Journal of Fish Biology (2007) **71,** 182–199
doi:10.1111/j.1095-8649.2007.01481.x, available online at http://www.blackwell-synergy.com

Fate of 2 year-old, hatchery-reared trout cod *Maccullochella macquariensis* (Percichthyidae) stocked into two upland rivers

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(Received 16 June 2006, Accepted 13 February 2007)

Radio-tracking was used in monitoring the reintroduction of on-grown 2 year-old trout cod *Maccullochella macquariensis* (Percichthyidae) (a nationally endangered freshwater fish) in both a large and small upland river. Thirty-six radio-tagged *M. macquariensis* were stocked into a site in each of the Murrumbidgee and Cotter Rivers (Australian Capital Territory). Restricted dispersal occurred in both rivers, with both samples of *M. macquariensis* remaining within 5 km of the release site for the duration of the study. Mortality was rapid and 1 month after release 61 and 31% of the sample was alive in the Murrumbidgee and Cotter Rivers, respectively. In the Murrumbidgee River, complete mortality had occurred 6 months after release. An individual survived in the Cotter River until 7 months after release. Predation by cormorants *Phalacrocorax* spp. and predation or scavenging by the common water rat *Hydromys chrysogaster* were the probable causes of mortality. Predator-assisted movement of radio-tags by cormorants occurred in both groups and had the potential to confound interpretation of active dispersal movements.

Key words: dispersal; *Maccullochella*; mortality; predation; radio-tracking; stocking.

INTRODUCTION

Radio-tracking has been used as a method for monitoring the short to medium-term success of hatchery-reared fishes stocked into rivers, in particular salmonids in the Northern Hemisphere (Jepsen *et al.*, 1998; Aarestrup *et al.*, 2005). This approach enables rates of mortality and dispersal to be quantified, facilitating adaptive management of fisheries (Aarestrup *et al.*, 2005) or threatened species recovery (Skalski *et al.*, 2001). There is scope for similar application in Australia, namely as part of reintroducing threatened freshwater cod of the genus *Maccullochella*.

The trout cod *Maccullochella macquariensis* (Cuvier) is one of four freshwater cod taxa in Australia [also Murray cod *Maccullochella peelii peelii* (Mitchell),

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Mary River cod *Maccullochella peelii mariensis* Rowland and eastern freshwater cod *Maccullochella ikei* Rowland], all of which are nationally threatened. Prior to the 1970s only one cod species (Murray cod) was recognized, with *M. macquariensis* formally described in 1972 (Berra & Weatherley, 1972). Recovery programmes have been in place for several years for three of the cod species, with a recovery plan currently being prepared for the fourth (*M. p. peelii*). *Maccullochella macquariensis* is a large species (maximum size 16 kg and *c.* 850 mm total length, L_T) that occupies a range of habitats including pools, riffles and runs but is usually associated with deeper water and instream cover such as logs and boulders (Douglas *et al.*, 1994; Ingram & Douglas, 1995; Growns *et al.*, 2004). *Maccullochella macquariensis* was formerly widespread in the southern Murray–Darling Basin, occurring mainly in the lowlands but recorded at *c.* 800 m altitude in the Murrumbidgee River. Sexual maturity is reached at 3–5 years of age with spawning occurring in spring. Like all of the freshwater cod species in Australia, *M. macquariensis* act as top and even apex predators, probably structuring fish communities historically (Ebner, 2006). The range and abundance of *M. macquariensis* has declined dramatically in the last 50 years, with the species now only known from three self-sustaining populations, two of them a result of historical translocations. The specific reasons for the decline are unknown, but are likely to be related to increased river regulation, impacts of alien fish species, overfishing and habitat modification (Douglas *et al.*, 1994; Ingram & Douglas, 1995).

For two decades conservation stocking of fingerling (*c.* 30–50 mm L_T) *M. macquariensis* has been conducted in the Murray–Darling Basin, in an effort to establish new self-sustaining populations (Lintermans & Phillips, 2005). There have been few signs of success from these stockings, presumably as a function of stocking insufficient numbers of fingerlings, poor release strategies and high post-release mortality (Brown *et al.*, 1998; Bearlin *et al.*, 2002; Todd *et al.*, 2004), however, stocking success has never been thoroughly assessed. Generally, fish populations suffer greatest natural mortality in early life-history phases (Jones, 1991) and this presumably applies to *M. macquariensis* (Todd *et al.*, 2004). Subsequently, stocking fish at more advanced stages than as fingerlings has been modelled and proposed as an alternative strategy (Todd *et al.*, 2004).

Freshwater percichthyids have been radio-tracked in Australia for two decades primarily to determine their movement and habitat-use (Koehn, 1997; Crook *et al.*, 2001; Simpson & Mapleston, 2002; O'Connor *et al.*, 2005). In these studies, high survivorship has been recorded or assumed, although, there have been cases of failing radio-tags, mortality and indeterminate status (Crook *et al.*, 2001; O'Connor *et al.*, 2005). Only recently, however, has radio-tracking been used to monitor releases of hatchery-reared threatened fishes in Australia. This has involved: 1) examining the suitability of techniques for radio-tagging *M. macquariensis* based on a 4 month aquarium trial ($n = 9$) and 2) radio-tracking small numbers of on-grown *M. macquariensis* following release at a single site in the lowlands of the Murrumbidgee River and in the Cotter River (an upland tributary of the Murrumbidgee River, in the south-eastern part of the Murray–Darling Basin) (Ebner *et al.*, 2006; B. Ebner, C. L. Johnston & M. Lintermans, unpubl. data). These two studies have

revealed retention of individuals to release sites or downstream dispersal, and poor survivorship. The finding of downstream dispersal is comparable with that from the more comprehensive literature based on hatchery-reared salmonid releases (Bettinger & Bettoli, 2002).

Large rivers have generally been the targets of *M. macquariensis* re-stocking programmes (Douglas *et al.*, 1994; Brown *et al.*, 1998). The annual production of *M. macquariensis* fingerlings in government hatcheries, however, is low (relative to recreational angling species; Gilligan, 2005; Lintermans *et al.*, 2005; Lintermans, 2006). This only allows small stockings of *M. macquariensis* that are unlikely to become established (Todd *et al.*, 2004). One alternative is to stock greater numbers of fingerlings at a site (Bearlin *et al.*, 2002; Todd *et al.*, 2004) and possibly to use a small river where there would be less dilution of *M. macquariensis* at the site and monitoring of survivorship could be more effective. A second alternative (mentioned earlier) is to stock fewer, larger individuals (Todd *et al.*, 2004). This approach has an empirical basis since the only definitive evidence of a self-reproducing population based on reintroducing *M. macquariensis* came from translocating an unknown number of individuals to Cataract Dam around 1914 (Harris & Rowland, 1996) and <150 large (*i.e.* greater than fingerling size) individuals into Seven Creeks in the 1920s (Douglas *et al.*, 1994). Evidence is emerging that fingerling stocking programmes have resulted in successful wild spawning of the species at some sites (Douglas & Brown, 2000; King *et al.*, 2005) but the establishment of self-sustaining populations remains elusive.

The aim of the current study was to compare dispersal and survivorship of 2 year-old, hatchery-reared *M. macquariensis* released into a large and a small upland river.

METHODS

SITE DESCRIPTION

The study was located in two rivers, the Cotter and Murrumbidgee Rivers, in the upper Murrumbidgee River catchment in the Australian Capital Territory (ACT), Australia (Fig. 1). A single site was selected on each of the rivers for the release of 2 year-old, hatchery-reared *M. macquariensis*. The Cotter River is an upland stream dominated by short riffle-run-pool sequences, with the release site, the Spur Hole (148°53′ E; 35°22′ S) (600 m altitude), situated *c.* 10 river km upstream of Cotter Reservoir. Mean ± S.E. annual discharge (1988–2005) is 63 ± 11 Gl. The Cotter River previously drained a well-vegetated catchment dominated by native vegetation in the upper reaches and plantations of pine in the lower catchment; however, bushfires in 2003 burnt much of the catchment, resulting in losses of riparian cover and increases in water turbidity (Carey *et al.*, 2003). The release site consisted of a 25 m long and 8–12 m wide pool, with water depth extending to 1·4 m, representing a typical pool for this river. During the study period discharge ranged from 12 to 1011 M l day^{-1} and water temperature was 10·3–29·6° C. The Murrumbidgee River within the ACT comprises long, deep, gorge pools interrupted by short riffles, with in-stream habitats dominated by bedrock and sand. Mean annual discharge (1977–2005) was 328 ± 59·6 Gl. The release site, Pine Island (149°04′ E; 35°26′ S) (540 m altitude), consisted of a 400 m long pool, of 20–60 m width and maximum water depths of 11 m. Discharge ranged from 4 to 1940 M l day^{-1} during the study and water temperature was 14·1–31·7° C.

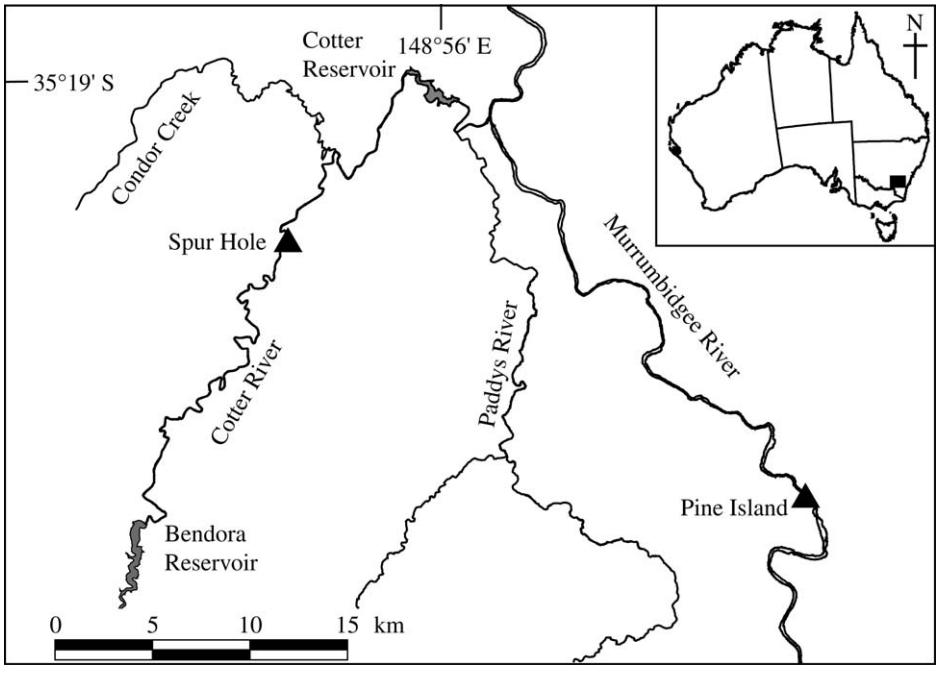

FIG. 1. Location of the release sites (▲) on the Cotter and Murrumbidgee Rivers in the Australian Capital Territory, Australia.

SURGERY AND IMPLANTATION OF RADIO-TAGS

Seventy-two on-grown, hatchery *M. macquariensis* (2 years of age, 330–424 mm L_T; 0·518–1·178 kg; first generation, bred from Murray River broodstock) were obtained from the Snobs Creek Research Station in Victoria. Initially post-larvae were reared in a fertilized earthen pond under semi-natural conditions. After harvesting the pond, fingerlings were transferred to hatchery facilities where they were weaned onto an artificial pellet diet, then on-grown in 500 l circular fibreglass tanks that were part of an intensive recirculating aquaculture system. Methods used for fry rearing, weaning and on-growing were similar to those employed for Murray cod, which are described in more detail by Ingram (2004).

The radio-tags used in this study were internal body implants with a 30 cm trailing whip antenna, models F1820 (8 g), F1830 (11 g), F1835 (14 g) and F1850 (25 g) [Advanced Telemetry Systems (ATS), Isanti, MN, U.S.A.] and were obtained without mortality switches based on projected fish body masses at the time of purchase. Each individual was implanted with a radio-tag of $\leq$2% of its body mass. Two-stage radio-transmitters were used on a frequency of 150–152 MHz and programmed on a duty cycle of 5 s on and 7 s off to increase battery life. The minimum warranty for battery life of radio-transmitters ranged from 175 to 504 days depending on radio-tag size. Frequency drift was not encountered despite checking for its occurrence prior to surgery and following release.

Radio-tags were inserted from 27 to 28 September 2004 under anaesthesia. Individuals were anaesthetized using 0·5 ml Alfaxan (Jurox, Rutherford, Australia) per litre of water. A 2 cm ventro-longitudinal incision was made into the peritoneal cavity along the ventral line anterior of the anus and posterior to the pelvic fin base. A modified cannular was used to exit the aerial of each radio-tag from the anterior of the caudal peduncle. The incision was closed with two or three sutures, and the temporary skin

adhesive Vetbond (3M, St Paul, MN, U.S.A.) was applied and given *c.* 20–30s to dry. An intra-muscular injection of the antibiotic enrofloxacin (Baytril) was administered at 0·1 ml kg^{-1}, immediately posterior of the nape. For external identification individuals were tagged with a dart tag between the second and third dorsal spines. Individuals were allowed to recover in a darkened enclosure holding 200 l of well-aerated water at 5 parts per thousand NaCl. The dentary was held to open the mouth, permitting the flow of aerated water from a power head over the gills, until an individual was clearly breathing independently. Time required for surgery (mean ± S.E.) was 5·2 ± 0·1, 15·2 ± 0·5 and 5·9 ± 0·3 min to achieve total anaesthesia, conduct surgery and perform recovery, respectively. Water temperature at the time of radio-tagging was 18·1–24·0° C.

Fish were held for an observation period of 2–3 days and on 30 September 2004 all 72 individuals were anaesthetized with 2 ml per 100 l clove oil, and transferred by bucket into two separate 2000 l water containers (mounted on a truck, and aerated with oxygen). The two samples, each containing 36 individuals, of comparable L_T (*t*-test, d.f. = 70, $P > 0{\cdot}05$) and mass (*t*-test, d.f. = 70, $P > 0{\cdot}05$) were transported from the Snobs Creek Research Station (Victoria) to the ACT (a 6 h journey). Upon arrival at each release site, samples were again anaesthetized (*c.* 2 ml per 100 l clove oil) and transferred by bucket to a 250 l container at the river edge. River water was bucketed into the container sporadically over 30–40 min to revive *M. macquariensis* from anaesthesia and acclimate them to river water. Late in the afternoon on 30 September 2004, 36 individuals were released at both Pine Island on the Murrumbidgee River and the Spur Hole on the lower Cotter River. Monitoring independent of this study demonstrated that sufficient prey resources (primarily small fishes and *Macrobrachium australiense* Holthuis) were available at and within close proximity to both release sites (unpubl. data).

Four underwater and two above-stream video cameras were deployed at the release site in the Cotter River (before: 14 September; during: 30 September to 4 October; after: 21 October 2004) to investigate both initial intraspecific and interspecific interactions. To maximize the chances of filming such interactions, all fish were released at a single location in each river, resulting in higher than natural densities of released fish. Filming during and after release, however, proved largely unsuccessful as a consequence of high turbidity arising from rainfall and sediment runoff. Therefore, the results and discussion of the filming component of this study are not expanded upon here and are provided elsewhere (Ebner *et al.*, 2006).

RADIO-TRACKING

A two-person crew undertook manual radio-tracking surveys weekly for the first 2 weeks, fortnightly for the first 3 months and monthly thereafter. Radio-tracking was conducted on foot or in a 3 m aluminium punt (powered by an 8 hp outboard motor), by directly positioning over the top of a radio-transmitter or where this was not possible by triangulating. Individuals were located during daylight hours using a scanning receiver (Australis 26k; Titley Electronics, Ballina, Australia, or R4100, ATS) and a three-element Yagi antenna (Titley Electronics or ATS). The location of each individual was recorded by obtaining three waypoints with a hand-held GPS [Garmin GPSII Plus or Garmin GPS 76 Marine Navigator; Figure of merit (F.O.M.) $\leq 5{\cdot}0$ at about 95% of locations, F.O.M. $\leq 7{\cdot}0$ at 100% of locations]. Where individual transmitter frequencies could not be detected in the study area by ground crews, a light aircraft with wing-mounted Yagi antennas, was used to search the river corridor and surrounding areas. This occurred six times throughout the study and involved searching a 100 km stretch of the Murrumbidgee River (all radio-tags were accounted for in the Cotter River). When an individual was located by the aircraft, a ground crew was sent within 24 h to obtain a more accurate location. At the end of the study, an additional aircraft tracking exercise was conducted to exhaustively search for missing radio-tags in the Murrumbidgee River (and tributaries), covering >250 km of river.

DATA ANALYSIS

GPS records were averaged to provide a single spatial location of each individual per radio-tracking fix. Spatial data were plotted in GDA94 format in ArcView 3.2™ (ESRI, Redlands, CA, U.S.A.) over a base-map. A polyline was generated based on the sequential locations of each individual using the Animal Movement Extension in ArcView (Hooge & Eichenlaub, 1997) and used to construct a time series of the distance moved between consecutive radio-tracking intervals. Polyline distances were calculated along a river midline. Where small to medium-scale movements took place between consecutive radio-locations, the line generated by the animal movement path extension was 'snapped' to the river midline vertices in ArcMap™. Where large-scale movement of an individual was detected, the segment of river midline between two points was measured by converting this line to a shape file and running an area and perimeter update using the ArcView 3.2™ X-Tools Extension. On occasions when individuals were not located they were assumed to have been stationary at their next known location and this potentially resulted in underestimates of movement.

MORTALITY, RADIO-TAG REJECTION AND MISSING FISH

Where an individual was recorded in the same location on consecutive occasions or was in a dubious location (*e.g.* extremely shallow water with no cover), attempts were made to startle it. If this produced no movement of the individual, attempts were made to locate the radio-tag using a modified gap-loop antenna (accuracy *c.* 10 cm) (Titley Electronics) and then retrieve it by snorkelling. Where radio-tags or fish remains were retrieved, signs of predator or scavenger involvement (*e.g.* common water rat *Hydromys chrysogaster* Geoffroy burrows and cormorant *Phalacrocorax* spp. guano] were recorded. In the event of locating a whole carcass, an autopsy was conducted. An individual was also considered to have undergone mortality in cases where a radio-tag was repeatedly found at a location, the radio-tag could not be retrieved (*e.g.* in deep water), the individual was not startled and movement was not detected by 4 h radio-tracking over a diel period. These cases were not considered to represent radio-tag rejections, and reasoning for this is provided at the beginning of the discussion section. The number of days at large was calculated based on the last recorded movement of an individual. Where mortality occurred, the distance moved from a previous location may have been a result of active transport by a predator.

RESULTS

MOVEMENT AND DISPERSAL

Maccullochella macquariensis moved small distances in both rivers and remained close to the release sites (<3 km) for the duration of the study (Fig. 2). At 1 month post-release the majority of the sample in the Murrumbidgee River was located immediately upstream of the release site within the release pool. The majority of the sample in the Cotter River remained immediately downstream of the release site, however, a few individuals had begun to disperse downstream in each river [Fig. 2(a)]. Similar patterns were observed at 3 months post-release, with the exception of an upstream (<1 km) movement in the Cotter River [Fig. 2(b)] made by an individual. The number of radio-tracked individuals had decreased considerably by the 3 month stage. At 6 months post-release a single survivor was being radio-tracked in the Cotter River and was located immediately downstream of the release site [Fig. 2(c)]. No survivors remained in the Murrumbidgee River 6 months after

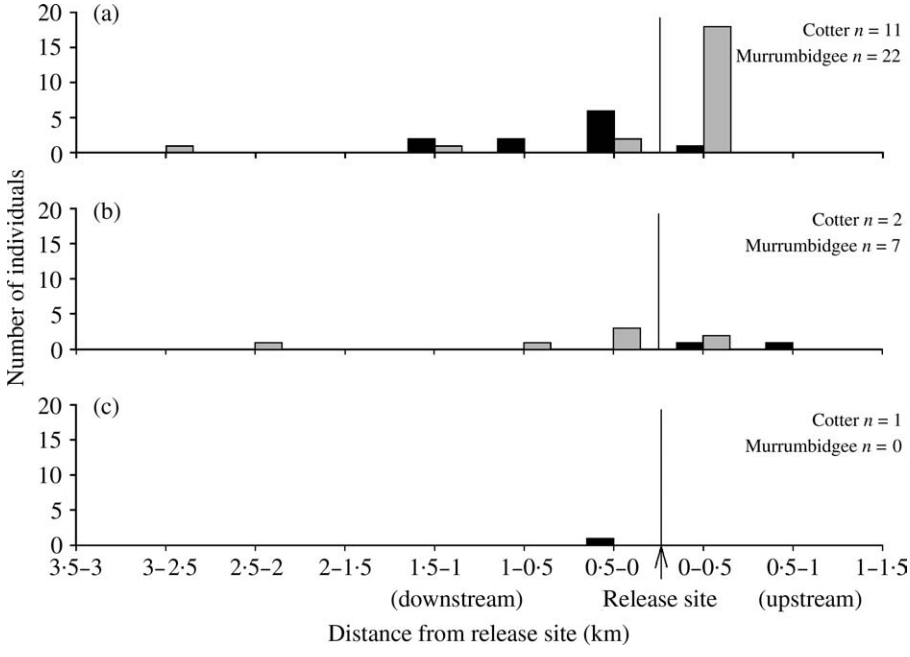

FIG. 2. Dispersal of *Maccullochella macquariensis* released in the Cotter (■) and Murrumbidgee (□) rivers at (a) 1, (b) 3 and (c) 6 months after release. Sample size at each time period is indicated.

release [Fig. 2(c)]. Dispersal distance was not related to body size in relation to the sample released in either the Cotter or Murrumbidgee rivers (Pearson correlation, both $P > 0{\cdot}05$).

MORTALITY AND RADIO-TAG REJECTION

This study identified 100% mortality or radio-tag rejection of *M. macquariensis* released into the Cotter River at the end of 7 months of radio-tracking (Table I). In the Murrumbidgee River, 86% of the sample were accounted for by mortality or radio-tag rejection by 7 months post-release (Table I). The remaining 14% of the sample were not expected to have comprised individuals that had actively emigrated from the study area as confirmed by radio-tracking from a plane. The fate of these individuals was attributed to predator assisted emigration (or predators destroying radio-tags) or radio-transmitter failure (Table I).

Survivorship was significantly prolonged in the Murrumbidgee River relative to the Cotter River (Mann–Whitney *U*-test, $P < 0{\cdot}05$, $n = 72$) (Fig. 3). Eleven individuals were alive 1 month after release in the Cotter River [Fig. 3(a)]. Survival continued to decline, with seven individuals alive after 2 months, two individuals alive after 3 months and one individual alive after 4 months. The latter survived for 6–7 months at which stage its radio-tag was recovered onshore. In the Murrumbidgee River, 22 individuals survived for at least

TABLE I. The mean ± S.E., total length (L_T), mass and subsequent fate of radio-tagged *Maccullochella macquariensis* following release at two sites in the Murrumbidgee and Cotter Rivers, Australian Capital Territory. Numbers of individuals are in parentheses

Group	n	L_T (mm)	Mass (g)	Radio-tag failure or predator assisted emigration (%)	Mortality or radio-tag rejection (%)
Cotter	36	363 ± 3·6	759 ± 26·8	0	100 (36)
Murrumbidgee	36	365 ± 3·9	767 ± 28·4	14 (5)	86 (31)

1 month after release at which stage survivorship continued to decline [Fig. 3(b)]. Two months after release 15 individuals were alive. There were no survivors 6 months after release.

Evidence for cause of mortality was more commonly found in the Cotter River than in the Murrumbidgee River. In the Cotter River three intact specimens were recovered, 19 individuals or radio-tags had evidence relating to

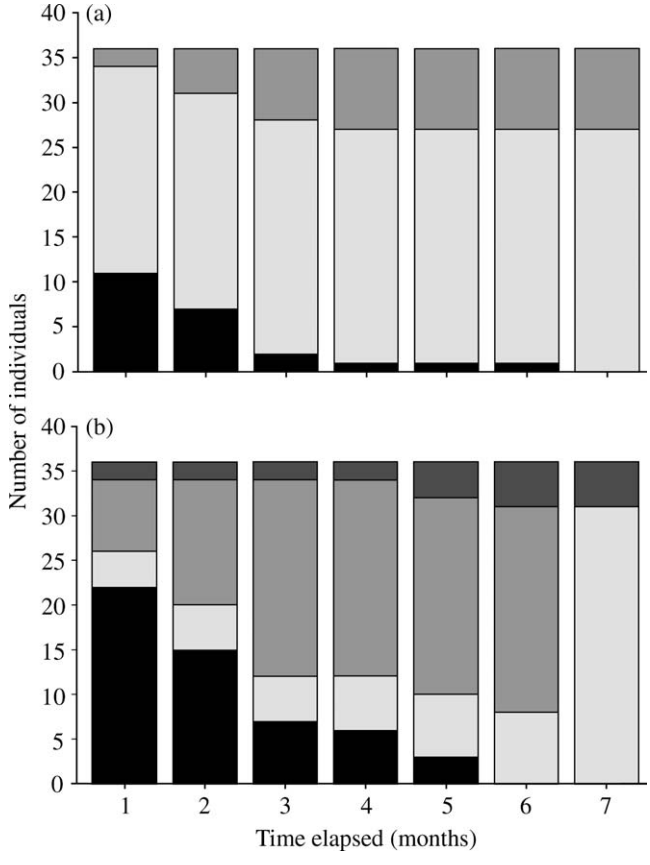

FIG. 3. Fate of *Maccullochella macquariensis* released in the (a) Cotter River (b) Murrumbidgee River for the duration of the study, represented as: alive (■), failed radio-transmitter or predator-assisted emigration (■), suspected mortality or radio-tag rejection (■), and confirmed mortality or radio-tag rejection (□).

direct predation or scavenging and 14 individuals were linked to radio-tag rejection or mortality (however, carcasses were not recovered) (Table II). In the Murrumbidgee River, of the 31 individuals without radio-tag failure or predator-assisted emigration, two intact specimens were recovered, five individuals or radio-tags had evidence relating to direct predation or scavenging and 24 individuals were classified as radio-tag rejections or mortality (Table II).

In the Cotter River, individuals surviving for <2 weeks were predominantly located or recovered in a large gorge *c.* 1 km downstream from the release site [Fig. 4(a)]. At 2–4 weeks after release, the terminal locations of six individuals were in Cotter Reservoir, 10–12 river km downstream from the release site. A specimen was also recovered from Condor Creek, a major tributary of the Cotter River. The majority of survivors were located close to the release site or downstream in the gorge. A radio-tag was also located in Cotter Reservoir at >4 weeks after release.

Three intact specimens were recovered from the Cotter River (at 1, 2 and 4 weeks post-release), <2 km downstream of the release site, and autopsy did not reveal the cause of death [Fig. 4(b)]. The specimens showed no signs of predation or scavenging, with healing of surgery wounds underway and no evidence of infection. Two individuals had empty stomachs and one had fish vertebrae in its stomach. All seven terminal locations in Cotter Reservoir were attributed to direct predation or scavenging [Fig. 4(b)], thought to be by cormorants, probably great cormorants *Phalacrocorax carbo* (L.). The remaining individuals that had been predated or scavenged [Fig. 4(b)] were located immediately downstream of the release site in a gorge. Fourteen individuals represent unidentified mortality or potential radio-tag rejection and were categorized by stationary radio-tags [Fig. 4(b)] located within close proximity to the release site.

Evidence of predation in this study came from the identification of strike-marks on specimens that were not consumed. Evidence of predation or scavenging included multiple radio-tags found under trees, *e.g. Casuarina cunninghamiana* Mique, where cormorants frequently perched in groups, and chewed radio-tags or retrieved radio-tags in or near common water rat *H. chrysogaster* burrows along the riverbank. Direct observations of predation or scavenging were not made in this study; however, multiple observations of live *M. macquariensis* were made in the early stages of the study, confirming initial survival of some individuals. At least five individuals were probably consumed by *H. chrysogaster* in the Cotter River. Of these, two were located in the gorge downstream of the release site, with the remaining three located in close

TABLE II. The number of *Maccullochella macquariensis* assigned to the categories: specimens recovered intact, stationary radio-tag and direct predation or scavenging (at the end of the study, 7 months post-release). Numbers of individuals are in parentheses

Group	Intact specimen (%)	Stationary radio-tag (%)	Direct predation or scavenging (%)
Cotter ($n = 36$)	8 (3)	39 (14)	53 (19)
Murrumbidgee ($n = 31$)	7 (2)	77 (24)	16 (5)

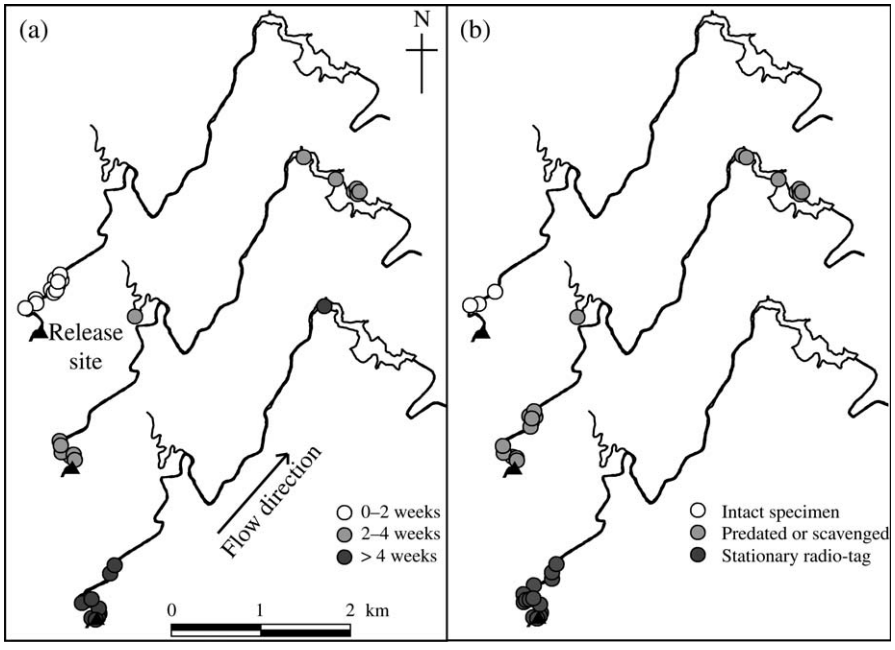

FIG. 4. The terminal locations and number of *Maccullochella macquariensis* released in the Cotter River, represented as (a) the time from release until mortality or tag rejection and (b) the fate of individuals. Note that large distances moved probably resulted from transport by avian predators.

proximity to the release site. Indirect evidence indicates that 12 individuals were killed or scavenged by cormorants in the Cotter River. Four of the seven radio-tags located in Cotter Reservoir were recovered <10 m apart under a tree commonly frequented by cormorants. Three radio-tags were recovered from the downstream gorge <2 weeks after release under a large tree in a large pile of avian guano with a scattering of fish bones and skin. Additionally, two individuals were recovered as partially intact specimens; however, the type of predator or scavenger could not be identified.

In the Murrumbidgee River, the terminal location of most individuals was within the release pool or immediately downstream [Fig. 5(a)]. The last individual survived for 5–6 months, with its radio-tag recovered 6 months post-release, 84 km downstream from the release site near Burrinjuck Reservoir. This radio-tag was recovered under a cormorant perch in water <50 cm deep, in a section of river devoid of instream structural habitat.

A single intact specimen was retrieved from the Murrumbidgee River at 4 and 5 months post-release, respectively. Both had healed surgical incisions and showed no signs of infection. One of these individuals was recovered onshore, 4 river km downstream from the release site (and its previous location) [Fig. 5(b)] following a high flow event. The cause of mortality was unknown in both cases; however, no signs of predation or scavenging were evident. Five individuals were killed or scavenged in the Murrumbidgee River and did not represent radio-tag rejections. Three of these were attributed to cormorants. One radio-tag was recovered from a *H. chrysogaster* burrow in the

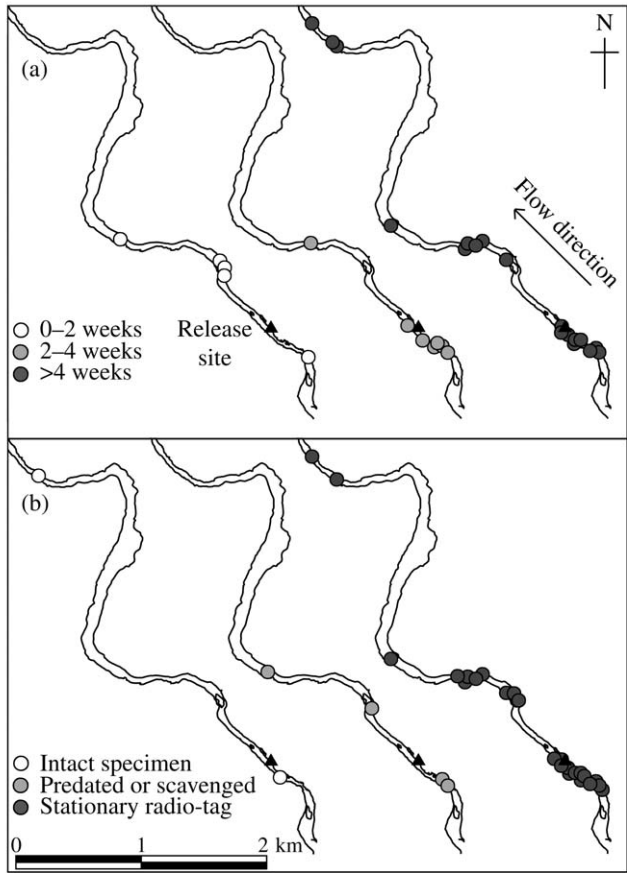

FIG. 5. The terminal locations and number of *Maccullochella macquariensis* released in the Murrumbidgee River, represented as the (a) time from release until mortality or tag rejection and (b) fate of individuals. Note that distance moved may have resulted from transport by avian predation. The final location of a radio-tag recovered 84 km downstream from the release site is not shown.

release pool. In one case, a carcass exhibited signs of predation or scavenging, however, the type of predator or scavenger was not evident. Twenty-three of the remaining 24 individuals were confirmed to either be mortalities or have rejected a radio-tag based on retrieval of radio-tags or a total lack of movement following radio-tracking at 4 h intervals over a diel period. Additionally, an individual was assigned to the mortality or radio-tag rejection category after the radio-tag had been repeatedly located in a position in shallow water and efforts to retrieve the radio-tag were unsuccessful (presumably the radio-tag was buried).

The capacity to distinguish mortality from radio-tag rejection was lower in the Murrumbidgee than the Cotter River. This difference was attributed to the Murrumbidgee being a larger, deeper and more turbid river, decreasing the opportunity to recover radio-tags and carcasses, and reducing the possibility for visual confirmation of survivors.

DISCUSSION

POSSIBLE REJECTION OF RADIO-TAGS

Rejection of radio-tags is considered unlikely in the current study despite frequent recovery of radio-tags and repeated confirmation of stationary radio-transmitters at locations. A number of lines of evidence support this contention. Five intact specimens, including three from the Cotter River and two from the Murrumbidgee River had retained radio-tags and showed good healing of surgical incisions. An aquarium trial including a 4 month observation period post-surgery demonstrated the suitability of this species to radio-tag implantation (B. C. Ebner, L. Johnston & M. Lintermans, unpubl. data) and comparable results have been achieved by others (S. Nicol, pers. comm.). It should be acknowledged that whilst these aquarium trials provide an indication that the species is suitable for radio-tagging, potentially important biotic (*e.g.* competitive interactions) and abiotic factors (*e.g.* stream flows) may have been overlooked under controlled conditions. Radio-tag rejection has been reported for some hatchery-reared individuals prior to release and was almost certainly a function of re-opened surgical incisions following sutures tearing through the abdominal wall in response to substantial fat deposits and an enlarged abdomen in a previous study (Ebner *et al.*, 2006). In contrast, *M. macquariensis* were not rounded and laden with fat deposits in this experiment. The length of surgical incisions was also greatly reduced in the current study in comparison with Ebner *et al.* (2006) (*c.* 1·5–2 cm, reduced from 3 to 3·5 cm). Inspection prior to release revealed excellent healing and no radio-tag rejection. Furthermore, *Maccullochella* spp. have been successfully radio-tagged *in situ* (Koehn, 1997; Simpson & Mapleston, 2002). Based on the assumption that rejection of radio-tags was not occurring in the current study, limited dispersal and high mortality in both small and large upland rivers were the major outcomes of releasing hatchery-bred *M. macquariensis*.

DISPERSAL

Conclusive evidence of large-scale movement or dispersal by live *M. macquariensis* was not obtained in the current study (Fig. 2). Radio-tags found substantial distances from release sites (>5 km) were probably the result of transport by avian predators (Figs 4 and 5). Rapid mortality may largely explain the lack of large-scale dispersal in the current study relative to that reported from another release of on-grown *M. macquariensis* (Ebner *et al.*, 2006).

In the current study dispersal was on small-scales, typically occurring at tens to hundreds of metres and less frequently kilometres (Fig. 2). Patterns of dispersal were characterized by retention to release sites and small-scale downstream dispersal. This retention to release sites has also been demonstrated for *M. macquariensis* when released as fingerlings (Faragher *et al.*, 1993; Douglas *et al.*, 1994). Retention to the release site is largely in agreement with releases of hatchery-reared salmonids (Bettinger & Bettoli, 2002). There was more substantial downstream movement and dispersal on the scale of kilometres, however, in a previous study of *M. macquariensis* (B. C. Ebner, L. Johnston & M. Lintermans, unpubl. data), and particularly in a larger lowland river

(Ebner *et al.*, 2006). Rapid mortality considerably reduced the opportunity for dispersal to occur in the current study, however, the role of stream morphology in contributing to this reduced dispersal may also warrant consideration. The only other study of *M. macquariensis* movement in upland rivers (B. C. Ebner, L. Johnston & M. Lintermans, unpubl. data) involved larger fish (388–511 mm) than that of the current study. It is unknown whether the different stream morphology of upland rivers (short pool, riffle and run sequences as opposed to long reaches of pool-type habitat in lowland rivers) may influence dispersal behaviour. For example, do mesohabitats such as shallow and fast-flowing rapids or riffles provide some constraint to ordinary ranging behaviour in these large-bodied fishes?

MORTALITY

Mortality principally occurred within 2 months of release. This is comparable with the fate of 2 year-old hatchery-reared *M. macquariensis* released into the Murrumbidgee River at a lowland site (Ebner *et al.*, 2006), although, difficulties with ascertaining the precise time of death were pronounced in that study. In contrast, high survivorship was reported for wild *M. macquariensis* over the entire 13 months of that study (Ebner *et al.*, 2006) and in a prior study in the Cotter River there was complete survivorship of large hatchery-reared *M. macquariensis* ($n = 8$) over the first 4 months post-release followed by complete mortality 4–9 months post-release (B. C. Ebner, L. Johnston & M. Lintermans, unpubl. data).

A number of differences among these studies provide potential explanation for the observed differences in the rate of survivorship of hatchery-reared *M. macquariensis* (excluding the issue of radio-tag rejection which was dealt with earlier). Whilst size at release can be an important determinant of survivorship (Brown & Day, 2002), it is unlikely to be the reason for different rates of survivorship among studies of on-grown *M. macquariensis* (Ebner *et al.*, 2006; B. C. Ebner, L. Johnston & M. Lintermans, unpubl. data; current study). There is considerable overlap in the size distribution of samples in each of these trials. Additionally, the previous Cotter River study (B. C. Ebner, L. Johnston & M. Lintermans, unpubl. data) made use of a 4 month holding period following surgery and fed live crayfish *Cherax* spp. prior to release. In contrast, *M. macquariensis* were released into the wild 3 days after surgery in the current study and 1–2 weeks after surgery in Ebner *et al.* (2006). Prolonged survivorship in a previous study (B. C. Ebner, L. Johnston & M. Lintermans, unpubl. data) may be due to the full recovery from surgery afforded under aquarium conditions (*e.g.* improved healing of incision and opportunity to overcome any initial infection) or the absence of anaesthesia used in the final step of moving fish from the transport vehicle to the stream. Further, the opportunity to recognize, capture and handle live prey during grow-out in farm dams and in aquaria may have been advantageous (Brown & Day, 2002; Thorpe, 2004), whereas, in the current study and that of Ebner *et al.* (2006) hatchery-reared *M. macquariensis* were fed a pellet diet.

The seasonal timing of release also differed among these studies of *M. macquariensis* (Ebner *et al.*, 2006; B. C. Ebner, L. Johnston & M. Lintermans,

unpubl. data; the current study), and studies of hatchery-reared salmonids indicate time of release to be an important determinant of survival (Cowx, 1998). The previous liberation of hatchery *M. macquariensis* involved a release in mid–late summer (B. C. Ebner, L. Johnston & M. Lintermans, unpubl. data), whereas, releases were conducted in early–mid spring in the current study and that of Ebner *et al.* (2006). It is possible that factors relating to time of year, for instance annual cycles of suitable prey availability, influence rates of survivorship. In terms of prey availability in the Cotter River, the abundance of the resident fish fauna [principally *Gadopsis bispinosus* Sanger and *Oncorynchus mykiss* (Walbaum)] was especially low in this study and the previous Cotter River study (unpubl. data) as a result of a catastrophic bushfire event in January 2003 (Carey *et al.*, 2003). There was, however, a high abundance of large *Macrobrachium australiense*, ideal prey for *M. macquariensis* (Baumgartner, 2007) in the first few months following release in the previous study, though, not in the current study (pers. obs.). The fish fauna remained relatively intact in the Murrumbidgee River following the bushfire event (unpubl. data) and therefore decreased prey availability does not provide an explanation for the death of the released *M. macquariensis* at that site. It would certainly be useful to develop an understanding of the feeding ecology of *M. macquariensis* following release through further study. To this end, investigation of survival of fish that have received different levels of training in feeding on live prey prior to release is warranted (Brown & Day, 2002; Thorpe, 2004).

Larger fish were released in a previous study in the Cotter River (B. C. Ebner, L. Johnston & M. Lintermans, unpubl. data) relative to the current study. Larger size can correspond to increased protection from predators (Hyvärinen & Vehanen, 2004). The habitat conditions in the Cotter River were also somewhat different in the earlier study, with the catchment in the very early stages of recovery from the 2003 bushfires. As such, turbidity was higher for extended periods (weeks) after rainfall events, potentially affording more cover to fish. By the time of the release of fish in the current study, the supply of sediment from the catchment had reduced substantially as vegetation cover re-established.

The Murrumbidgee River in the ACT is historically more turbid than the Cotter River, with a lower proportion of the catchment burnt, and the severity of the fire reduced in comparison to that of the Cotter catchment (Carey *et al.*, 2003). The Murrumbidgee River, however, has suffered from excess sedimentation for decades as a result of gully erosion and channel incision in the upper catchment (Eyles, 1977; Prosser *et al.*, 2001; Olley & Wasson, 2003). As a consequence, much of this coarse eroded material is stored in the channel, and is reworked with every large rainfall event. This coarse sediment has severely degraded pool habitats in the Murrumbidgee River in the ACT, severely reducing substratum diversity, one of the major sources of cover for fishes in upland rivers (Lintermans, 2002, 2005). As a result of this loss of substratum complexity in the Murrumbidgee in the ACT, coupled with the general scarcity of in-stream structural woody habitat resulting from riparian degradation, refuges for sub-adult fish are likely to be suboptimal (though still capable of supporting populations of the congener *M. p. peelii*). Lack of cover coupled with the potential naivety of hatchery-reared *M. macquariensis* may have contributed

to high mortality of released fish. Habitat rehabilitation and reduction of densities of the potential competitor *M. p. peelii* are factors that warrant attention in future reintroductions of *M. macquariensis*.

In this study, mortality and rejection of radio-tags accounted for 100 and 86% of *M. macquariensis* released into the Cotter and Murrumbidgee Rivers, respectively. In the Murrumbidgee River, it is possible that the remaining 14% of the sample was the result of avian or human-assisted (illegal take by anglers) emigration from the study area. Certainly the finding of a radio-tag 84 km downstream of the release site along the Murrumbidgee River is indicative of avian predators acting as a vector on a large-scale (Marchant & Higgins, 1990) and at the limits of detection capabilities. Furthermore, the high dependability of radio-tags manufactured by ATS supports the argument that the 14% of missing radio-tags was related to transport or destruction by avian predators or anglers.

Cormorants and to a lesser extent common water rats, were the primary predators or scavengers of *M. macquariensis* based on available evidence in this study. Of the 72 individuals released, cormorants (probably *P. carbo*) and common water rats were associated with at least 15 and six cases, respectively. It is likely that these are underestimates and it is acknowledged that the present approach was incapable of detecting in-stream predation by *M. p. peelii* in the Murrumbidgee River (*M. p. peelii* does not occur in the Cotter River). A number of radio-tags were recovered long after mortality had taken place based on the condition of specimens and movement data, and a large number of radio-tags were never recovered (*e.g.* from deep water) thus precluding an opportunity to conduct autopsies and reach a conclusion regarding the cause of death. Therefore, more frequent radio-tracking (*e.g.* daily) should be incorporated into future studies, at least in the first 2 months post-release. Ensuring hatchery-reared fish are of a sufficient size to receive radio-tags fitted with mortality switches is also recommended.

Phalacrocorax carbo is an effective piscivore capable of feeding on even larger fishes than the *M. macquariensis* released in the current study (Marchant & Higgins, 1990). A study of *P. carbo* in south-eastern Australia revealed that fish comprised in excess of 80% of the diet, and those taken by cormorants exceeded the commercial and recreational harvest (Coutin & Reside, 2003). Coutin & Reside (2003) recommended that cormorant predation be taken into account in stock enhancement programmes. The results of the current study certainly support that recommendation. *Hydromys chrysogaster* has also been found to prey upon fishes comparable in size to that recorded in the current study (Woollard *et al.*, 1978) and avian and mammalian predators have had significant impacts on other hatchery-reared fishes released into the wild (Derby & Lovvorn, 1997; Dieperink *et al.*, 2001; Aarestrup *et al.*, 2005). There are also a number of additional mechanisms that could account for the mortality of *M. macquariensis* in this study, including predation or competitive exclusion by *M. p. peelii*, capture by anglers or succumbing to disease. A better understanding of predator effects and avenues for enhancing the release of hatchery-reared *M. macquariensis* into rivers (Griffin *et al.*, 2000) should be incorporated into recovery of this species. To this end, progress towards successful reintroduction of *Maccullochella* spp. should be achieved by pre-training

hatchery-reared fishes, discerning their ecology upon release into the wild and adopting an experimental approach to releases that relates survivorship to management options.

This research was funded by the Fisheries Research and Development Corporation, Parks, Conservation and Lands (ACT Government) and New South Wales Department of Primary Industries with additional contributions from Victorian Department of Primary Industries, Cooperative Research Centre for Freshwater Ecology, Murray–Darling Basin Commission, the Arthur Rylah Institute for Environmental Research, RECFISH Australia, NSW State Water and the Department of Infrastructure, Planning and Natural Resources. B. Broadhurst and L. Johnston provided assistance with surgery. B. Broadhurst, M. Jekabsons, L. Johnston, K. Ryan and K. Watson assisted with radio-tracking. M. Dunford provided GIS support. Staff at the Snobs Creek Research Station, including P. Boyd, B. Ingram and P. Ryder reared fish and provided support. This research was conducted under authorization (CEAE 04/11) from the Committee for Ethics in Animal Experimentation, University of Canberra. D. Gilligan, B. Ingram, K. Frawley and four anonymous referees improved the manuscript. This research was conducted in Ngunnawal Country.

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