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Review

Indirect Consequences of Recreational Fishing in Freshwater Ecosystems: An Exploration from an Australian Perspective

Shelley Burgin

School of Health and Science, Western Sydney University, Locked Bag 1797, South Penrith Distribution Centre, Penrith 2751, Australia; sburgin@westernsydney.edu.au; Tel.: +61-7-55621129

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Abstract: Recreational fishing in freshwater ecosystems is a popular pastime in Australia. Although most native fish are endemic, the fauna is depauperate compared to any landmass of similar size. With commercial fishing no longer a major industry in the country's freshwaters, the future sustainability of these ecosystems will depend heavily on the actions of recreational fishers. However, there has been limited focus on the consequences of recreational fishing in freshwaters. There is particularly a dearth of information on the indirect consequences of fishers on the waterbodies they depend on for their sport. After outlining the respective trends in commercial and recreational fishing in Australia as a basis for placing the sport in context, the indirect impacts of fishers on water quality, movement (walking, off-road vehicles), the introduction/translocation of fauna (particularly fish), the dispersal of flora and the transmission of fish disease and pathogens are reviewed. It is concluded that with the decline of commercial fishing, the competition between commercial fin-fishing and recreational fishing is negligible, at least throughout most of the country. It is also concluded that each of the issues addressed has the potential to be detrimental to the long-term sustainability of the freshwater ecosystems that the fishers depend on for their recreation. However, information on these issues is scant. This is despite the current and predicted popularity of freshwater recreational fishing continuing to increase in Australia. Indeed, there has been insufficient quantitative assessment of the impacts to even determine what is required to ensure a comprehensive, adequate and representative protection of these freshwater ecosystems. To underpin the sustainability of inland recreational fishing in the country, it was concluded that research is required to underpin the development and implementation of appropriate policies. The alternative is that the integrity and biodiversity loss of these ecosystems will ultimately result in their collapse before the indirect consequences of recreational fishing have been directly assessed and appropriately protected. However, the lack of protection of wetlands is not restricted to Australia; there is a deficit of freshwater protected areas worldwide.

Keywords: angling; commercial competition; inland wetlands; boating; water quality; off-road vehicles; fishermen wading; wetland integrity; fish translocation; disease and pathogen transmission

1. Introduction

The Australian native freshwater fish fauna (including diadromous species) is depauperate [1–4]. It comprises substantially fewer than 300 species, the smallest number of any similar-sized landmass [3,5]. Effectively all native freshwater fishes are endemic to the continent, largely because the continent has been completely separated from other landmasses for approximately 37 million years [6]. While many native species are known to be in decline [7–9], the details are often nebulous since, as the Action Plan for Australian Freshwater Fish [10] acknowledges, there is much subjectivity associated with the data. That is because there is limited available information on many species and particularly those that do not have a direct commercial or recreational value.

One of the potential impacts on the sustainability of freshwater native fish is recreational fishing. For example, in an Australian nationwide survey [11], it was estimated that AUD$1.8 billion was spent annually on the sport, and in a country with a population of approximately 24 million [12], effectively 20% of 'Australian residents' (≥5 years of age) participated in recreational fishing at least once within the year-long period of the survey. Of these, approximately 20% fished in freshwater ecosystems and 35% in estuarine habitats where diadromous species may also be encountered during their residence of estuaries [11].

Over the survey, the reported fish haul included more than two million feral European carp *Cyprinus carpio*, and this represented the greatest number of any species. Over one million of another introduced species, redfin (or European perch) *Perca fluviatilis*, were caught in equivalent numbers to the native golden perch *Macquaria ambigua* and in considerably greater numbers than the introduced trout/salmon taxon (Salmonidae; 824,558). All other species were caught in much lower numbers (≤280,612) [11]. These data indicate that introduced freshwater fish species make up a substantially greater proportion of the recreational fish catch than native species, undoubtedly a reflection of comparative species abundance, at least in preferred fishing areas.

Despite this substantial recreational fishing effort, previous publications of the ecological impacts of recreational activities in Australia [13–18] have tended to focus on terrestrial environments and not freshwater ecosystems, although there are exceptions (e.g., [19–24]). The consequences of the introduction of non-native fishes [25–29] and the potential impacts of climate change [30–34] have been more thoroughly addressed.

Some of this research would have incidentally encompassed attributes of the environmental consequences that arise from recreational fishing, for example recreational impacts on soils and vegetation (e.g., [13,16,35]), including trampling by recreationists [22,23,36,37], and off-road vehicle use [13,38,39]. Instream recreational impacts are generally least understood [40–42], despite their disproportionate importance as focal points for recreation [41,43]. However, research focused on the impacts of recreational fishing has received relatively scant attention, although there are exceptions (e.g., [42–44]).

The lesser interest in the consequences of recreation on aquatic ecosystems than in the terrestrial environment may be because changes are less immediately obvious [35,36], and threshold stress levels are often difficult to define and measure [45,46]. This is particularly problematic when a specific activity (e.g., boating) is used for multiple recreational activities, and thus, the proportional contribution to degradation caused by one activity (e.g., recreational fishing) may be masked by the cumulative impacts. For example, in addition to recreational fishing, lakes may be used for kayaking, sailing, water-skiing and swimming [35,47,48], all of which entail boating. An additional complication is that fishing may be water and/or shore based [48,49].

Within the Australian context, there has been some explicit consideration of the direct consequences of freshwater recreational fishing [4,11,50], particularly associated with over-fishing [4,10,50]. However, more generally, the sport's impacts (e.g., fishing pressure, including selectivity and associated evolutionary change, trait-mediated effects, size structure of the population, age truncation, catch-and-release fishing, bycatch [42]) tend to be species specific. In contrast, the indirect impacts of recreational fishing tend to be more generic. This is because the sport often incorporates activities that are shared with non-recreational fishers (e.g., boating, off-road driving [35,47,48]) with indistinguishable differences in impact. Consequently, a focus on the indirect consequences of recreational fishing will provide a better understanding of a broader range of outdoor recreational activities than recreational fishing alone. However, despite the substantial interest in recreational fishing in Australia [11], the indirect impacts associated with Australian freshwaters have not been reviewed, and related reviews that have been published do not generally directly focus on recreational freshwater fishing (e.g., freshwater biodiversity [47]; salinity [51]). This paper reviews such impacts with a focus on Australian recreational fin-fishing in freshwater ecosystems. It commences with a brief comparison of recreational and commercial fin-fishers of freshwater ecosystems to place the sport in an Australian context. This is followed by a consideration of the indirect impacts of recreational fishing in freshwater ecosystems: infrastructure effects on water quality; impacts from walking tracks, off-road vehicles and boating; overland dispersal of non-native plants; disease and pathogen transmission; and non-native fish species. The paper concludes with comments on the priorities for further management to underpin sustainable management to support recreational fishing.

2. Competition between Commercial and Recreational Fishers in Inland Waters

Commercial fishing is commonly considered to be a major reason for the decline of global fish stocks [52]; however, in Australian freshwater ecosystems, commercial fishing is no longer a major industry. Arguably, the exception is the harvest of eels. The most widely-targeted eel species are the long-finned *Anguilla reinhardtii* and short-finned *A. australis*. They are fished commercially, at least, in Queensland [53], New South Wales [54] and Victoria [55], while in Tasmania, only short-finned eel is available in commercially-viable numbers [56]. Eels may be trapped under licence, either as elvers and small eels for 'stock enhancement' or netted as adults (e.g., Victoria [57], Queensland [58]).

Overall, however, the commercial production of eels is low. For example, in Victoria, in the last financial year with comprehensive data available (2010–2011), the auction price of eels at the Melbourne Fish Market (a major Australian outlet) represented <1% of the total fishery's production (5.6% of combined teleost/chondrichthyan production) [59]. The eels would have been auctioned as chilled fish, and the sales are therefore considered to represent local demand. In Queensland, 'almost all' commercially-sold eels are exported live to Asia [58]. However, this represents a very modest catch since Australia overall provides <1% of the world's commercial eel take, while fewer than 1000 adult eels were harvested annually between 1977 and 1999, and the indigenous fishers' catch represented 0.05% of the number of 'organisms' collected in the same period. By 2001, there had been a decline in 'speculative interest' in eel aquaculture [60], and there does not appear to have been a resurgence of interest subsequently.

These data demonstrate the lack of interest in eels as a table fish in Australia. Another indication that eels are not targeted by Australian recreational fishers is that approximately 85% of all recreational fishing in inland waters is based on angling (i.e., rod and line fishing) [11], and all commercial eels are netted [56,58,59]. There is thus no evidence that there is competition between commercial and recreational fishers for eel in Australia.

Except for the commercial eel harvest, most Australian states have limited (or no) inland commercial fishing. For example, there are no explicit provisions for commercial fishing in freshwater ecosystems of the Northern Territory (see, e.g., [61]), Tasmania (see, e.g., [62]) or Queensland (see, e.g., [53,63]), or at least there is no emphasis on inland commercial fishing. For example, in 2002, the Victorian government bought out all extant inland commercial fisheries' licences (except eel licences) [64], while all commercial fishing in Western Australia is associated with a single constructed wetland, Lake Argyle [65]. In New South Wales, the freshwater commercial fishing operation has been reduced to a small 'restricted fishery'. Indeed, since 2001, there has been a deliberate redirection of the inland fin-fish fishery away from native species to greater dependence on the introduced European carp, albeit that change has been largely driven by concern for the decline of native fish stocks and the opposition to commercial operations focusing on the species preferred by recreational fishers [54]. However, overall, Australia's fisheries, including the aquaculture industry, produce <2% of the global supply, and the focus of the export industry is on high unit value products (e.g., tuna, unfrozen lobster, abalone, crayfish) [66], generally not products of inland freshwater ecosystems.

Even such scant data indicate that competition between recreational and commercial fishers in inland waters is limited. Indeed, apart from Western Australia where the overlap would be in Lake Argyle, the only state where there may be a substantial overlap between recreational and commercial fishers is in the 'Lakes and Coorong multiple-species fishery' of South Australia.

Furthermore, including marine and estuarine resources, this fishery is a 'community-based', small-scale, multi-species fishery shared between recreational and commercial fishers. The South Australian Government acts as 'custodian' to ensure ecologically-sustainable usage of the fishery [67]. Within the freshwater lakes of the fishery, commercial fishers target golden perch, bony bream *Nematalosa erebi* and the introduced European carp and redfin perch [68]. In contrast, the preferred species of recreational fishers are mulloway *Argyrosomus japonicas*, yelloweye mullet *Aldrichetta forsteri* and black bream *Acanthopagrus butcheri*, with both mulloway and black bream having 'very high' (>70%) catch and release rates [69]. Despite the high release rates on mulloway, however, greater restrictions on recreational fishing of the species in the Coorong will have been introduced in late 2016 due to concern for this fishery [70]. Despite the changes being implemented, because of the differences in target species, the competition between commercial and recreational fishers for particular fin-fish species would appear to be negligible.

3. Recreational Infrastructure Effects on Water Quality

3.1. Impacts of Effluent Discharge

Sewage effluent, including detergents and/or chemical toilet discharge from shore-based recreational facilities, campsites and/or houseboats, is arguably the most extensive pollutant associated with aquatic recreational activities [20,71]. The proportion of such discharges specifically associated with recreational fishing activities is, however, generally an unknown fraction of the total discharge [20,35]. Concentrations of pollutants are also usually low except where there is restricted flow, malfunction of equipment, including overflow of systems, and/or specific recreation infrastructure developments [20]. However, the potential for indirect impacts on recreational fishing is demonstrated by the observations that may be gleaned when effluent is released into an impoundment. For example, Donnelly et al. [72] reported that sewage effluent discharged into a shallow oligotrophic 'billabong' (approximately 1.6 m in depth) initially resulted in nitrification, and this was followed in succession by collapse of the wetland's macrophyte communities and ultimately increased prevalence of algal blooms over approximately a 15-year period. Such anthropogenic changes typically have a substantial impact on aquatic fauna [73,74], which may be exacerbated when endocrine disrupting compounds are released in human effluent [75–77], even with tertiary treatment [78,79].

3.2. Impacts from Walking

For walking tracks, when developed informally, are poorly designed and constructed, not maintained or overused (a typical scenario where informal tracks have developed), their surface will continue to deteriorate over time [80]. In such situations, sediment is typically delivered to a catchment's freshwater ecosystems [81], resulting in instream changes in sediment loads [82,83], potentially destroying native aquatic ecosystems [82].

The informal walking tack to access Claustral Canyon (Greater Blue Mountains World Heritage Area (GBMWHA)) provides an example of the erosional impacts within an otherwise wilderness setting. Discovered in 1961, the canyon had only 'pioneering visits' before canyoning gained momentum in the area in the 1990s [84]. Ultimately, it became the most popular canyoning destination in the region [85,86]. No reliable visitor numbers are documented for this canyon; however, early in the 2000s, at the height of canyoning popularity, across 13 canyons (not including Claustral Canyon, but other popular canyons), it was estimated from Hardiman and Burgin [84] that annually, there were fewer than 5500 visits (11,000 passes made by canyoners). Claustral Canyon visitation is assumed to be somewhat less than this estimate.

Over its history, the entrance track to Claustral Canyon became badly eroded, particularly on the four steepest slopes ($\leq$1.5 m deep). In places, the track had also expanded to 2 m in width. The ultimate destination of this eroded material is the canyon [85,86]. However, despite the aesthetic impact of the erosion, the calculated lifetime soil loss from the track was estimated to be approximately

220 million cm^2, less than estimated to be delivered in a single rainfall event immediately after bushfire [85]. While the extent of damage from such tracks varies due to the level of use, the physical characteristics of the landscape, deterioration, often irreversible (e.g., increased depth - trenching, gullying; widening, 'quagmire development', braiding, duplication), will continue without intervention [87]. While such erosion is typically worst on slopes, in more open areas, 'dense footpath networks' may be developed by anglers moving along a wetland's banks [88].

Preparation for angling also often results in physical damage that leads to erosion. For example, to gain access to a desirable angling site, deliberate (or inadvertent) modification of the vegetation may occur. Once on-site, anglers may further clear and/or modify the wetland's bank to improve the angling experience, for instance to allow for greater ease of casting [88]. The level of use of a site influences the consequences. This is reflected in a study [89] that compared differences between 'high' and 'low' use angling sites. In high use sites, the percent of bare earth, soil compaction, terrestrial and aquatic macrophyte density and the height and diversity of vegetation were all significantly impacted compared to low use sites. Shore-line angling thus altered the riparian environment.

Wading associated with instream angling also has indirect consequences on the associated ecosystem. The impact of fly-fishing, used to target salmonids, has apparently not been investigated in Australia. However, Roberts and White [90] reported such impacts, including fishing for two salmonid species (brown trout *Salmo trutta*, rainbow trout *Oncorhynchus mykiss*) that were introduced to Australia explicitly for recreational fishing [91,92]. There was a significant difference in egg and larvae development where anglers waded, although the extent of damage depended on developmental stage. However, with only twice-daily wading, up to 96% of eggs and pre-emergent fry were destroyed [90].

Some of the consequences of wading may, however, be subtle and within natural environmental fluctuations. For example, in the wilderness canyons of the GBMWHA, simulated canyoner trampling showed no discernible effects on macroinvertebrate assemblages at visitation levels of between unvisited and 100 tramples/day for seven days [22]. Similarly, compared to the numerically much larger changes due to natural rainfall fluctuations, only modest microbiological impacts were observed in rainforest streams due to hikers swimming [93]. However, evidence that such changes may occur over time with increasing recreational use is reflected in the observation that over approximately a decade (1990–1999), planktonic chlorophyll *a* concentrations were significantly increased in the dune lakes of Fraser Island (Australia), although total phosphorus concentrations were variable (similar to higher concentrations) [94]. Urination by swimmers also increased nutrient levels, and concern associated with the use of sunscreens, soaps and detergents by swimmers. Potential changes in the chemical structure of the lake due to human use were considered sufficient for park management to ban the use of such products in the lakes [94–96].

4. Impacts of Off-Road Vehicles

Off-road vehicles including sports utility vehicles (SUVs) and motorised trail bikes also potentially pose an environmental risk to freshwater ecosystems and the sustainability of recreational fishing. For example, terrestrial impacts in coastal areas, especially physical disturbance from the use of such vehicles, may increase soil erosion, reduce vegetation cover and destroy habitat, all leading to enhanced erosion [97–99].

Although research on the effects of off-road vehicles on freshwater ecosystems is scant, they are recognised to exert substantially higher stress on terrestrial ecosystems than human trampling and horse riding [39]. It has also been suggested [100] that the effects of walking and biking will slowly increase over time relative to that of motor vehicle use of an area. One quantification of these differences indicated that, on average, a single vehicle pass was equivalent to 10 foot passes with the greatest impact occurring at the initial phases of track formation. It was also suggested that, compared to motor vehicles, the impact of walking and biking increased slowly over time. However, Buckley [101] noted that the impact of off-road vehicles was dependent on the 'how and where' they were operated. He suggested that if they were driven on roads or tracks that were not well formed, the impacts could include changed overland water flow, destruction of vegetation and, thus, soil erosion. Although his discussion was confined to the consequences for terrestrial environments, previous researchers [81,82,88] have suggested that such tracks could cause substantial instream changes due to erosion. Off-road vehicles could, therefore, deliver indirect impacts to recreational fishing especially when used near the water's edge, for example when associated with the movement of watercraft and/or trailers and other paraphernalia [102].

5. Impacts of Boating

A major indirect impact of recreation (including recreational fishing) in freshwater ecosystems is associated with boating [102]. For example, particularly in restricted areas, the movement of boats may be detrimental to fry [103] and disrupt invertebrate communities [102], thus ultimately modifying the productivity of the fish assemblage. This is because juvenile swimming performance, in particular, may be affected in the presence of 'bank-directed navigation-induced physical forces'. In restricted areas, such as shallow impoundments of a relatively small size (typical of many creeks and impoundments of Australia), bank wash from boats along the shoreline, especially adjacent to boat launching sites, may cause substantial erosion [102] and, thus, impact flora and fauna [102–105].

Even the most benign recreational boating activity, canoeing, may disrupt (or eliminate) benthic invertebrates in the littoral zone [48], for example by dislodging them and thus, for example, increasing drift and/or clogging respiratory structures with suspended sediment. Power boats, particularly, may cause 'far-reaching' erosional damage to the shoreline even away from the immediate impact area [102]. The impacts are also likely to increase in parallel with growth in leisure time [20,101,106], wider affordability and new technologies [20,87,107] as diverse as equipment made from lighter weight synthetic fabrics [107] to communication equipment (e.g., cellular and digital telephones, GPS) [87,107].

Despite the substantial impacts of recreational boating on aquatic species [102,103,108] and personal observations of propeller strikes on fish, data specifically related to freshwater recreational fishing are scant. However, some indication of the consequences may be gleaned from studies of recreational boating and/or boating more generally. For example, in freshwater tidal reaches of James River (Virginia), the carcasses of all Atlantic sturgeon *Acipenser oxyrinchus oxyrinchus* with identifiable cause of death had injuries consistent with boat strike [109]. It was concluded, however, that unless noise modified the behaviour of fish (which may be the situation [110]), 'small recreational boats' would not typically be responsible for the death of such fish [109]. Justification for this suggestion was that sturgeon predominantly remained within a metre of the substrate. However, several Australian native species targeted by recreational fishers (e.g., golden perch; Australian bass *Macquaria novemaculeata*) are pelagic [111] and, thus, more vulnerable to boat strike. This is reflected in the observations of Bennett and Litzgus [112]. They reported that across several species of freshwater turtle (animals that are active throughout the water column), between 12.8% and 48.5% of those sampled had injuries consistent with propeller strike. They also noted that whether water flow was fragmented due to dams/locks or in unobstructed reaches, turtles had similar injury rates. These data indicate that fish, particularly pelagic fishes, suffer boat strike whether in impoundments or rivers.

In addition to physical impacts, Whitfield and Becker [113] noted that pressure waves due to boats may affect fish shoal dynamics. One reason for this is that shoaling fish emit 'complex and overlapping sound and pressure curves' [114], and in addition, their sense organs may be 'highly sensitive' to pressure changes [114,115]. Fish also rely on pressure waves created by the shoal, which play a role in alarm, distress signalling [116] and spawning [117]. Fish also respond to sound [118–120] and produce it [121,122], for example during swimming, at least within shoals [123,124] and during spawning [125–127]. Pressure waves and noise emitted from boats are, therefore, likely to interfere with social behaviour, including communication [110], orientation and avoidance behaviour, and interrupt spawning.

Additional consequences of recreational boating may be wash erosion [101,128] and water pollution (e.g., fuel and oil discharge) [20,35,129]. For example, in addition to the direct impacts on fish, recreational boats may cause physical damage to plants while anchors typically cause physical disturbance, often destructive, of plants and the substrata [48,129–131]. Long-term impacts may include habitat alteration due to wave wash damaging the banks and littoral zone. The intensity and extent of such impacts is dependent on factors such as craft speed, wave height, soil type, riparian vegetation density and root depth. For example, substantial detrimental effects on fishes may be a consequence of waves and wash eroding the land-water and/or land-air interface [113]. For example, damage may be inflicted on emergent and floating water plants, erosion of soil around littoral plant roots and (ultimately) a change in the distribution of aquatic vegetation [102].

Localised erosion may also occur at boat launching sites, while boat propellers typically cause re-suspension of sediments, which is often extensive. The severity of turbidity depends on boat hull design, motor power output, water depth (more severe in shallow water) and sediment composition (e.g., clay suspenoids typically stay in suspension for substantially longer than other sediment constituents) [102].

Elevated sedimentation may also occur because of bank slumping and damage to habitat and/or disruption of bank integrity, plant communities and even changes to water quality. The resulting turbidity may have consequences for fauna, including fishes and their prey. For example, macrophyte and associated microhabitat losses may occur due to reduced light penetration with potential additional flow-on effects that affect the fish habitat [102].

6. Inadvertent Overland Dispersal of Non-Native Plants

In addition to impacts on water quality, the movement of vehicles, boats and/or trailers between freshwater waterbodies has the potential to support the dispersal of organisms, including plant propagules [96,102,132–135]. Of particular concern is that non-native invasive aquatic weeds (alligator weed *Alternanthera philoxeroides* [133–135]; salvinia *Salvinia molesta* [135]) have been transported substantial distances on vehicles, boats, trailers, motors and other gear used in recreation [96,136–138].

The consequences of the introduction of non-native invasive plant species to freshwaters may ultimately result in hydrological changes because of their ability to form dense stands that blanket the water (e.g., salvinia [139]) to the exclusion of other aquatic species and, in turn, impact on water chemistry and quality, fauna and flora diversity [136,140] and, ultimately, recreational fisheries [141,142]. Despite such outcomes, Rothlisberger et al. [137] observed that the owners of more than two-thirds of small trailered boats (e.g., powerboats, recreational fishing boats, sailboats and personal watercraft, including canoes and kayaks) failed to clean their craft after use. They also reported that 'visual inspection and hand removal' or high-pressure washing could reduce the presence of macrophytes by approximately 90%. Because of their observations, they concluded that trailered boats could be an 'important vector' in the spread of aquatic invasive species. Indeed, it has been suggested [141] that the movement of such craft among inland waters of North America plays a role in the continued dispersal of invasive aquatic species.

In a Northern Australian (Kakadu National Park) investigation of recreational vehicles as vectors of weed seeds, Lonsdale and Lane [38] reported that although some vehicles carried such seeds, they were in low density, and none carried the floating aquatic noxious weed salvinia. Based on these observations, they concluded that the likelihood of vehicles transporting propagules was low. However, Rea and Storrs [143] subsequently retrieved salvinia seeds from the mud attached to vehicles. Another noxious weed, alligator weed, that continues to expand its range in Australia [144–146] has been successfully translocated to up-catchment wetland sites on the wheels of (non-recreational) vehicles [145,146]. Despite the contradictions, it is apparent that recreational fishers could play an indirect role in the movement of weeds that could impact on recreational fishing.

7. Disease and Pathogen Transmission

In addition to the introduction and translocation of plant propagules, recreational fishing may also result in the introduction of parasites and diseases [147,148]. Native species, such as the Macquarie perch, are vulnerable to fatal infection by the epizootic haematopoietic necrosis virus, which may be carried by introduced redfin and trout [28,35,149]. Both of these feral taxa, redfin [11] and trout [27], are targeted by recreational fishers, and salmonids continue to be released for recreational fishing. For example, between 1960 and 1990 in Victoria alone, approximately 35 million trout were released [149], and the stocking of streams with trout is ongoing (see, e.g., [150]).

Together with carp, redfin and salmonids, other exotic fishes have been introduced for a range of reasons, including recreational fishing. This has resulted in the establishment of the Asian fish tapeworm *Bothriocephalus acheilognathi*, which infects native fishes, for example the western carp gudgeon *Hypseleotris klunzingeri* [147].

While there are limited data on the Australian situation, Gozlan et al. [151] reported that the major route for fish pathogen introductions into Europe was via movement of aquatic animals associated with trade and recreation. Some 80% of these 'aquatic animal' introductions were freshwater species, and although the majority (53%) were associated with aquaculture, 12% of the introductions were concomitant with recreational fishing. While acknowledging an aquaculture bias due to otherwise limited data, nearly 100 known pathogens originating from a wide range of taxa have been introduced to European freshwaters. Recreation together with trade were viewed as the 'main pathway' for the introduction of these pathogens and parasites.

Although not an infection of fish, chytrid fungus *Batrachochytrium dendrobatidis* has caused the widespread decline of amphibians [152,153], which are prey for many fish species (e.g., [152]). Among the vectors proposed for the transferal of this fungus is its presence on live bait, and/or vehicles, or other equipment used, among others, by recreational fishers [152,154].

8. Introduction of Non-Native Fish Species

It is not, however, simply the diseases introduced by non-native fish that impact on freshwater ecosystems. Seeding waterways with exotic fish for recreational purposes has created catastrophic ecological problems that are difficult and expensive to control and effectively impossible to remove [92,155,156].

A major source of movement of non-native species among catchments has been a result of recreational anglers using carp as bait [26,27,157] or, together with other coarse fish, to develop new recreational fishing opportunities [26,27,158]. However, while not all non-native species have been introduced to enhance recreational angling, 34 species of exotic freshwater fish have become established in Australian waters, and a further 53 native fish species have been translocated among catchments [27]. Indeed, in some, the number of established non-native species exceeds that of resident native species. The consequences of such introductions include competition for space and food [51,159,160] and direct predation (e.g., trout are strongly aggressive and territorial) [161]. However, some species have been specifically introduced (and translocated) for recreational purposes [161–163]. Perhaps the most detrimental fish introduction to Australia, and prized for recreational angling, has been trout (e.g., brown trout, rainbow trout) [27].

With the introduction of any species to a waterbody, there is the potential for the ecosystem to be transformed. For example, Lyle et al. [11] suggested that since carp were first introduced in the mid-1800s, it had become the most abundant large freshwater fish in southeastern Australia. This is reflected in their catch by recreational anglers being approximately twice (i.e., >2 million/annually) that of any other species [11] and the focus of commercial fin-fish operations on carp [54]. However, the impact of this species has been further exacerbated due to the hybridisation of two taxa with the subsequent emergence of the vigorous Boolarra strain and the associated large increase in carp numbers [25,164,165].

Impacts of carp include destruction of aquatic plants and an associated increase in water turbidity. These perturbations result in reduced prey availability and further impacts on native fish that require sight, for example for foraging [26,164,165]. Carp also tend to outcompete native species due to their greater abundance, high fecundity, robustness and tolerance of a wide range of aquatic conditions [166].

In addition to the translocation of non-native fish, recreational fishers have also been implicated in the movement of native fishes to enhance recreational outcomes [3,27,166]. For example, the endemic black bream was illegally introduced into a small inland lake in Western Australia. An estuarine species, individuals of this bream species have subsequently been translocated and become established in several other saline lakes and estuaries in southeastern Western Australia to create a recreational fishery. However, although populations of the species are now self-sustaining, there is continued demand for stock enhancement to sustain the fishery. This is because the overall fish diversity and abundance have been reduced due to environmental degradation and fishing pressure. The introduction of 'appropriate' species was consequently considered a 'simple and quick' response compared to restoration of the degraded water bodies [167].

Despite the recognition of the potential ecological impacts, legal stocking of some non-native species (e.g., salmonid species) for recreational angling also continues. For example, between 1998 and 2002, a total of 36.2 million fish were released by the New South Wales Department of Fisheries [27], and annual stocking of waterbodies for recreational fishing continues [150].

In the process of fishing, non-target species are also frequently accidently introduced to the wild, for example as undetected live fingerlings among target fish species and as bait bucket introductions [165]. Indeed, although illegal in many areas of Australia, some species (e.g., goldfish *Carassius auratus*, oriental weatherloach *Misgurnus anguillicaudatus*, carp) continue to be used illegally as bait. Such (effectively) accidental introductions may be a pathway to the establishment of introduced fish species, and it has been demonstrated to cause local extinctions due to hybridisation [27,44,166].

Another factor that may result in the collapse, and ultimate extinction, of freshwater species is overfishing by recreational anglers [28,167–170]. However, whether recreational fishing has been the primary cause of collapse (or even of serious decline) of an Australian freshwater species does not appear to have been confirmed. Post [171] suggested that such assessment would require, for example, knowledge of the species' life history, angler behaviour and the response of managers. One species that may be in peril, the Australian bass *Macquaria novemaculeata*, is heavily fished within the Hawkesbury-Nepean River at the fringe of Australia's largest city, Sydney. However, despite knowledge of its vulnerability (e.g., [172–174]) confirmed recently by clear evidence of size truncation in the Hawkesbury-Nepean River, the species continues to be fished legally, albeit with restrictions [4].

Although Liddle [35] suggested that recreational angling was likely to have a substantial impact, the consequences are frequently difficult to separate from, for example, commercial harvesting. However, as outlined above, in Australia's inland waterways, fin-fish harvesting is now effectively restricted to recreational angling. Such effort is not homogenously distributed across river basins, and as with inshore coastal waters [175], recreational fishing may be heavily skewed toward specific locations [4,66,67,70], for example Lake Argyle (Western Australia) [66], Hawkesbury-Nepean River (New South Wales) [4] and Coorong (South Australia) [67,70]. Such evidence may also be gleaned by comparison among states. For example, Lyle et al. [11], reported that recreational fishing effort was 'heavy skewed', with some states (e.g., Australian Capital Territory) being net providers of fishers to other states.

9. Conclusions

Reid et al. [176] suggested that freshwater fishes may be the most threatened vertebrate taxon globally. Among the threats they listed, which may also combine or be synergistic, were overfishing, invasive species, pollution and habitat modification. As outlined in this review, the indirect consequences of recreational fishing are contributing to such threats, and the sport is thus playing a role in intensifying the stress on Australia's freshwater ecosystems. In 1997, Liddle [35] suggested that recreational fishing may be having at least the equivalent impact to commercial fishing. It can be assumed that with the decline in commercial fishing during the intervening period and the substantial level of fishing that Lyle et al. [11] identified, recreation would probably now be the major segment of freshwater fishing in Australia. The current indirect consequences due to fishing are therefore, also likely to be largely due to recreational fishing.

However, with the most recent country-wide survey of recreational fishing having been undertaken over a decade ago [11], even the trends in recreational fishing in Australia's freshwaters are largely unknown. There is even less information on the indirect consequences of the sport. Without informed decision-making and the implementation of the resulting policies, it is predicted that the impacts on freshwater ecosystems due to recreational fishing will accelerate because of increased visitation.

This is because the Australian population is on an upward trajectory (2015–2016, 1.4% [177]), and the profile is changing. There are increasing numbers of aging, affluent individuals [178], with a penchant for the 'great outdoors', as evidenced by the increasing numbers of 'grey nomads' that 'take to the road' each year [106,179]. Many of these people are seeking 'nature' with extended, unstructured activities [106], which often includes the water-related activity of recreational fishing. Australian governments recognise the employment and commercial potential of encouraging this segment of the tourism industry and consequently seek to attract tourists to natural areas, even in hitherto little-visited wilderness zones [180].

Compared to terrestrial reserves, there is a deficit of freshwater protected areas internationally [181], and there are some 57 million ha that have been recognised as worthy of listing in Australia [182]. Some 230 of the wetlands encompassed under this listing are recognised as being under pressure [183,184]. On the driest inhabited continent, the impacts of climate change (e.g., changed flow regimes, temperatures, seasonality) are likely to place additional major stresses on biodiversity within freshwater aquatic ecosystems.

Despite these issues, there has been limited quantitative assessment to even determine what is required to ensure a comprehensive, adequate or representative protection of freshwater ecosystems [185]. To underpin sustainable recreational fishing in freshwater ecosystems, research and the development of appropriate policies to underpin the implementation of sustainable management is required. The alternative is that the integrity and biodiversity loss of these ecosystems will ultimately result in their collapse before the indirect consequences of recreational fishing have been directly assessed.

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