

A systematic review of methods used to study fish in saltmarsh flats

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Abstract. There is a growing body of research highlighting the importance of saltmarshes as habitats for fish for feeding, refuge from predation and reproduction. However, more work is needed on fish on vegetated marsh flats (or surfaces). We reviewed 60 studies that used 21 methods to sample fish assemblages on saltmarsh flats. Drop samplers, fyke nets and pop nets were most frequently employed, with considerably more studies being conducted in graminoid than succulent marsh. Reporting of sampling temporal and tidal details, environmental variables and fish attributes was inconsistent. Most of the papers focussed on one or more of conservation management, comparisons among habitat types, and the use of saltmarsh (including fish activity type or residency status). Important potential areas of research include the relationships between the fish assemblages of saltmarsh flats and coastal fisheries, the effects of invasive plant species and marsh restoration efforts in areas outside the United States, and the potential effects of sea-level rise on vegetated flats as fish habitat. Sampling methods that provide density measures are likely to be most useful for most of this research. Thus, drop samplers and pop nets are an appropriate choice, the former in graminoid saltmarshes and the latter in succulent saltmarshes.

Additional keywords: estuary, fish community, research design, *Sarcocornia*, *Spartina*, tidal marsh.

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Introduction

Saltmarshes form in low-energy coastal environments such as estuaries and embayments. They are defined by the presence of salt-tolerant plants, occurring in areas that are flooded regularly to occasionally. These habitats provide foraging, refuge and nursery sites for resident and transient fish (e.g. Hettler 1989; Minello and Zimmerman 1992; Peterson and Turner 1994; West and Zedler 2000; Minello *et al.* 2003; Crinall and Hindell 2004; Platell and Freewater 2009). In addition to providing fish habitat, saltmarshes contribute to broader coastal seascape productivity through outwelling and the export of nutrients, organic matter and live organisms (Odum 2002; Kneib 2003; Creighton *et al.* 2019). Through these and several other ecological functions, saltmarshes provide a broad range of highly regarded provisioning, supporting and cultural ecosystem services (Barbier *et al.* 2011; Rogers *et al.* 2016).

Fish use of saltmarsh habitat is complex, with the effects of seasonality, tidal patterns, water depth, diel period, temperature and salinity influencing fish assemblages (e.g. Connolly *et al.* 1997; Crinall and Hindell 2004; Mazumder *et al.* 2005b; Prahalad *et al.* 2019). Fish either (1) remain on the marsh at all times (finding refuge in pools and depressions during low tide), (2) are present on the marsh at high tide but return to subtidal habitat at low tide, (3) venture only onto the marsh edge at high tide and return to subtidal creeks at low tide, or (4) remain

in subtidal creeks without venturing onto the marsh itself (Peterson and Turner 1994).

The ‘saltmarsh habitat’ is necessarily a complex of sub-habitats including vegetated marsh flats (or vegetated marsh surfaces), intertidal creeks, subtidal creeks and marsh ponds and pools (Minello *et al.* 2003; Fig. 1a). These subhabitats, in the context of fish use, can be delineated by frequency of flooding and water availability (Rountree and Able 2007). Of these subhabitats, fish use of saltmarsh creeks has received much attention, particularly in the United States (e.g. Rountree and Able 1992; Able *et al.* 2001; Hampel *et al.* 2003; Paterson and Whitfield 2003; Green *et al.* 2009), as have marsh edges (e.g. Baltz *et al.* 1993; Kaneko *et al.* 2019). In comparison, vegetated saltmarsh flats, disproportionate to the area they occupy within saltmarshes (e.g. see Fig. 1a), have received much lesser attention. The results of sampling conducted in creeks cannot be used to demonstrate fish use of adjacent vegetated flats (Peterson and Turner 1994; Connolly 1999).

Vegetated marsh flats can be largely dominated by graminoids, such as *Spartina* spp., *Phragmites* spp. and *Elymus* spp. in parts of the United States and Europe (Fig. 1b), or succulents, such as *Sarcocornia* spp. and *Samolus* spp. in Australia and New Zealand (Fig. 1c; e.g. Hettler 1989; Connolly *et al.* 1997; Kneib 2003; Prahalad *et al.* 2019).



Fig. 1. (a) Saltmarsh subhabitats for fish, including vegetated marsh flats (or vegetated marsh surfaces), tidal creeks and marsh ponds (or pools), saltmarsh (b) dominated by graminoids in Westerschelde estuary, Netherlands, and (c) dominated by succulent herbs and shrubs in Spring Bay, Australia. Photographs: V. Prahalad.

Several previous reviews have described fish use of saltmarshes and survey methods, but none has focussed solely on flats. Existing reviews of fish use of saltmarsh have demonstrated several complexities associated with sampling and surveying flats, perhaps suggesting why consistent sampling

strategies and global comparisons of fish activity in this sub-habitat have not been undertaken. For instance, [Connolly \(1999\)](#) addressed difficulties in sampling design and methods of sampling nekton in saltmarshes as a whole. He recommended that sampling methods should prioritise transportability (to facilitate replication) and that reporting of flooding regime should be standardised. [Minello *et al.* \(2003\)](#) discussed the nursery role of saltmarsh as a whole, specifically the patterns of density, growth and survival of nekton. They constrained their review parameters to studies that utilised methods that provide densities of animals per 'area of bottom' (i.e. habitat area). [Rountree and Able \(2007\)](#) reviewed sampling design and equipment selection for estimating densities of nekton in saltmarsh and other shallow estuarine habitats. [Rozas and Minello \(1997\)](#) discussed sampling design and methods used in shallow estuarine habitats, including saltmarsh flats, and recommended use of enclosure samplers because of their capacity to measure fish density. As more than 20 years of research has been conducted since the publication of these reviews, and a wide range of methods is still used to survey fish, an updated and more targeted investigation of methodological approaches is needed to support researchers in designing and undertaking future studies in saltmarsh flats.

The primary aim of the present study was to review the methods used to study fish assemblages on saltmarsh flats, including the relationships of field equipment and sampling design to vegetation type and research topic. We identify research gaps and offer a guide for sampling methods in relation to environment (i.e. vegetation type) and other practical considerations (e.g. portability, ease of deployment, catch efficiency). Our focus is on the methods appropriate to fill gaps in our knowledge of the fish ecology of saltmarsh flats. For a review of substantive findings relating to the nursery role of saltmarsh, see [Minello *et al.* \(2003\)](#), and for marsh function and patterns of fish use, see [Rountree and Able \(2007\)](#).

Materials and methods

We followed established methods ([Moher *et al.* 2009](#); [Pickering and Byrne 2014](#)) to conduct a systematic search of the peer-reviewed literature on fish assemblages of vegetated saltmarsh flats. The electronic databases Google Scholar, Web of Science and Scopus were used to source original research papers published in English language in peer reviewed academic journals, with searches conducted between January and March 2019. The search terms used to identify papers were 'saltmarsh' or 'salt marsh', 'fish assemblages' and 'sampling'. The keyword 'fish assemblages' was used to avoid papers that focussed solely on individual fish species. The keyword 'sampling' was used to select for papers that involved field sampling methods. Wild-cards were used to ensure we did not omit papers that used other variant endings of the keywords. We did not specify a start or end limit for publication date.

The process of identification, screening and assessment for eligibility and inclusion of papers is represented in [Fig. 2](#) (adapted from the Preferred Reporting Items for Systematic Review Recommendations; [Moher *et al.* 2009](#)). Only papers that describe the results of original research were included. Book chapters were excluded. Papers on single taxa (e.g. [Geary *et al.* 2001](#); [Able *et al.* 2012](#)), rather than assemblages, were excluded. We also excluded

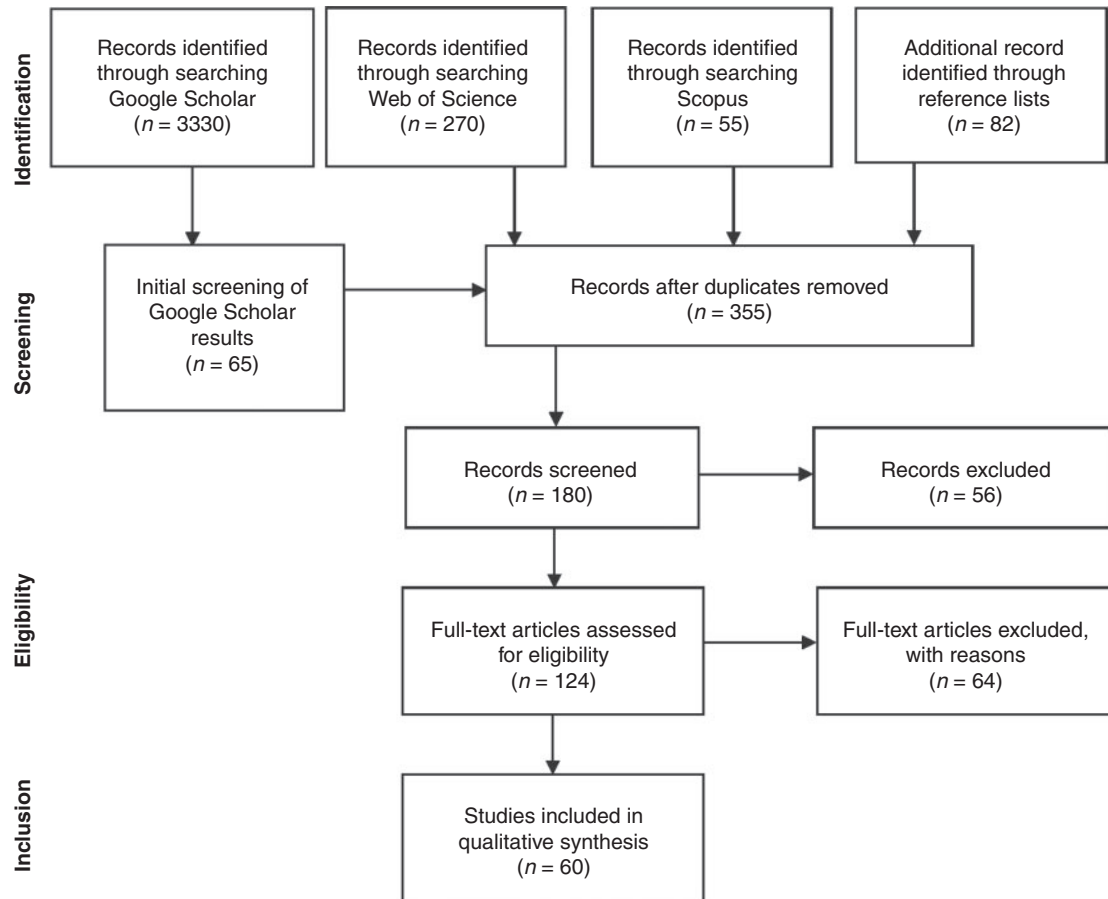


Fig. 2. PRISMA diagram of the process of identification, screening and assessment for eligibility and inclusion of papers (Moher *et al.* 2009).

papers that did not include field research. Papers that focussed solely on creeks (e.g. Hampel *et al.* 2003; Paterson and Whitfield 2003), pools (e.g. Davis *et al.* 2014) or artificial ponds, ditches and impoundments (e.g. Stevens 2006; Carswell *et al.* 2015) were excluded. Papers were also excluded in cases where they appeared to address the relevant topic but lacked important details (such as sampling location and design). Searches were concluded when either all results had been assessed for initial suitability (in the cases of Web of Science and Scopus) or when no relevant results were found within six consecutive pages with 10 results per page (in the case of Google Scholar). The reference lists of all selected papers were assessed for any further relevant peer-reviewed papers that met the criteria.

From the final selection of papers, we extracted the following information: (1) authorship, year of publication, country and hemisphere where the research was conducted, paper and journal titles; (2) fish-sampling methods; (3) dominant vegetation type; (4) other taxa surveyed in addition to fish; (5) sampling details including tidal magnitude and stage, diel phase, sampling month and number of months sampled; (6) variables measured or described including species identification, fish length, temperature, salinity, depth, dissolved oxygen and pH, and fish biomass; and (7) the research subject, including assemblage composition, food chains, webs or diet, fish use type (fish residency status and

also activity type, e.g. feeding), restoration, marsh modification and degradation, fisheries, sampling techniques, temporal variations, and habitat comparisons. Some studies also included other taxa and habitats outside the scope of the present review. In such cases, information on sampling methods used only for the other taxa and habitats was excluded.

The database was then analysed to detect patterns and to identify gaps in the research. For the most frequently used methods, Pearson's chi-square tests were used to test association between methods and vegetation type, diel period and the more popular subjects of research (temporal variation and marsh restoration). Vegetation type was grouped as either graminoid or succulent. If vegetation had a mixture of graminoids and succulents as dominant species, it was classed as succulent. The statistical software R (R Core Team 2019) and R Studio (RStudio Team 2016) were used to analyse data. Results of publication date, methods used, sampling diel period, sampling month, variables measured and reported, and other taxa surveyed were visualised using the function ggplot (Wickham 2016).

Results

Publication time, journal and study location

Sixty journal articles were selected, with publication dates ranging from 1984 to 2019 (Fig. 3). Papers were published in

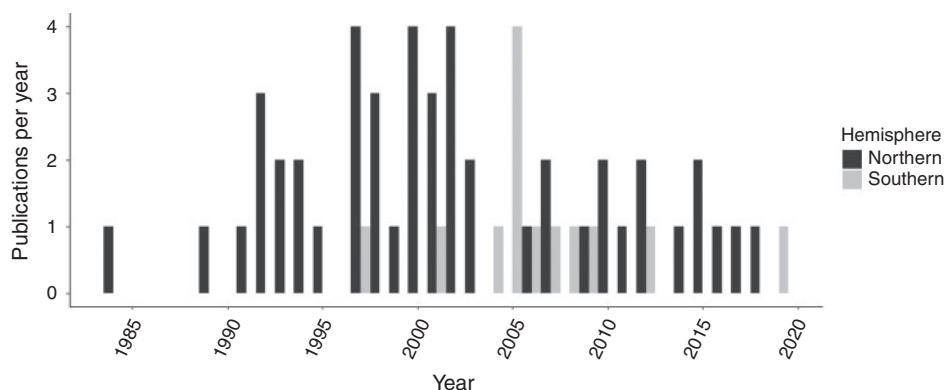


Fig. 3. Time series of the number of articles published per year in northern and southern hemispheres.

21 journals. Those journals in which most papers were published were *Estuaries and Coasts* (previously *Estuaries*) and the *Marine Ecology Progress Series*, which featured 25% ($n = 15$) and 22% ($n = 13$) of publications respectively. Northern hemisphere studies accounted for 78% ($n = 47$) of papers, whereas southern hemisphere studies accounted for 22% ($n = 13$; Fig. 4a). Of the northern hemisphere studies, 83% ($n = 39$) were conducted in the United States. Of the southern hemisphere studies, 92% ($n = 12$) were conducted in Australia. Within these two countries, there was a strong regional bias, with the states of Louisiana and Texas in the Gulf Coast of the USA and the state of New South Wales in eastern Australia being disproportionately represented (Fig. 4b, c). Of the total number of studies, the USA contributed more than any other country, accounting for 65% ($n = 39$).

Methods used to sample fish

Twenty-one methods were used to sample fish assemblages in vegetated intertidal saltmarsh flats (Table 1). Many studies (22%, $n = 13$) used a combination of these methods. The most frequently used were drop samplers (18%, $n = 11$), followed by fyke nets (22%, $n = 13$) and pop nets (13%, $n = 8$).

Methods used to sample fish were either active (requiring field personnel to be on site to release nets or traps) or passive (requiring only initial set up or placement before being left to passively collect fish as they move into the trap; Kneib 1991). Active sampling methods include the use of drop samplers, pop nets, lift nets, seine nets, throw traps, trawls, cast nets, drop traps, flume weirs, plankton nets and hand nets. Several of these active methods, including pop nets, lift nets and drop traps, use remote-release systems to trap fish, thus allowing personnel to be stationed further from nets and traps. Passive sampling methods include fyke nets, Breder traps, pit traps, baited wire mesh traps, block nets, flume nets, minnow traps and simulated aquatic microhabitats. Only one study employed chemical methods, with the poison rotenone being used in conjunction with drop samplers (Rakocinski *et al.* 1992).

Many methods were used only once. Those that were used more frequently (pop nets, fyke nets and drop samplers) were used for more years than were the other methods (Fig. 5).

Tide, diel period, sampling month and season

Of the 60 studies, 72% ($n = 43$) provided details about the tidal conditions that occurred during sampling. Fifty-seven per cent ($n = 34$) noted that sampling had been conducted at high tide, whereas one study was conducted at low tide (Yozzo and Smith 1997). A further study sampled during both high and low tides (Jovanovic *et al.* 2007). Two other studies sampled during incoming tides (Lechêne *et al.* 2018) and incoming, slack high and ebb tides (Kneib and Wagner 1994). Twenty-three studies (38%) reported whether sampling occurred during spring or neap tides. Twenty of these sampled during spring tides, and three sampled during both spring and neap (and other lower-amplitude) tides.

Only 42% of studies ($n = 25$) reported diel phase (Fig. 6), with 8% conducting sampling at night, 17% during the day, 12% during both day and night, and 5% changing diel phase according to season (winter afternoon or night sampling and summer morning or daytime sampling).

Ninety per cent of studies ($n = 54$) reported the months when sampling occurred, whereas 7% reported the sampling season without listing sampling months. Two studies (3%) did not report either the sampling month or the season. In the northern hemisphere, sampling peaked in the warmer months (April to October). In the southern hemisphere, sampling was performed during all times of year (Fig. 7).

Environmental variables and fish attributes

Most studies identified fish to species level. Commonly measured fish attributes included fish length, which was recorded in 60% of studies ($n = 36$), and fish biomass (either dry or wet weight per fish, per area sampled, or per sampling effort, in milligrams, grams or kilograms), or volume (millilitres per fish), as recorded in 30% of studies ($n = 18$). Of the environmental variables measured, water temperature was recorded in 58% of studies ($n = 35$), water salinity in 58% of studies ($n = 35$), water depth in 57% of studies ($n = 34$), dissolved oxygen in 25% of studies ($n = 15$), and pH in 5% of studies ($n = 3$) (Fig. 8).

Seventy-three per cent ($n = 44$) of papers surveyed other taxa as well as fish. These other taxa were mainly invertebrates, including molluscs (gastropods, bivalves and cephalopods), annelids (oligochaetes and polychaetes), spiders, mites, pycnogonids, centipedes, insects (coleopterans, dipterans, hemipterans, orthopterans and collembolans), crustaceans (decapods,

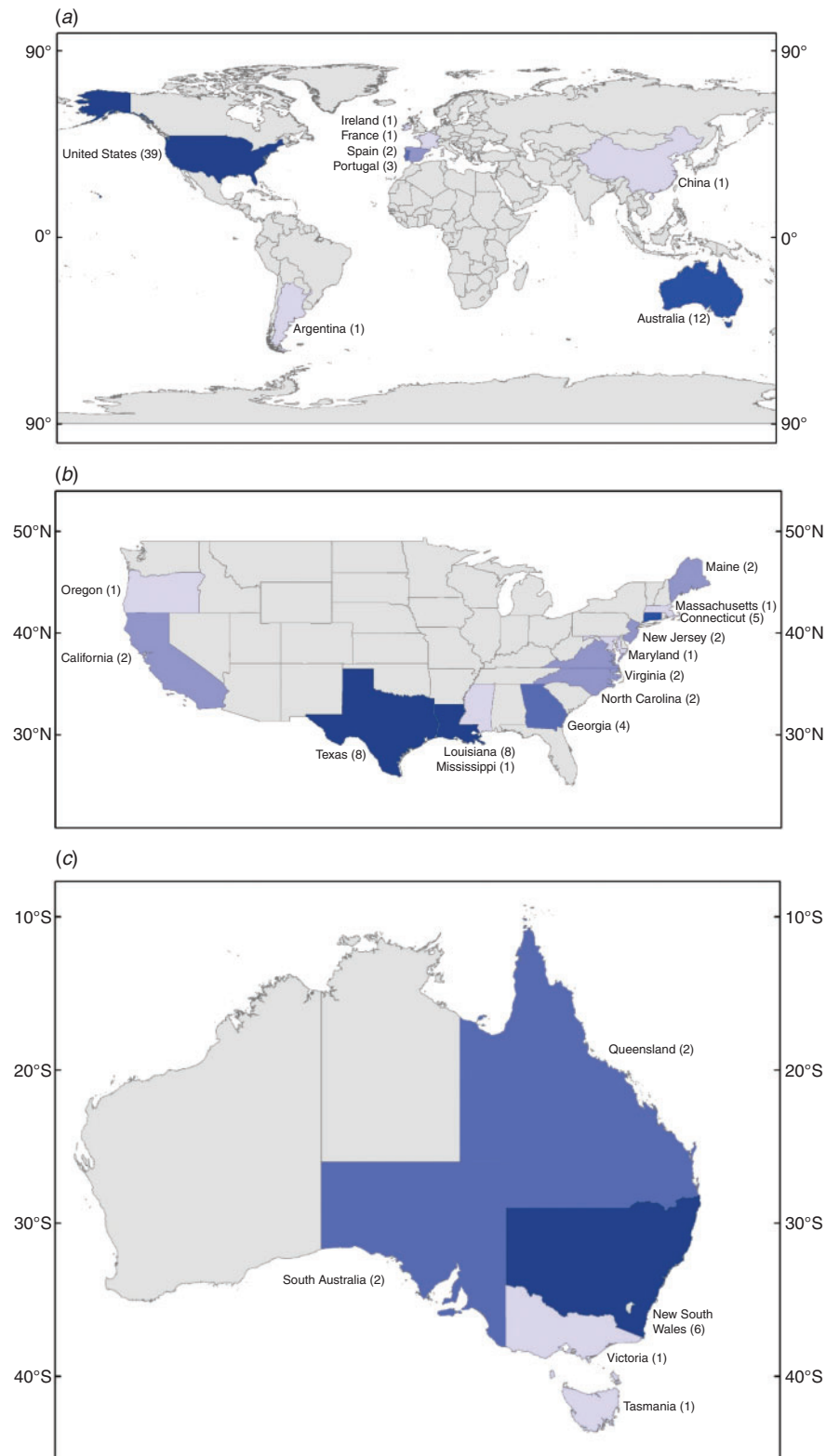


Fig. 4. (a) Locations of studies sampling fish assemblages on vegetated saltmarsh flats, (b) locations of studies within the United States, and (c) locations of studies within Australia.

Table 1. Survey methods used in vegetated saltmarsh flats

Methods reported only for habitats outside the vegetated saltmarsh flats are not included. If 'beam trawls' and 'trawls' are classed as the same survey method, and 'dip nets', 'hand nets' and 'scoop nets' are also classed together, the total number of survey methods used is 21

Method	Number of publications where method is used	References
Drop sampler ^A	10	Minello and Zimmerman (1992); Minello and Webb (1997); Rozas and Minello (1998); Rozas and Minello (1999); Minello (2000); Rozas and Zimmerman (2000); Minello and Rozas (2002); Zeug <i>et al.</i> (2007); Merino <i>et al.</i> (2010); Rozas and Minello (2010)
Fyke net ^P	8	Burdick <i>et al.</i> (1996); Dionne <i>et al.</i> (1998); Meyer <i>et al.</i> (2001); Cornu and Sadro (2002); Mazumder <i>et al.</i> (2006); Saintilan <i>et al.</i> (2008); Prado <i>et al.</i> (2017); Lechêne <i>et al.</i> (2018)
Pop net ^A	7	Connolly <i>et al.</i> (1997); Thomas and Connolly (2001); Bloomfield and Gillanders (2005); Connolly (2005); Mazumder <i>et al.</i> (2005b); Saintilan <i>et al.</i> (2007); Prahald <i>et al.</i> (2019)
Beam trawl ^A	3	França <i>et al.</i> (2009); França <i>et al.</i> (2012a); França <i>et al.</i> (2012b)
Breder trap ^P	3	Swamy <i>et al.</i> (2002); Warren <i>et al.</i> (2002); Fell <i>et al.</i> (2006)
Flume weir ^A	3	Kneib (1991); Kneib and Wagner (1994); Kneib (2003)
Lift net ^A	3	Rozas (1992); Rozas and Reed (1993); Osgood <i>et al.</i> (2003)
Pit trap	2	Varnell and Havens (1995); Yozzo and Smith (1997)
Multiple methods: lift net ^A and pit trap ^A	2	Quan <i>et al.</i> (2011); Ennis and Peterson (2015)
Seine net ^A	2	Jovanovic <i>et al.</i> (2007); Valiñas <i>et al.</i> (2012)
Baited wire-mesh trap ^P	1	Able <i>et al.</i> (2015)
Block net ^P	1	Hettler (1989)
Multiple methods: drop trap ^A (including plankton net) and seine net ^A	1	Chamberlain and Barnhart (1993)
Flume net ^P	1	Warren <i>et al.</i> (2001)
Minnow trap ^P	1	West and Zedler (2000)
Simulated aquatic microhabitat ^P	1	Kneib (1997)
Throw trap ^A	1	Rudershausen <i>et al.</i> (2016)
Multiple methods: cast net ^A and throw trap ^A	1	Stein <i>et al.</i> (2014)
Multiple methods: drop sampler ^A , rotenone ^C	1	Rakocinski <i>et al.</i> (1992)
Multiple methods: flume net ^P and fyke net ^P	1	Raposa and Roman (2001)
Multiple methods: flume net ^P and seine net ^A	1	Peterson and Turner (1994)
Multiple methods: fyke net ^P and scoop net ^A	1	Platell and Freewater (2009)
Multiple methods: fyke net ^P and seine net ^A	1	Crinall and Hindell (2004)
Multiple methods: pit trap ^P and flume net ^P	1	Able and Hagan (2000)
Multiple methods: plankton net ^A , dip net ^A and pit trap ^P	1	Talbot and Able (1984)
Multiple methods: pop net ^A and fyke net ^P	1	Mazumder <i>et al.</i> (2005a)
Multiple methods: trawl ^A , fyke net ^P , minnow trap ^P , hand net ^A	1	Gutiérrez-Estrada <i>et al.</i> (1998)

^AActive sampling method; ^PPassive sampling method; ^CChemical sampling method.

amphipods, isopods, mysids, tanaids, ostracods, copepods), priapulids, nematodes and nemerteans. Only one paper (Warren *et al.* 2002) reported on another vertebrate taxon (birds) in addition to fish. Decapods (crabs, prawns and shrimp) were the most common taxa studied in addition to fish (surveyed in 70% of studies, $n = 42$). Of these, 55% of studies ($n = 33$) surveyed only decapods in addition to fish (Fig. 9).

Vegetation

Most papers (87%, $n = 52$) provided a description of the dominant vegetation type found at the sampling location. The most common marsh vegetation, reported in 58% of papers ($n = 35$), was graminoid marsh. Mixed graminoid and succulent vegetation was reported in 17% of papers ($n = 10$), and succulent vegetation was reported as dominant in 12% of papers ($n = 7$).

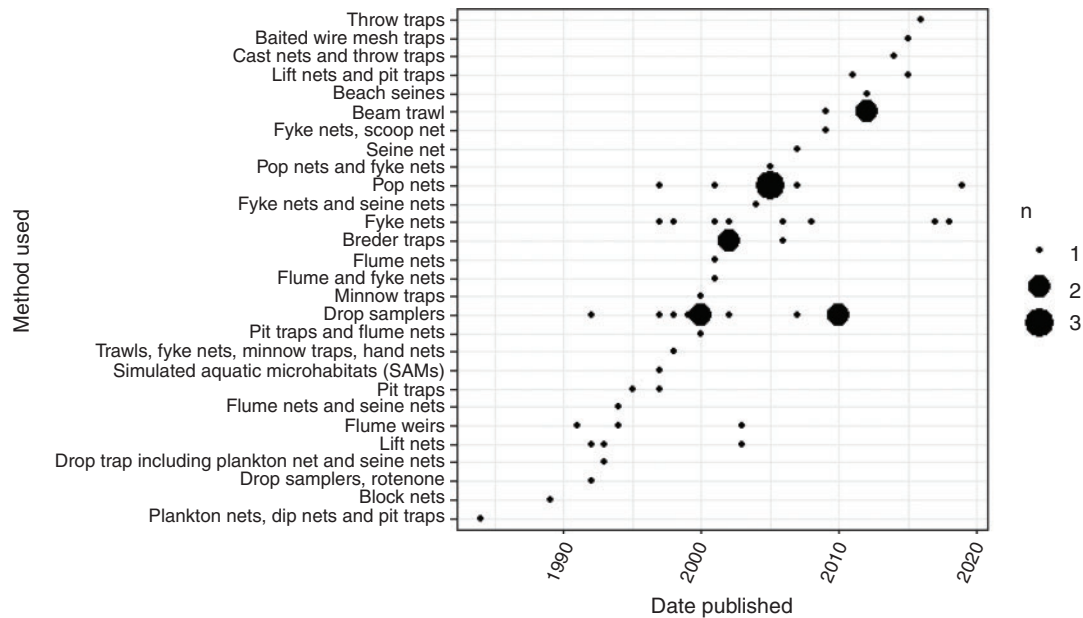


Fig. 5. Methods employed, ordered by median publication date per method, with number of publications indicated by circle size.

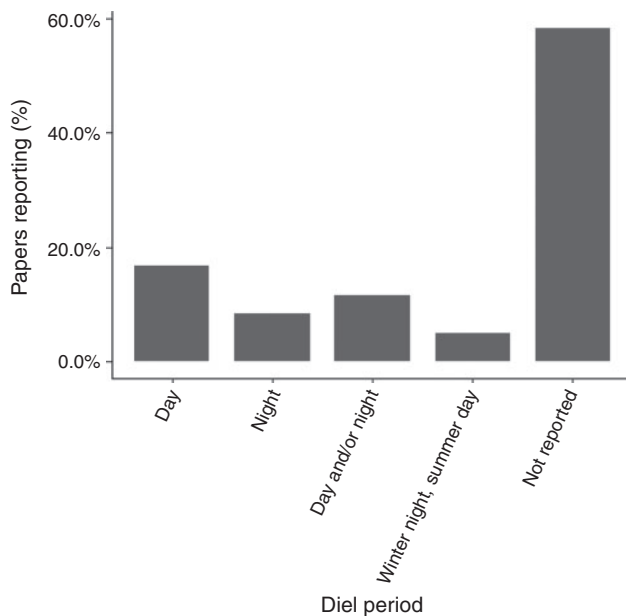


Fig. 6. Number of papers that reported sampling during each diel period.

Topics investigated

All papers reported assemblage composition (a criterion for inclusion in the present review). Forty-seven per cent of papers ($n = 28$) discussed types of fish use of saltmarsh flats (including fish use of the flats for foraging, as a refuge, or as a nursery, and habitat occupancy, whether flats are used as a permanent habitat for resident fish or temporary habitat for transient fish).

Seventeen per cent of papers ($n = 10$) discussed the contribution of saltmarsh flats to fish diet, food chains and in terms of production more broadly. Many studies (87%, $n = 52$)

included comparisons among habitats, whether within saltmarsh (e.g. vegetated flats, ponds, edges or creeks, and flats of different elevations), between saltmarsh and other habitats (e.g. mangrove, seagrass, non-vegetated flats and freshwater wetlands) or among saltmarsh modifications (e.g. hydrologically restricted and unrestricted saltmarshes, introduced and native vegetation types, and restored or created saltmarshes and unaltered saltmarshes). Sixty-three per cent of studies ($n = 38$) included analysis of temporal variation (whether tidal, diel or seasonal) in the fish assemblages using saltmarsh flats.

Thirty-five per cent of papers ($n = 21$) investigated marsh modification or degradation (hydrological modification, coastal development, pollution, and invasive plant species). Of papers investigating marsh modification and degradation, 18% ($n = 11$) addressed hydrological modification of saltmarshes (and implications for fish assemblages), 12% ($n = 7$) discussed invasive plant species, 5% ($n = 3$) discussed the effects of coastal development on saltmarsh fish assemblages and 3% ($n = 2$) looked at the effects of pollution (including nutrient input and oil spills). Invasive fish species (and the implications of their presence for native fish assemblages) were discussed only in 5 per cent of papers ($n = 3$). Thirty per cent of papers ($n = 18$) discussed saltmarsh restoration or artificial creation. Twenty-two per cent of papers ($n = 13$) discussed the contribution of saltmarsh fish to fisheries.

In addition to those papers investigating topics related to fish habitat use, ecology and management considerations, 13% of papers ($n = 8$) focussed on sampling techniques, either comparing sampling gear types or describing newly developed techniques.

Relationships between research context and method selection

Marsh restoration studies did not differ from the rest in terms of the methods used ($\chi^2 = 3.186$, d.f. = 2, $P = 0.203$), with

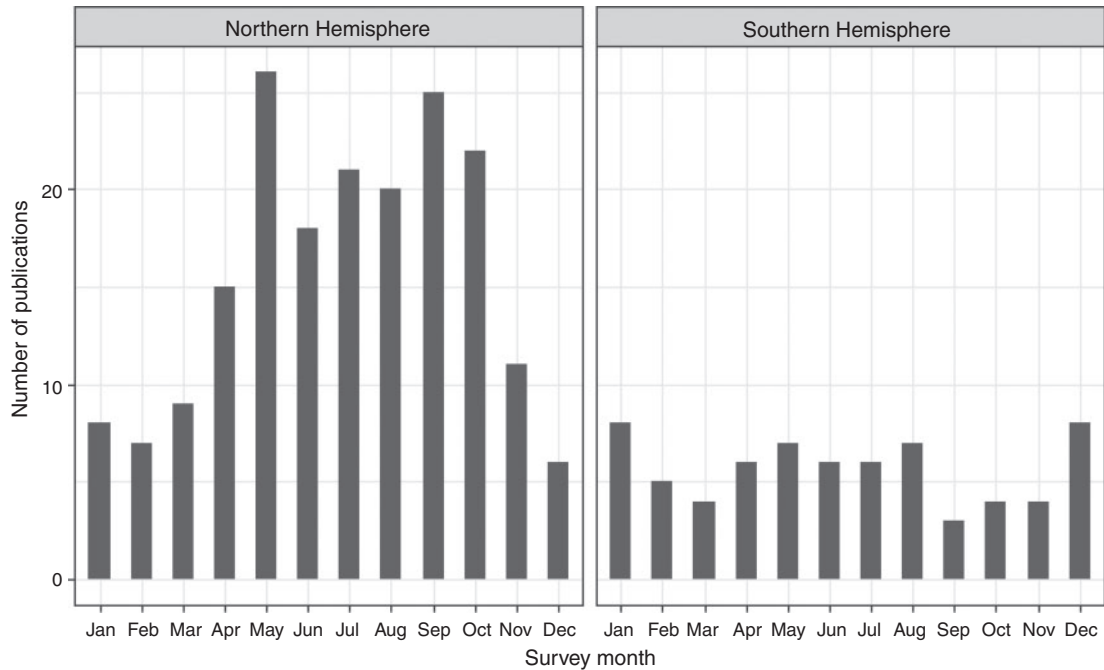


Fig. 7. Months when sampling occurred.

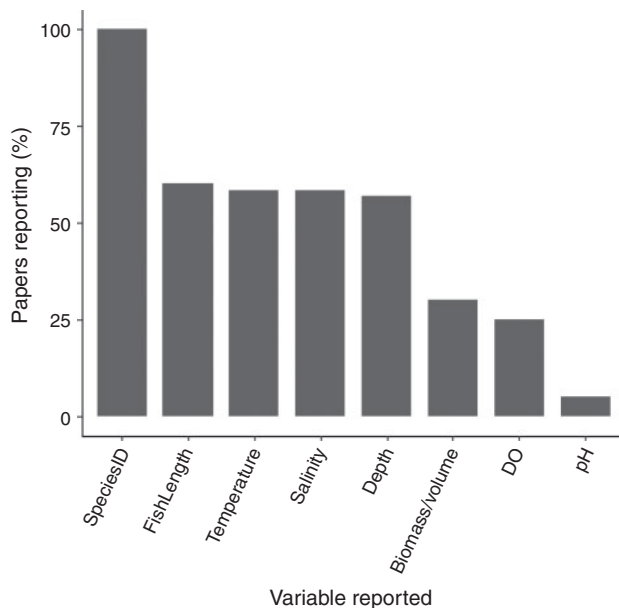


Fig. 8. Fish and environmental attributes reported.

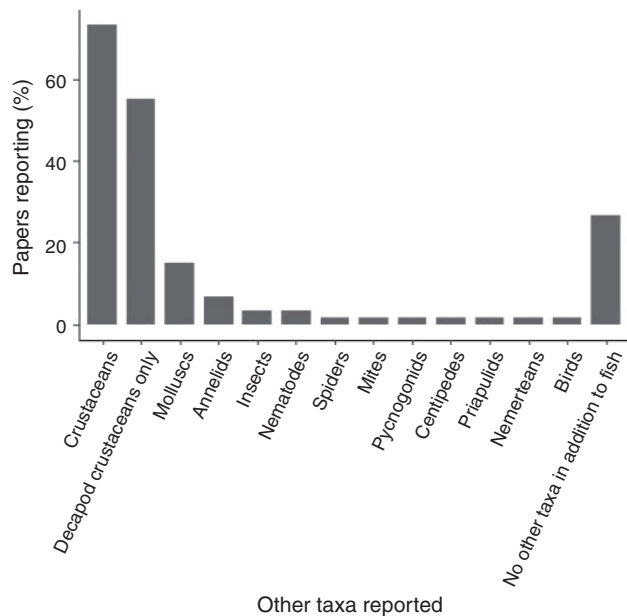


Fig. 9. Number of papers that reported other taxa, by taxon.

there being no clear preference in the method used for this research focus. Studies that compared saltmarsh flats with other fish habitat also showed no clear preference for a method ($\chi^2 = 3.214$, d.f. = 2, $P = 0.201$). Pop nets and drop samplers were more frequently used in studies that investigated temporal variation in fish assemblages, whereas fyke nets were used in studies that did not investigate temporal variation

($\chi^2 = 6.227$, d.f. = 2, $P = 0.045$). Pop nets were used only in succulent-dominated vegetation and drop samplers were mostly used in graminoid vegetation ($\chi^2 = 11.54$, d.f. = 2, $P = 0.003$). Fyke nets were used in both vegetation types. Drop samplers were used only during daytime sampling and pop and fyke nets were used in sampling that included night and day and/or night sampling ($\chi^2 = 11.66$, d.f. = 2, $P = 0.003$).

Discussion

Geographic distribution

Our data showed a broader geographic range in studies of the fish assemblages of saltmarsh flats than has previously been observed for saltmarsh in general. We found the percentage of papers published on the USA saltmarshes to be lower than in previous reviews (65%, $n = 39$), with a greater variation in study location. This may partly relate to the different foci of the reviews, as well as increases in studies outside the USA. New studies represent areas including Australia, Argentina, China, Ireland, France, Portugal and Spain. Yet, there are still many regions poorly represented in the literature (Fig. 4a). For example, fish use of southern African marsh creeks has been studied (e.g. Paterson and Whitfield 2003), but the use of the surrounding flats has not yet been studied. Similarly, research has been published recently in Europe and Asia that provides information on creek fish assemblages, but not on fish assemblages of the flats (e.g. Hampel *et al.* 2003; Kaneko *et al.* 2019).

Sampling methods

The need to overcome difficulties associated with sampling in often densely vegetated shallow-water environments may be related to the development of the wide range of sampling methods observed in the present study and earlier reviews (Rozas and Minello 1997; Connolly 1999). In addition to vegetation type, other important considerations when sampling fish in vegetated flats include tidal and landscape patterns, issues with access, fish-movement patterns and data requirements such as density and size class.

Connolly (1999) recommended use of sampling equipment that is easily transportable, allowing for repeated random sampling. Rozas and Minello (1997) focussed on the importance of gear types meeting the requirements of the data, and specific study objectives, and the necessity of having high and temporally stable catch efficiency (defined by Rozas and Minello (1997) as the proportion of target animals collected from the sample unit area). In addition, if nekton densities are to be compared over time or among locations, quantitative sampling methods that allow the sample-unit area to be known, and methods that sample the whole water column are necessary (Rozas and Minello 1997). Meta-analyses, such as that by Minello *et al.* (2003), are enabled by studies that provide measures of density. To these previously recognised requirements of portability, catch efficiency and density measurement, we add suitability for different saltmarsh vegetation types (tall graminoid compared with succulent vegetation) and suitability for use in different diel periods. Because diel patterns in fish diversity and abundance on saltmarsh flats have been reported (Pralhad *et al.* 2019), it is important that method choice takes suitability for use at night as well as day into account.

Of the 21 methods employed, drop samplers were used most frequently. Drop samplers are often chosen to provide a precise measure of density and to efficiently capture organisms within a defined area, usually enclosing between 1 and 2.6 m² (Minello 2000; Merino *et al.* 2010). Drop samplers have been commonly used in the dense, tall graminoid vegetation that is dominant in many saltmarshes in the USA (e.g. Minello 2000; Rozas and Zimmerman 2000; Zeug *et al.* 2007). They are often

preferentially used in vegetation dominated by graminoids because they can be successfully deployed from a boat over this vegetation where use of other methods may be hindered. A major disadvantage with drop samplers is that, because they require access by boat for deployment, their use is limited by water depth. This restricts drop samplers from being used in marsh flats with shallow depths (Peterson and Turner 1994). We also noted that drop samplers were used only during the day, possibly because boat access may be more difficult at night.

Fyke nets were the second-most frequently employed method. Fyke nets passively sample fish retreating from the marsh and are composed of a long funnel-shaped net with wings extending from the net mouth, channelling fish in as the tide recedes. Fyke nets are frequently chosen owing to their portability and ease of deployment, low cost (Dionne *et al.* 1998) and because, as a passive capture method, there is less disturbance caused by the presence of researchers during deployment. In some cases, fyke nets have also been found to catch more species than do other methods (Mazumder *et al.* 2005a). Fyke nets have been used in both tall graminoid marshes and succulent marshes; so, they may be useful if comparisons between marsh vegetation types are needed. They have also been used in both day and night sampling. Fyke nets can be put in place at low tide while the marsh is not flooded, which may make sampling during the night less difficult. The most notable disadvantage of fyke nets is that, unlike the other two most commonly used methods, they do not provide an immediate measure of fish density, although some studies have calculated the area of marsh drained and sampled by the net (e.g. Dionne *et al.* 1998). An additional disadvantage of fyke nets (and also block nets and flume nets) is that, because they are generally located at drainage points on the marsh, often near a marsh edge, they cannot provide as detailed a picture of marsh subhabitat utilisation as do other gear types. They catch fish from the wider area drained, including species that do not venture further than the edge of the flats (Peterson and Turner 1994). Because fyke nets capture fish as they retreat during the falling tide, they are also less useful for sampling during different tidal stages.

Pop nets were the third-most frequently employed method. Pop nets are installed at low tide and held down by weights until release at high tide. Fish are captured when the buoyant-topped net walls are remotely released by removing the weights. Like drop samplers, pop nets also provide a measure of density with good catch efficiency, but for larger areas than do drop samplers (net area commonly 25 m²). We found that, along with drop samplers (which also provide a measure of density), pop nets were more frequently used than were other methods in investigations of temporal variation in fish assemblages. This may be due to their providing a standardised, readily replicable measure that can be applied year-round. Although pop nets have previously not been recommended for use in tidal marsh (Rozas and Minello 1997), they have since been frequently successfully employed in Australia. Indeed, all studies using pop nets were conducted in Australia (e.g. Bloomfield and Gillanders 2005; Prahalad *et al.* 2019), in locations where the vegetation is commonly composed of lower, succulent-dominated vegetation. It is possible that the recommendation against this method by Rozas and Minello (1997) was made considering only tall graminoid marshes. Like fyke nets, pop nets are highly portable,

facilitating replication, and do not require a boat for deployment. They have been used in both day and night sampling and, unlike fyke nets, can be used during both flood and ebb tides.

Other methods were less frequently used. Among the rarely used older methods, poisoning may have been abandoned because of its unnecessary lethality for target and non-target species. Many studies that do not require fish to be retained after capture (e.g. for biomass measures) release fish once identified and measured. Other infrequently used methods employed recently, such as cast nets (Stein *et al.* 2014), have been used in other habitats, such as estuarine wetland pools (Sheaves and Johnston 2008). Cast nets were chosen because of their covering a large area per sampling effort, and their suitability for catching large fast-moving nekton (Stein *et al.* 2014). Other methods used recently, such as seines and beam trawls, have also been used elsewhere in different shallow habitats such as seagrass because they are easy to deploy over larger areas (Guest *et al.* 2003).

Additional, less frequently used, gear types (including pit traps and simulated aquatic microhabitats) are better suited for catching small resident species that remain in marsh subhabitats such as pools and ditches during low tide (e.g. Kneib 1997; Able and Hagan 2000), than species that return to other habitats when the tide ebbs (Peterson and Turner 1994). Smaller highly portable traps, such as Breder traps, also capture resident marsh fish but may exclude larger fish (Fell *et al.* 2006). These physically small traps may have less overall catch efficiency but they are highly portable, facilitating replication. The opposite is true for the flume weir (Kneib 1991), a large semipermanent structure that cannot be easily moved among locations but catches a high proportion of species present over an extensive area (100 m²). This type of method has, therefore, provided valuable information on seasonal and tidal variation in fish use (Kneib 1991; Kneib and Wagner 1994), but with limited spatial replication.

There are methods that have been used in other shallow habitats that are yet to be used on vegetated saltmarsh flats. These include underwater digital video cameras (Meynecke *et al.* 2008) and high-resolution imaging sonar (Rieucan *et al.* 2015). Within saltmarsh, they have been used in an intertidal creek and saltmarsh pool respectively. The benefits of these recording techniques include their low impact on organisms compared with trap or net gear types, their independence from human presence and ability to generate a large volume of data relative to sampling effort. Their limitations include inability to provide a positive species identification where the visuals are unclear, and not being able to reliably indicate either diversity or density.

Studies that focus on comparing sampling methods are highly valuable in providing information on relative catch efficiency and ease of deployment and replication. Where new methods are being employed, descriptions of these methods can be particularly useful when they are trialled with other previously established methods, providing direct *in situ* comparisons (e.g. Stein *et al.* 2014). This approach would be appropriate in future studies that use novel techniques or equipment not previously employed in saltmarsh flats.

Fish attributes and environmental factors

Some of the tidal and temporal variables assessed were found to be more consistently reported than were others. Tidal conditions

during sampling, for example, were frequently reported (in 72% of reviewed papers). Sampling most commonly took place during high tides, with papers often specifying spring high tides, which in many locations is the only time when the marsh flats are fully inundated and accessible to fish (e.g. Bloomfield and Gillanders 2005; Quan *et al.* 2011). Several sampling techniques, such as, for example, fyke nets, block nets and flume nets, depend on the ebb tide to passively catch fish leaving the marsh surface (Hettler 1989; Dionne *et al.* 1998; Warren *et al.* 2001). Because diel phase can influence fish species richness and numbers (Prahallad *et al.* 2019), the frequent absence of information relating to diel phase during sampling is notable. Although assessing fish-assemblage responses to the patterns of environmental conditions of diel, tidal and seasonal scales can be challenging practically (Rountree and Able 2007), reporting the details of when sampling took place (and the associated environmental conditions present) is important for any study of fish on vegetated flats, because tidal variation, diel period and seasonal variation have all been found to influence saltmarsh-flat fish assemblages (e.g. Kneib and Wagner 1994; Thomas and Connolly 2001; Crinall and Hindell 2004). Previous reviews have noted the diversity of sampling methods and lack of standardisation in terms of reporting in studies of fish use of saltmarsh (Rozas and Minello 1997; Connolly 1999). Reporting of tides and flooding regimes has been an important recommendation (Connolly 1999). The variation in environmental variables, fish attributes and taxa recorded reflects the range of research subjects being investigated, but also limits the potential for comparing among studies.

Ecological relationships and management considerations

The most frequent subject of research has been comparisons between vegetated saltmarsh flats and other habitats, including other saltmarsh subhabitats and neighbouring habitats outside saltmarsh. Differences in the habitats being compared and the methods employed limit the potential for meta-analyses. Minello *et al.* (2003) found that only 32 studies met their research subject and density measurement criteria, and, of these studies, only six included vegetated inner marsh. For studies to be used in meta-analyses, methods that provide a measure of the number of fish per marsh area (as used by Minello *et al.* 2003) need to be employed, and environmental details such as landscape structure and tidal conditions and patterns need to be reported (Connolly 1999).

The influence of marsh modification and degradation on fish assemblages, including hydrological modification and the effects of invasive species, has been frequently investigated. The influence of less direct impacts on marsh hydrology on fish assemblages have also been investigated. These less direct impacts include changed watershed imperviousness associated with coastal development (Rudershausen *et al.* 2016) and marsh submergence associated with changes in sediment supply (Rozas and Reed 1993).

The effects of invasive plant species were also frequently investigated. With the exception of one study conducted in China, which compared invasive *S. alterniflora* marshes to native *Scirpus mariqueter* marshes (Quan *et al.* 2011), studies on the effects of invasive plant species were confined to the

United States, where the invasive reed *Phragmites australis* has become increasingly prevalent along north-eastern coasts. There is, therefore, an opportunity for future research in places such as Australia where invasive plant species (such as *Spartina anglica*) are present (Prahalad 2014) and the implications for fish habitat are not yet known.

The potential effects of sea-level rise on saltmarsh was mentioned briefly in some studies (e.g. Ennis and Peterson 2015; Lechêne *et al.* 2018) but this was not specifically studied in terms of implications for fish habitat. Coastal saltmarsh is vulnerable to climate change and rising sea levels. Changes in saltmarsh plant communities associated with climate change have already been documented (Prahalad *et al.* 2011). Changes to saltmarsh area and vegetation type as a result of rising sea levels (particularly if inland retreat is not possible), as well as changes in climate, may affect fish habitat availability and requires research. 'Within-range' expansion of mangrove into saltmarsh flats, related to climate change and rising sea levels, also has implications for fish habitat and requires research (Kelleway *et al.* 2017).

Many regions have faced widespread pressures on formerly large areas of marsh, including subsidence as a result of large-scale inland land-use changes, impoundments, coastal development and invasive plant species, with some extensive restoration projects taking place as a result (e.g. Warren *et al.* 2002). Consequently, several studies have focussed on the effects of these restoration efforts on fish assemblages. In parts of the USA, particularly the Atlantic and Gulf Coasts, marsh restoration research has been ongoing for nearly 40 years (Warren *et al.* 2002). There is a dearth of information on restoration works and implications for fish assemblages in other parts of the world (Creighton *et al.* 2019).

The relationships between fisheries and saltmarsh flats was addressed less frequently in the literature we reviewed. The limited number of studies that investigate this subject may be related to the challenge of distinguishing the contribution of saltmarsh flats compared with other potential saltmarsh habitats, and the influence of other confounding variables such as changes in fishing effort (Connolly 1999). Because many estuarine species rely on several habitats during their life histories, determining the direct contribution of saltmarsh to particular fisheries can be challenging (Kneib 2003). Several studies have reported fisheries species caught on saltmarsh flats (e.g. Connolly *et al.* 1997; Prahalad *et al.* 2019), and the dietary contribution of saltmarsh flats for fish is a reasonably frequently studied subject of research (e.g. Warren *et al.* 2002; Crinall and Hindell 2004; Platell and Freewater 2009), but demonstrating links to commercial and recreational fisheries species can be more difficult. Connolly (1999) suggested that large-scale, long-term adaptive-management studies are needed to demonstrate any link between saltmarsh loss and reduced fisheries, or, alternatively, small-scale studies on caloric requirements or isotopic studies to portray food webs. A different approach was taken by Saintilan *et al.* (2008), who studied changes in saltmarsh fish assemblages following the closure of commercial fishing, rather than investigating the effects of changes to saltmarsh habitat itself on fisheries. Future studies using techniques such as isotopic analysis will be beneficial in understanding links between saltmarsh-flat habitat and fisheries.

Conclusions, research gaps and recommendations

Although the variety of methods noted in previous reviews is still apparent, the present review found that three methods were used more frequently than others. Drop samplers, pop nets and fyke nets all have positive attributes that make them suitable choices in relation to environment, research questions and practical considerations. On the basis of suitability for vegetation type, capacity to directly measure density, portability, and suitability for use during both day and night, recommendations for methods can be made. Drop samplers are more suitable for tall graminoid marsh, where access for deployment of other nets and traps is more difficult, whereas pop nets are more suitable for succulent marsh. Fyke nets can be used in both vegetation types. Drop samplers and pop nets both provide measures of density, which is valuable not only for comparisons being made within a single study, but also allows data to be used in meta-analyses of multiple studies and to compare different habitats or changes in habitat condition. Fyke nets have been used in both succulent and graminoid vegetation types, but they do not allow fish density to be directly measured. All three are portable, facilitating replication in sampling design, although drop samplers rely on boat access for deployment. Both pop and fyke nets do not require a boat for deployment and can be used for both day and night sampling. An additional important environmental consideration is tide stage. Unlike drop samplers and pop nets, fyke nets may be less suitable for studies investigating variation in fish use by tidal stage.

There are many regions where research on fish use of vegetated saltmarsh flats is still absent or limited. Given the global variation in vegetated-flat habitat, including differences in marsh plant community composition and inundation patterns, this represents a distinct gap in the literature. Research in locations currently understudied will be valuable, particularly given the ongoing loss and degradation of saltmarsh. The relationships between the fish assemblages of vegetated saltmarsh flats and coastal fisheries, the influence of invasive plant species on fish assemblages in Australia and areas where this has not yet been investigated, and the potential effects of climate change, sea-level rise and mangrove incursion are also worthy of more research.

Our review will enable investigations that build on the important previous work and reviews to expand knowledge of how fish use saltmarsh flats. In particular, our inventory of methods and design will help inform sampling approaches to under-researched questions.

Conflict of interest

The authors declare that they have no conflicts of interest.

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