were stream channels (streams), fire dams, floodplain wetlands, and flooded vegetation. Channels and fire dams are permanent habitats that contain water all year round while floodplain wetland and flooded vegetation habitat types are temporary in nature, with the former usually inundated with water from winter to late summer, and the latter being more temporary, dominated by terrestrial vegetation and only inundated for several weeks to months during the same time period depending on habitat size.

In January 2011, a major flood event occurred in the GNP and in response to this, funding was made available to the authors to carry out research into the impacts of flooding on GNP aquatic habitats and their fauna. One aspect of this project was an assessment of the impact of flooding on GNP crayfish populations. The same methods that were used in the two previous projects were again used for the post-flood project, thus allowing direct comparisons to be made. The funding allowed two post flood surveys to be carried out in each of Spring 2012 and Spring 2013. However, for the Spring 2013 survey, a subset of eight of the original 24 sites were sampled due to funding constraints and because past surveys revealed that these sites consistently contained the largest crayfish populations. Thus site selection was prioritised to maximise the detection of any impacts of flooding on significant GNP crayfish populations. Thus, this paper presents information on the post-fire post-flood crayfish populations for the first time, using the original (and more extensive) pre-fire project data as a 'before disturbance' baseline against which the impacts of subsequent extreme events of fire and flooding on GNP crayfish populations were evaluated.

Crayfish Sampling Methods

Crayfish surveys employed both day and night sampling, so as to include diurnal variations in crayfish activity and used different capture techniques (these methods have been successfully used in previous GNP freshwater crayfish research (Johnston 2008 and Johnston and Robson 2009a). Day sampling involved a series of random 30-second dip-net (250 μm mesh) sweeps of a 25 m^2 area in lentic habitats (or the littoral zone of fire dams) or a 50 m length of channel habitats for one hour. Night sampling involved the use of three box bait traps (baited with beef liver) which were placed randomly at each site sampled that day. Traps were left in place overnight and collected the next morning. Each crayfish individual was identified to species before being released unharmed.

Data Analysis for Fire and Flooding Impacts on Crayfish Populations

Crayfish were often patchily distributed in space and time resulting in many zero values for multiple sites across the sampling period. Interpreting these zeroes is problematic, because it is always possible that some individuals were present at a site but were not captured. Furthermore, different species have quite different distributions among both catchments and habitats (Johnston and Robson 2009a). This means that the best method of analysing this occupancy data is as counts against a binomial distribution, where the null hypothesis is an approximately equal frequency of occurrence between the items being compared. Such analyses interpret only the counted individuals and do not reflect patterns of zeroes in the data. Therefore, each crayfish species response to the flooding and fire were analysed separately using tests of homogenous frequencies summed across the same set of sampled sites at each time (sites used differed among species reflecting their distribution pattern) (3 levels: before fire, post- fire, post-flood) to test the null hypothesis that the abundance of a species did not alter before or after the Mt. Lubra fire and after the January 2011 floods. All tests had fewer than 20% of the cells with counts < 5. *Euastacus bispinosus* was only collected at five sites, all but one were streams, and so only stream sites were included in the test of homogenous frequency. The other three species occurred across all habitat types, but *C. destructor* was most common in fire dams and *G. insolitus* and *G. falcata* were most common in floodplain wetland and flooded vegetation habitats. The test for homogenous frequencies for *C. destructor* was completed separately for fire dams (n = 6 sites pooled) and for floodplain wetlands (n = 4 sites pooled) where it was most abundant. For *G. falcata* and *G. insolitus* tests were completed separately on flooded vegetation (n = 5, n = 4 sites pooled, respectively) and floodplain wetlands (n = 5, n = 3 sites pooled, respectively) where they were most abundant. Qualitative visual observations of the impacts of construction work are presented.

RESULTS

A general trend of decreasing mean relative abundance of crayfish was found at GNP sites across the study period (Table 1). In post-fire sampling, *G. falcata* was the crayfish species least affected by fire, occurring at 12 of the original 13 pre-fire sites (Table 1). In contrast, in post-fire sampling, *G. insolitus* was found at just four of the ten sites that it occurred at in pre-fire sampling and was not recorded in the Wannon River Catchment post-fire. Similarly, post-fire *C. destructor* occurred at 11 sites compared to its pre-fire presence at 17 sites in the GNP. Interestingly, total post-fire site occurrences of *E. bispinosus* increased from four pre-fire sites to five sites post fire, with abundances also increasing relative to pre-fire sampling for several sites (Table 1).

Post-flood sampling found a decrease in crayfish abundance for all species (except for *G. falcata* and *G. insolitus* in floodplain wetland habitats only) (Table 1). Also post-flood, each species (except *G. insolitus*) was found to occupy fewer study sites than they had either pre- or post-fire (Table 1). *Cherax destructor* was the most frequently occurring crayfish species in the GNP post-flood (occurring at 10 sites) but its abundances were lower than for pre- and post-fire sampling (Table 1). *Geocharax falcata* was found at one new site following the flood, but was absent at seven sites where it had been recorded post-fire (Table 1). In contrast, *E. bispinosus* appeared to be least affected by flooding, occurring at a similar number of sites in post-flood sampling (3 sites) compared with pre-fire sampling (four sites). *Gramastacus insolitus* appeared to have been substantially impacted by both fire and flood, occurring at a greater number of sites (nine sites) pre-fire compared to post-fire and post-flood sampling (four and five sites respectively) (Table 1).

Tests of homogenous frequencies carried out on each crayfish species separately to determine whether the abundance of a species altered before or after the Mt. Lubra fire or after the January 2011 floods, found that lower crayfish abundances were associated with flooding and fire but effects depended on species and habitat type. *Euastacus bispinosus* abundances in stream channels declined both post-fire and post-flood ($\chi^2 = 39.9$, $P < 0.01$) as did *C. destructor* abundances in fire dams ($\chi^2 = 948$, $P < 0.01$). However, *C. destructor* abundance in floodplain wetlands did not decline significantly following the fire, but declined dramatically following the flood ($\chi^2 = 144$, $P < 0.01$). *Geocharax falcata* and *G. insolitus* abundances in flooded vegetation declined both post-fire and post-flood ($\chi^2 = 247.5$, $P < 0.01$; $\chi^2 = 342$, $P < 0.01$, respectively), but in floodplain wetlands, *G. falcata* only declined after the fire, and not after the flood ($\chi^2 = 78.4$, $P < 0.01$). *Gramastacus insolitus* abundances in floodplain wetlands declined after the fire and then increased again following the flood ($\chi^2 = 468.5$, $P < 0.01$).

DISCUSSION

Impacts of Natural Events on Freshwater Crayfish Populations

Wildfire and drought

The Mt. Lubra wildfire was a large-scale and intense fire that profoundly affected the GNP landscape. It removed significant amounts of terrestrial and riparian vegetation, leading to soil destabilisation and mass movement of eroded sediment and ash into streams via wind and rain (Figure 2). In the GNP, riparian vegetation forms only a very narrow strip along the edges of streams and wetlands. It generally constitutes semi-aquatic vegetation on the moist habitat perimeter, sometimes with the addition of a single canopy-width of trees. Thus, the entire aquatic vegetation and canopy cover of a site can be quickly lost (especially during drought when vegetation is dryer) if it catches alight during fire events. This was observed in post-fire sampling for this study, when almost all sites had their riparian zones burnt and their substrates severely altered by a thick layer of sediment and ash following the wildfire (Figure 2). The sediment layer had the effect of reducing habitat heterogeneity by burying boulders, cobbles and woody debris, simplifying habitats and reducing water depth (especially in the case of stream pools which filled with ash and sediment), thereby also reducing habitat area (Figure 2). An increase in fine sediment is a common finding in studies examining fire effects on aquatic ecosystems (Oliver et al. 2012; Verkaik et al. 2014). Such sediment may also be washed downstream where it may also affect unburnt reaches (Lane et al. 2006; Peat et al. 2005; Oliver et al. 2012).

Previous studies acknowledge that fire and drought are common in freshwater habitats in Mediterranean type climates, but the impacts of each disturbance are often difficult to disentangle (Verkaik et al. 2014). In the present study, pre- and post-fire wildfire sampling was conducted whilst the region was concurrently affected by a long-term drought. So the results represent the impacts of fire together with prolonged drought. The GNP crayfish species studied have exhibited a decreasing trend in abundance since the 2003 – 2005 pre-fire sampling survey. Because of the millennium drought, several sampling sites were drying or dry immediately following the 2006 fires, which probably made survival more challenging for crayfish. The decreasing capture rates across the study period are of concern and the prolonged drying of seasonal water bodies in the GNP (Chester and Robson 2011) will likely present a continuing challenge for crayfish in this region as climate change progresses. This may lead to a continued reduction in crayfish abundances and distributions. As such, it will be important to protect permanent sources of surface water from disturbance (both natural and anthropogenic) in the future to minimise the impacts of drought on freshwater crayfish (Chester and Robson 2011, 2013).

The current study is the first to examine impacts of fire specifically on freshwater crayfish. However, several studies have shown weak effects of fire on other stream invertebrates but most have examined either prescribed burns or less intense fire events than the Mt. Lubra fire (e.g., Bêche et al. 2005; Arkle and Pilliod 2010; Verkaik et al. 2014). Minshall (2003) suggested that intense fires will have larger effects on stream fauna, which has been corroborated by findings following an intense fire in California (Oliver et al. 2012) and another in central Victoria, Australia (Verkaik et al. 2014). In contrast, some authors suggest that wetland invertebrates cope well with a variety of stresses (Beganyi and Batzer 2011) and may show little response to fire compared to stream communities (Minshall 2003). Our findings support this conclusion for *G. falcata*, which typically occurs in seasonal wetland and flooded vegetation habitats and appeared to be least affected by fire. In contrast, *G. insolitus* was recorded at just four of the ten sites where it occurred prior to the fire and was not recorded in the Wannon River Catchment post-fire. These absences may have been partly attributed to the fire, but two sites were also dry during the post-fire surveys (GFW2 and WFW1) making it difficult to assess whether these two populations were impacted by fire. Sites with high abundances of *G. insolitus* post-fire were wetlands and waterways that were damp/wet and had lush green aquatic vegetation and intact riparian zones following the fire, suggesting that these wetlands provide a fire refuge. *Gramastacus insolitus* is a small non-burrowing crayfish commensal with *G. falcata* and *C. destructor* and requires moist burrow environments for aestivation over summer in seasonal wetlands (Johnston and Robson 2009b). Thus, it is not surprising that this species was negatively impacted by the intense mid-summer wildfire, as the heat produced would have dried host crayfish burrows in dry wetlands.

Overall, total post-fire abundances of *E. bispinosus* increased relative to pre-fire sampling for several sites. However, a closer examination of crayfish abundances recorded in the first two post-fire sampling occasions show substantially lower abundances for all crayfish species (but especially *E. bispinosus*) compared to the following two post-fire sampling occasions. The initial decrease in *E. bispinosus* abundance at sites was possibly the result of crayfish mortalities arising from stream sedimentation after the fire, which in-filled crayfish burrows and covered the stream bed rendering it featureless. This would have forced *E. bispinosus* to live and forage in exposed conditions, making them more vulnerable to visual predators. In contrast, the high *E. bispinosus* abundances recorded on the last two post-fire sampling occasions were likely the result of the streamside vegetation having regrown sufficiently to offer protection from visual predators. By this time, the general stream environment and any changes in water quality, possibly would have recovered sufficiently to support higher *E. bispinosus* abundances. It is also likely that sufficient time would have passed for *E. bispinosus* individuals from other sections of the study streams to have moved into and repopulate the study site. Verkaik et al. (2013a) have previously suggested that species with poor mobility and limited dispersal capacity may recover very slowly after fire. This finding may apply to these *E. bispinosus* populations because this species has been previously reported to be restricted to permanently flowing streams with good water quality and it has limited dispersal capacity (Morgan 1983; Johnston 2008). This

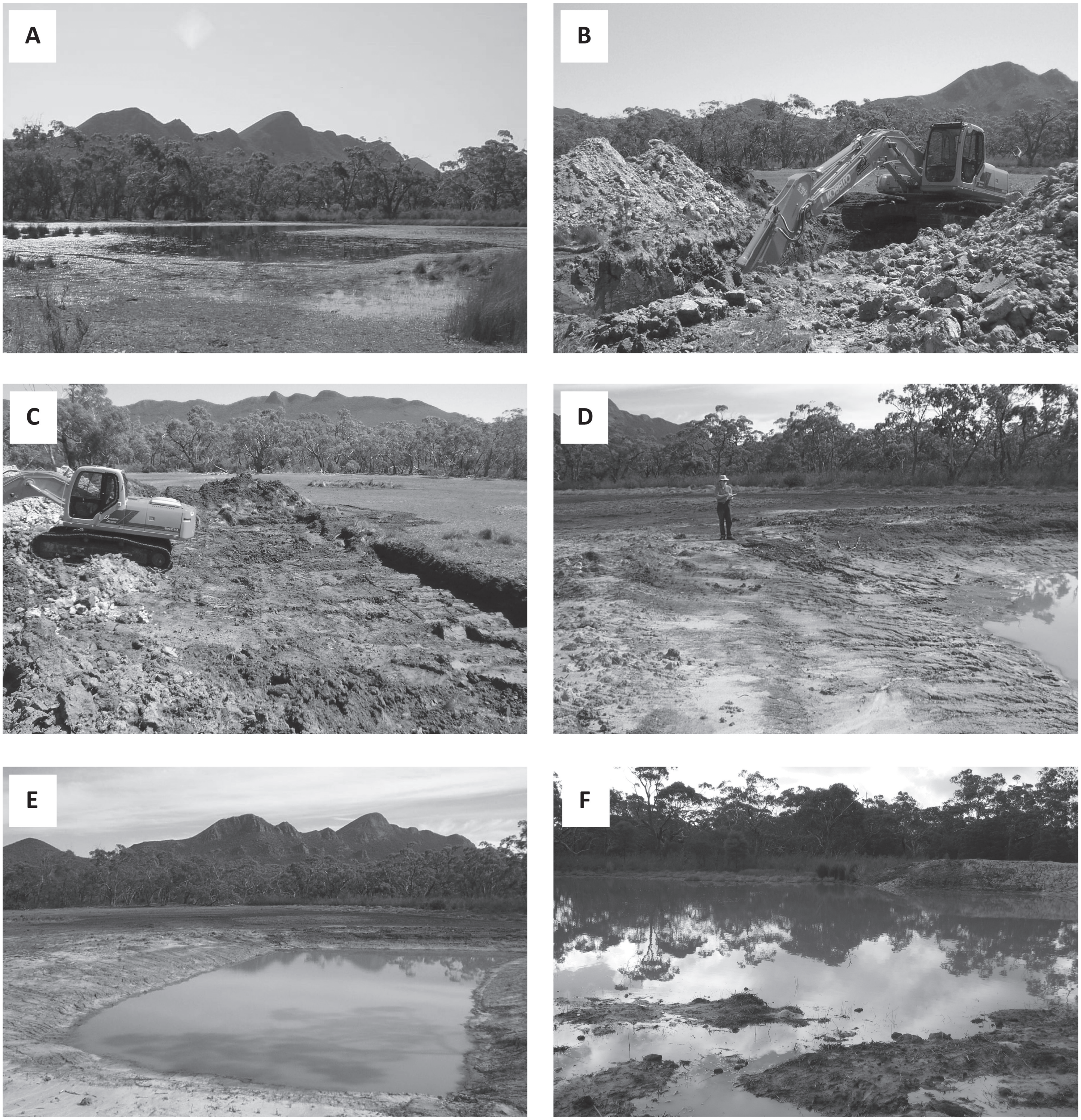

Figure 3. Photographs of site WFW1 before and after fire dam construction. A, an intact WFW1 before fire dam construction; B, photo showing the WFW1wetland being excavated to enlarge the existing adjacent fire dam; C-D, photos showing the extent of WFW1 excavations into the peat layer and the piling up, spreading out and compaction of excavated sediments onto unexcavated part of the wetland; E, the completed fire dam; F, completed fire dam and connected wetland upon first filling by precipitation – note the turbidity of the water and the absence of any aquatic vegetation.

crayfish species is also one of the most narrowly distributed within the GNP and potentially the least flexible with respect to habitat use (Johnston et al. 2011). Therefore, its long generation time, low population density, and relatively low fecundity (Honan and Mitchell 1995) potentially make it more vulnerable to large scale disturbances such as intense wildfires. For example, *Euastacus bispinosus* was particularly abundant at site SC1 (Figure 1) prior to the fire, but no individuals were found there during the first two post-fire sampling occasions. Morgan (1983) suggested that damage to riparian vegetation that causes stream banks to become unstable and slump can influence *E. bispinosus* populations by reducing water quality and availability of undercut banks for burrowing; the Mt. Lubra fire had such impacts. In addition, the smothering of substrate and woody debris by sediment observed after the Mt. Lubra fire (Figure 2) caused sites to become shallow and featureless, while the smothering of woody debris reduced availability of important habitat for predator evasion and foraging. Furthermore, the limited mobility of *E. bispinosus*, together with its restricted distribution, may greatly limit its ability to recolonise sites where local extinctions occur. Therefore, post-fire management efforts that minimise impacts of fire on this threatened species, together with population monitoring, will be important in future conservation efforts.

Flooding

In mediterranean climates, fires are often followed by intense flooding, partly because fires frequently occur in late summer or autumn and are often followed by intense winter rainfall (Verkaik et al. 2013b). The GNP has a near mediterranean climate and the intense flooding that occurred in January 2011, constituted one of the largest floods in recorded history. However, the flooding occurred during summer, when many seasonal wetlands and streams were dry or had low water levels and it caused extensive erosion and movement of sediment and woody debris. This is significant because streams in semi-arid and mediterranean climates usually experience predictable seasonality, with a hot dry summer-autumn and cool wet winter-spring (Hershkovitz and Gasith 2013).

Flood data for the present study were restricted by limited funding, permits and access to the study region, which resulted in two post-flood sampling occasions (Spring 2012 and Spring 2013) following the January 2011 floods. As such, they cannot directly detect the impacts of flooding, not only because of the delayed timing of the sampling but also because of the absence of data collected immediately prior to the flood. However, these data do show some potential indicators of recovery since the 2006 fires.

Post-flood sampling found a statistically significant decrease in crayfish abundance for all species (except for *G. falcata* and *G. insolitus* in floodplain wetland habitats). Also, post-flood, each species was found to occupy substantially fewer study sites than they had either pre- or post-fire. *Cherax destructor* was the most frequently occurring crayfish species in the GNP post-flood, but its abundances were lower than for post-fire sampling, suggesting this species was negatively affected by flooding. This species occurs in all four common aquatic habitats in the GNP, but is particularly common in fire dams (Johnston and Robson 2009a). These habitats are likely more stable environments than seasonal water bodies given that they hold water year-round, which potentially buffers crayfish from both drought and wildfire. *Cherax destructor* is also a very adaptable species, having a wide water temperature tolerance and an ability to persist in waters with low dissolved oxygen and high salinity (Johnston 2008). These traits are beneficial traits for coping with drought and fire impacts. Intense flooding may have particularly affected *C. destructor* in fire dams because these habitats likely over-topped, connecting these habitats to other nearby waterbodies. Dilution, turbidity and increased flow in these normally lentic habitats may explain why *C. destructor* abundances were substantially reduced post-flood and also why it was found at two new sites in post-flood sampling.

While *G. falcata* was found at one new site following the flood, it was also absent from seven sites that it had been recorded at post-fire. It is uncertain why this species showed such variation in abundance and distribution (in some habitats) post-flood, since it is a habitat generalist capable of living in several different habitat types in the GNP (Johnston and Robson 2009a, b). In contrast, *G. insolitus* and *E. bispinosus* appeared to be least affected by flooding, occurring at a similar number of sites in post-flood sampling compared with post-fire sampling. This is possibly because *E. bispinosus* occurs in permanent streams which frequently exhibit considerable differences in flow throughout the year as a result of seasonal change, while *G. insolitus* is adapted to dealing with large fluctuations in water level because it occurs largely in seasonal wetlands that exhibit an annual wetting and drying cycle. There was a possibility that aseasonal large-scale flooding may have triggered a 'false start' in *G. insolitus*, whereby floodwaters interrupt its aestivation period and stimulate it to emerge and continue its life cycle at a disadvantageous time. However, this did not seem to occur in response to the 2011 flooding, since post-flood abundances in wetlands were similar to post-fire abundances. Thus, they were not reflective of the low abundances that would be expected after a false start that caused subsequent large mortalities when wetlands again dried out.

Impacts of Post-event Management Actions on Freshwater Crayfish Populations

Several management actions carried out in the GNP over the eleven year duration of this study were observed to have a direct negative impact on freshwater crayfish and their habitats. However, we acknowledge that these are qualitative observations and that further research is required into the impacts of these actions on GNP freshwater crayfish populations.

Construction of fire dams

Prior to the Mt. Lubra fires and the winter 2006 pre-fire sampling occasion, one Wannon River catchment flooded vegetation site (WFW1), was substantially altered by ground works using heavy machinery (Figure 3). This work partially excavated this wetland where previously the highest abundances of *G. insolitus* and *G. falcata* in the GNP had been recorded. This work was carried out to enlarge a small fire dam directly adjacent to this site by approximately ten times its original size. This meant that around one fifth of the wetland was also excavated and much of the remaining wetland surface had excavation tailings deposited upon it. During this work, burrows that *G. falcata* had dug down to the water table to facilitate its survival during summer drying were buried, and also affected the commensal *G. insolitus*. This work was likely the main reason why no *G. falcata* (and few or no *G. insolitus*) were captured at this site in either of the post-fire or post-flood sampling. Ground compaction reduces burrowing activity by crayfish (March and Robson 2006), so compaction caused by heavy machinery may have directly impacted these crayfish populations. This construction work also reduced the cover and types of aquatic vegetation present, and these changes are still evident eight years post-disturbance. Reduced *G. insolitus* abundances were likely also associated with the reduced abundance of their preferred vegetation types at this site, and their replacement by more opportunistic and disturbance tolerant plant species, because *G. insolitus* is entirely herbivorous (Johnston et al. 2011). The extended period of drying that this wetland has experienced during the millennium drought will have restricted the post-fire recovery of *G. insolitus* populations since seasonal wetlands like this one were inundated less frequently, and for a shorter duration, affecting its summer survival rates. In another example, a completely new fire dam was created at a flooded vegetation site in the Scrubby Creek catchment (SFV2) between the post-fire and post-flood sampling. This is one of the few remaining sites at which *G. insolitus* occurs in the southern and central GNP. Post-flood sampling similarly revealed greatly reduced abundances of *G. insolitus* at this site after construction was completed. In the future, fire dam construction should aim to minimize disturbance to sensitive seasonal wetlands and instead, be constructed at some distance from them or preferably pre-existing fire dams that are not associated with seasonal wetlands, should be enlarged to hold extra water capacity.

Bridge and road building

Bridge and road building can greatly alter aquatic habitats and the crayfish occurring in them. After the Mt. Lubra wildfire and 2011 floods, many road sections and bridges were destroyed (particularly wooden bridges) and required replacement. While no information exists in the literature on the effects of bridge and road building on freshwater crayfish (or other aquatic fauna), one particular road and bridge construction event in the GNP indicates that these activities can negatively impact crayfish populations. After the Mt. Lubra wildfire, a new bridge (and associated road) was constructed at a Glenelg River channel site. This site is one of only five sites in the GNP that the threatened *E. bispinosus* is known to occur in reasonable numbers (Johnston and Robson 2009a). The work compacted the surrounding soil and removed sections of the riparian zone to accommodate a larger bridge. Also, the remaining road-building gravel was spread around the bridge base and into the stream beneath the bridge. The removal of riparian vegetation reduced stream shading, while the spreading of gravel reduced the available cover for crayfish from visual predators, by filling in undercut banks. The river also became shallower. For the first two post-fire fieldtrips following bridge construction, no *E. bispinosus* were captured at this site. This species requires good water quality and access to undercut stream banks and woody debris and are largely intolerant of environmental change (Johnston 2008), so it is not surprising that this species was impacted by these activities. Also, the loss of riparian vegetation and shallower water may have elevated stream temperatures above those tolerable for *E. bispinosus*. Therefore, where freshwater crayfish are present in river channels adjacent to roads and/or bridges, consideration should be given to construction methods (particularly after other large disturbances which may have already affected crayfish populations and their habitats) and left over building materials should be removed from sites, rather than being spread out around and into aquatic habitats.

Flow regulation

Water extraction for human use is particularly common in first to third order streams in semi–arid and mediterranean climate zones (Gasith and Resh 1999), and may lead to perennial streams becoming intermittent or, at the very least, prolonging dry periods in intermittent streams (Mackie et al. 2012). This process might increase fire impacts on crayfish aestivating in dry streambeds. The GNP region contains numerous water extraction points and reservoirs that alter stream flow regimes causing substantial negative impacts on algae, fish and invertebrates (e.g., Robson et al. 2008; Robson and Mitchell 2010; Chester et al. 2014). Many of these impacts are associated with recolonization and movement processes of the biota, because weirs used for water extraction act as barriers to movement both directly and by creating sections of dry streambed immediately downstream (Mackie et al. 2012; Chester et al. 2014). Although another GNP study (at a different group of streams) showed that another species of *Geocharax* was resilient to drought and flow regulation (Chester et al. 2014), this resilience was founded on the ability of this species to rapidly build aestivation chambers in stony streambeds. The species of crayfish found in the present study do not share this ability, and channel-dwelling species such as *E. bispinosus* might not be equally able to both resist drying and recolonise locations after disturbance when their movement is blocked by weirs. Thus, water regulation and constructed barriers to flow may have a negative impact on the capacity of crayfish populations to recover from extreme events by preventing dispersal. Further research is needed into the impacts of barriers and water regime regulation on crayfish movement and response to extreme events.

CONCLUSIONS

This study has demonstrated the potential impacts of flooding and wildfire in combination with long-term drought on freshwater crayfish distribution and abundance. The frequency and intensity of wildfires, drought and intense flooding are predicted to increase across southeastern Australia (CSIRO 2007; Nyman et al. 2011) as the region moves further towards a mediterranean or semi-arid climate. Similar trends are already occurring in other areas with dry mediterranean climates, such as Spain, where fire events are occurring more frequently, often followed by intense flooding (Verkaik et al. 2013a). This study detected lower crayfish abundances, both after wildfire and flooding, and at sites both modified by construction work and not affected by construction work. Although the effects of extreme events were depended on species and habitat type, the construction work, clearly served to compound the negative impacts on crayfish at the sites they were conducted. *Euastacus bispinosus* abundances in streams declined both post-fire and post-flood, possibly because of the changes to stream habitat availability and quality. *Cherax destructor* also exhibited large declines in abundance in all habitats post-flood but especially in fire dams, which was potentially related to the effects of flow in occurring in these typically lentic habitats. *Geocharax falcata* and *G. insolitus* abundances declined in flooded vegetation post-fire and post-flood, possibly because these habitats are very temporary and were completely dry at the time of both the Mt. Lubra fire and 2011 flood, thus enhancing the impacts of these events.

However, *G. insolitus* in floodplain wetlands showed decreases in abundance post-fire (as did *G. falcata*) but increased in abundance post-flooding, which was likely because fire would have dried out the crayfish burrows where these species were aestivating. However, flooding had little impact on *G. insolitus* populations in floodplain wetlands due to the seasonal nature of these habitats and this species' adaption to the normal annual wetting and drying cycle of these wetlands. Finally, the general trend of decreasing crayfish abundances across the GNP region over the eleven year study period is of concern. Although the reasons for this remain unclear, it is likely strongly associated with the shrinking of available habitat during the millennium drought, compounded by wildfire, flooding, and in some cases the reconstruction activities necessitated by wildfire and flood damage. Future management activities in national parks and other landscapes where crayfish are present need to minimise physical disturbance to aquatic habitats (particularly seasonal wetlands) to facilitate recovery of crayfish populations after extreme events.

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