



# The drivers of anguillid eel movement in lentic water bodies: a systematic map

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**Abstract** Anguillid eels are near globally distributed catadromous fishes with marine spawning areas and inshore and inland growth areas in both lotic (rivers, estuaries) and lentic (lakes, ponds, lagoons) water bodies. As predators, anguillid eels play an important ecological role in both marine and freshwater systems, and several species are harvested commercially for food. However, some of the more widely distributed species have undergone severe declines in recruitment and their population status is now of significant concern. Given the multiple and lengthy migrations undertaken by anguillid eels, understanding of the drivers of movement is fundamental for species conservation and management. Yet, despite the importance of lentic systems to their ecology, most studies on anguillid eel movement have been

conducted in lotic systems. Given that key influences on eel migration in lotic water bodies, such as fluctuations in flow and water temperature, may be minimised in lentic environments, the transferability of findings between lotic and lentic systems cannot be assumed. A systematic map was constructed to synthesise current knowledge on the extrinsic and intrinsic drivers of anguillid eel movement in lentic systems. The current state of knowledge of the drivers of eel movement in lentic systems is presented and compared to the relatively well-understood drivers of movement in lotic systems. We also discuss current knowledge gaps and limitations, and identify key future research requirements to inform the management and conservation of anguillid eels in understudied lentic systems.

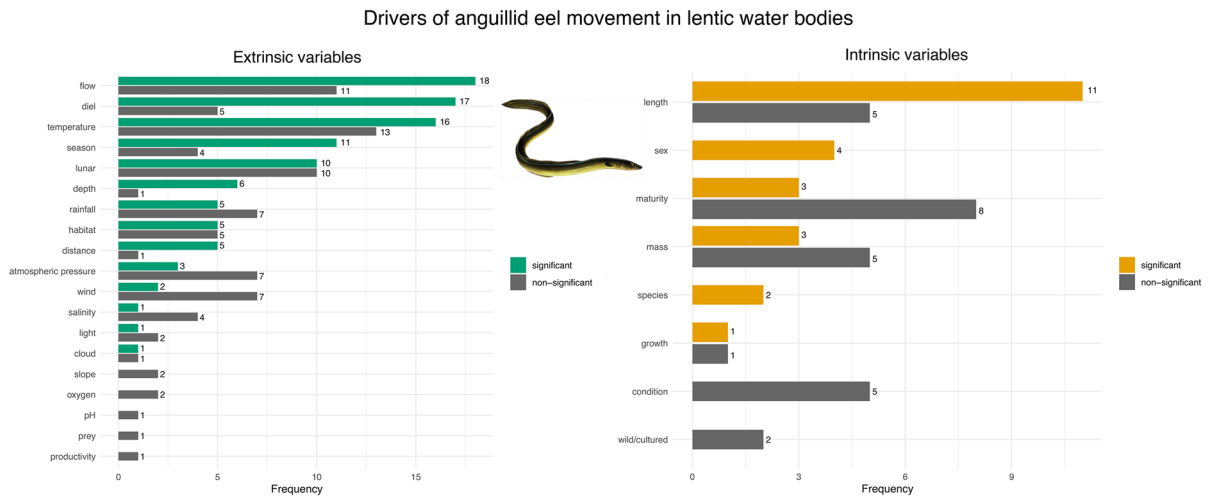
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## Graphical abstract



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## Introduction

Anguillid eels are a taxonomic group comprised of 19 different species and subspecies (Arai 2020; Righton et al. 2021; Jellyman 2022) that are globally distributed, with the exception of the eastern Pacific and South Atlantic (Jacoby et al. 2015; Béguier-Pon et al. 2018a, b; Arai 2020; Righton et al. 2021). Anguillid eels have a unique set of morphological and behavioural traits which has enabled them to become a successful and widespread genus (Jellyman 2022). These traits include high fecundity and semelparous spawning, physiological and behavioural adaptability to diverse aquatic environments, resilience to extreme environmental conditions, and being energetically conservative (Arai 2020; Jellyman 2022). However, despite their resilience and adaptability, and in line with other marine and freshwater populations (WWF 2016, 2020), many anguillid eel species have experienced considerable declines in recent decades (Jacoby et al. 2015; Drouineau et al. 2018). These are due to a combination of factors including exploitation, climate change and natural system modifications (Jacoby et al. 2015; Drouineau et al. 2018). Juvenile glass eel recruitment in the European eel (*Anguilla anguilla*), American eel (*A. rostrata*), Japanese eel (*A. japonica*) and New Zealand longfin eel (*A. dieffenbachii*) have

declined by over 90%, 95%, 80%, and 75%, respectively, since 1970s/1980s (Arai 2022a). As such, 13 of the 19 species and sub species are threatened by extinction (Jellyman 2022). Due to these population declines, their importance as a food source (Dekker 2019; Arai 2022a), their cultural significance in many countries and their ecological role in both marine and freshwater ecosystems, the conservation and management of anguillid eels is starting to be recognised as an essential part of national and international conservation plans (Jacoby et al. 2015; Kaifu et al. 2021; Arai 2022a).

In contrast to lotic waterbodies which are characterised by flowing or swiftly flowing water, (e.g. rivers and streams), lentic systems pertain to still waterbodies with minimal or no flowing water, such as ponds, lakes and lagoons (Prescott & Eason 2018; Mochev & Pavlov 2021). Lentic systems represent important habitats for facultatively catadromous anguillid eels (Jacoby et al. 2015; Jellyman 2022) which may spend a significant portion of their growth phase in these waterbodies (Vélez-Espino & Koops 2010; Arai et al. 2019). Lacustrine areas are particularly important for the production of females (Oliveira et al. 2001; Vélez-Espino & Koops 2010) because they provide deeper waters and access to large prey that support high densities of eels which may not

be available in lotic systems (Degerman et al. 2019; Piper et al. 2020). Other lentic environments, such as coastal lagoons at the interface between land and sea, provide important habitats for a range of anguillid life history stages (Arai et al. 2019). Lentic waterbodies may be open, with inlets and outlets that permit the movement of water and aquatic biota between the water body and surrounding catchment, or they may be considered closed systems, such as many reservoirs, where natural inflow and outflow are severely restricted or absent. Although natural migration of eel into reservoirs is severely impeded, they may enter as juveniles via pumped inputs and, with favourable habitat and little or no opportunity for escapement, form significant populations (Bašić et al. 2019).

Closed lentic waters thereby represent an important resource in terms of eel conservation, both for the populations they already hold, and the large area of prime eel habitat contained within them that could be utilised through measures to facilitate in- and out-migration. ‘Trap and transport’, where adult eel are aided in their spawning migration through capture and translocation to areas with good seaward access is one such intervention (Béguet-Pon et al. 2018a, b; Piper et al. 2020). Closed systems may also provide important sources of eel for restocking, a conservation measure which aims to increase population numbers by translocating either from different areas or from captive grown populations (Pratt and Threader 2011; Jacoby et al. 2015). Further, these water-bodies offer opportunities for controlled experimentation to address fundamental questions in eel biology without the impacts of immigration and emigration from the system (Jacoby et al. 2015; Béguet-Pon et al. 2018a, b; Arai 2020; Righton et al. 2021). However, despite the widespread use of lentic systems by anguillid eels, relatively little research on eel movement and behaviour has been conducted in these, as opposed to lotic, systems (Béguet-Pon et al. 2018a, b).

Animal movement data is increasingly recognised as being vital to formulating effective conservation and management strategies for threatened species (Martin et al. 2007; Allen and Singh 2016). However, there remains a paucity of movement data on some species, particularly those within marine and freshwater environments (Donaldson et al. 2014; Hussey et al. 2015; Allen and Singh 2016). Movement data on anguillid eels have been collected using a wide range of approaches. Coarse scale movement patterns

can be inferred from otolith microchemistry (Cairns et al. 2004; Lamson et al. 2006; Clément et al. 2014) and mark-recapture studies using passive integrated transponder (PIT) tags (Imbert et al. 2010; Riley et al. 2011), or visible markers, such as floy (Dekker 1989; MacNamara and McCarthy 2014), Carlin (Westin 1990; Sjöberg et al. 2017), streamer tags (Glova et al. 1998; Calles et al. 2013), or dyes (Jellyman and Ryan 1983; Chisnall and Kalish 1993). Finer scale movement data may be obtained through the use of satellite and acoustic telemetry (Béguet-Pon et al. 2018a, b), enabling investigation of migration behaviour [e.g. Jellyman et al. (2002), Aerestrup et al. (2009), Manabe et al., (2011), Righton et al., (2016)], predation (Béguet-Pon et al. 2012; Wahlberg et al. 2014), passage at barriers [e.g. Calles et al., (2012), Piper et al., (2013), Eyler et al., (2016)], habitat selection [e.g. Béguet-Pon (2015), Noda et al., (2021)], site fidelity [e.g. Thibault et al., (2007), Itakura et al., (2018)], movement activity [e.g. Dutil et al., (1988), Kim et al., (2020), Piper et al., (2022)] and environmental drivers of movement [e.g. Crook et al., (2014), Stein et al., (2016), Sudo et al., (2017)].

Animal movement is driven by a variety of extrinsic (biotic and abiotic) and intrinsic (physiology, neurology, life history) factors (Nathan et al. 2008; Williams et al. 2020). The extrinsic and intrinsic drivers of fine scale and large scale movement in anguillid eels have been relatively well investigated in lotic systems (Béguet-Pon et al. 2018a, b) but questions remain over whether the same drivers of movement are applicable in lentic systems. Lentic and lotic systems, for example, have different levels of productivity (Randall et al. 1995; Vélez-Espino & Koops 2010), and many factors, such as flow, current and turbidity, are severely reduced in lentic water bodies (Haro 2003; Piper et al. 2020; Trancart et al. 2020), which can cause differences in ecosystem functioning (Reynolds et al. 1994; Abril et al. 2015). Flow is a significant driver of movement and migration in anguillid eel, and the majority of studies on eel movement ecology have been undertaken in lotic waterbodies (Béguet-Pon et al. 2018a, b; Bašić et al. 2019; Piper et al. 2020). As such, the influence of abiotic variables may vary considerably between the lentic and lotic systems. Given the important role that lentic water bodies play in anguillid eel ecology, understanding the drivers of anguillid eel movement in lentic water bodies is both pertinent and necessary

to formulating effective conservation measures for the many threatened species of anguillid eel.

As a first step towards this goal, we constructed a systematic map of the literature to review the extrinsic and intrinsic drivers of anguillid movement in lentic systems with the following aims: (1) examine current knowledge of anguillid eel movement ecology in lentic water bodies, (2) summarise the intrinsic and extrinsic variables that appear to drive eel movement in these systems, based on currently available evidence and (3) highlight gaps in knowledge and potential future directions in the field.

## Materials and methods

This systematic map was generated using a methodology outlined in James et al. (2016), CEE guidelines (Collaboration for Environmental Evidence, 2013) and the RepOrting standards for Systematic Evidence Syntheses (ROSES) as developed by Haddaway et al. (2018) (Supplementary Information 1).

### Stakeholder engagement

Informal conversations with stakeholders from UK government agencies and non-profit organisations [Environment Agency, Centre for Environment Fisheries and Aquaculture Science (Cefas), and Zoological Society of London], confirmed that this topic is relevant and important for progressing knowledge and assisting the conservation and management of freshwater eel species world-wide.

### Objective of the review

The objective of this systematic map is to provide an overview of the intrinsic and extrinsic drivers of eel movement in lentic ecosystems. Our primary question was: what are the extrinsic and intrinsic drivers of eel movement in lentic systems?

Most common questions in systematic maps have four definable elements, often referred to as PI/ECO (Population, Intervention/Exposure, Comparator,

Outcome). We evaluated our primary question according to the PI/ECO framework (Collaboration for Environmental Evidence, 2013; James et al. 2016). These components, and a definition of PI/ECO elements, can be found in Supplementary Information 2 Table S1.

### Literature search

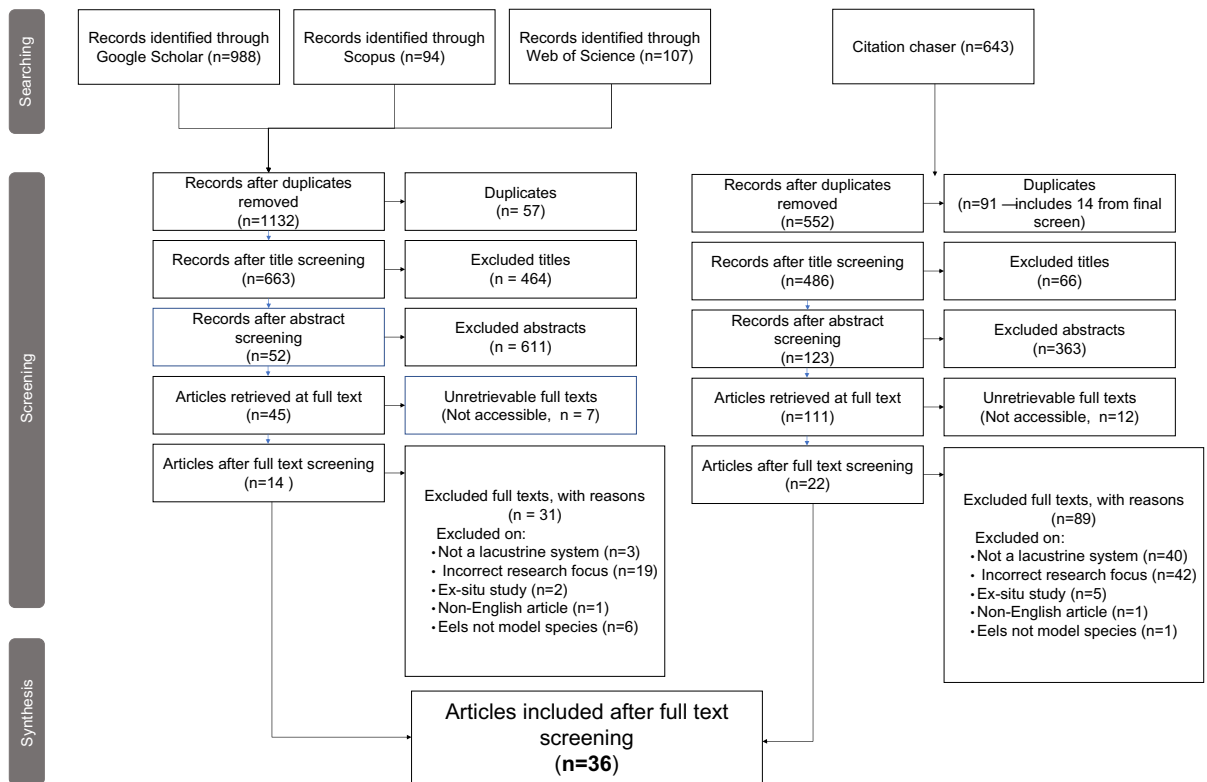
Searches followed the now industry standard process for collating and synthesising documented evidence (Haddaway and Macura 2018; Haddaway et al. 2018). Boolean keyword searches were conducted in three online databases: Web of Science,<sup>1</sup> Scopus<sup>2</sup> and Google Scholar,<sup>3</sup> to incorporate a range of literature from multiple sources (Bramer et al. 2013; Giustini & Boulos 2013; Haddaway et al. 2018). All searches were conducted in English in Google Chrome using incognito mode. All studies identified before 25 February 2022 were included. The search string Eel\* OR Anguilla\* was included for the population components of the primary questions. The terms lentic\* OR still water\* OR lake\* OR lacustrine\* OR pond\* OR reservoir\* were included to cover the exposure/intervention components of the research question (see Supplementary Information 2 Table S1), with environment\* OR habitat\* addressing the comparator components. Finally, we added behaviour\* OR movement\* OR telemetry\* OR tag\* OR mark\* to cover the outcome components of the research questions. Search terms and search options (the location in the journal that the keywords were searched for) for each search engine can be found in Supplementary Information 2 Table S2.

Web of Science identified 107 articles and Scopus 94 articles which were extracted as csv files (Fig. 1). Google Scholar identified 2,220 results. To extract articles from Google Scholar, the software Publish or Perish was used, which can extract up to the first 1000 articles of a Google Scholar search (Harzing 2007). This software extracted 988 from our search. A total of 1,189 articles were imported in Zotero (Trinoskey et al. 2009), where duplicates (57) were removed. The final 1,132 articles were imported into Sysrev (<https://sysrev.com/>) and filtered for suitability following a set of predetermined rules for eligibility (Supplementary Information 2 Table S3).

<sup>1</sup> <https://www.webofscience.com/wos/zoorec/basic-search>

<sup>2</sup> <https://www.scopus.com/>

<sup>3</sup> <https://scholar.google.co.uk/>



**Fig. 1** Flow diagram for systematic mapping protocol, adapted from (Haddaway et al. 2017). Numbers from each search, and subsequent screening, are provided

## Screening of evidence

Screening was undertaken primarily by MJW; however, spot checks of the final outcomes were undertaken by ATP. In detail, articles were excluded if, first, their titles did not contain one of the terms ‘eel’, ‘fish’, ‘movement’, ‘telemetry’, ‘environmental’ or ‘ecology’ (or correlates of these terms); second, if it was clear that eels were not the model species, that the study was not undertaken in a lentic system, and the study was not movement ecology focused, and third, if a full text could not be retrieved using either the Institute of Zoology or the University College London institution subscriptions. Finally, a full text screening of the articles was undertaken to ensure that eel species were the primary or secondary model species, the study was undertaken in a lentic system, the study was not ex situ, and the article was in English. The screening process and inclusion criteria of articles in relation to PE/ICO elements is summarised in Supplementary Information 2 Table S3.

Along with web-based searches, an additional search technique known as ‘citation chasing’ was used. This obtains lists of references from a group of selected studies (backward citation chasing), and lists of articles that cite that group of studies (forward citation chasing) (Whear et al. 2014; AlKhars et al. 2020). Articles obtained from successful screening of web-based searches were uploaded into the citation chaser app, citationchaser (<https://estech.shinyapps.io/citationchaser/>) (Haddaway et al. 2021), to generate a list of new articles from backward and forward citation chasing for review, which were screened using the process outlined above. The outputs of all searches can be found at: <https://zenodo.org/record/7250310#.Y1g6zHZKjDc>. The full workflow for identification and screening of articles for this review is outlined in Fig. 1 The complete database is available to download from <https://sysrev.com/u/6827/p/116118>.

**Table 1** Summary statistics of length and mass per eel species extracted from the 36 reviewed articles

Species	Min length (mm)	Max length (mm)	Median length (mm)	Min mass (g)	Max mass (g)	Median mass (g)
<i>A. anguilla</i>	46.0	1140.0	727.0	90.0	1970.0	799.5
<i>A. australis</i>	55.0	920.0	343.2	NA	NA	NA
<i>A. dieffenbachii</i>	63.0	1372.0	1036.0	260.0	8800.0	3445.0
<i>A. japonica</i>	525.0	693.0	609.0	212.0	526.0	344.9
<i>A. rostrata</i>	150.0	820.0	593.0	40.0	1373.0	398.0

### Metadata extraction

A broad range of metadata was extracted from the articles remaining after screening (Supplementary Information 2 Table S4), consolidated into a database (Supplementary Information 3), and changes to these categories and variables reported in the systematic map. Metadata that could not be obtained was coded as “UA” (unattainable). Any metadata category that was not applicable to a study was coded as “NA” (not applicable). There may be variability, or lack of consistency, between articles in how they refer to extracted metadata. For example, multiple measurements related to a single variable might be used in one article (e.g. water level or daily change in water level), or the same variable might be referred to differently in different articles (e.g. moon phase, or lunar phase). As such, for each metadata extraction category, where feasible, measurements were collated and grouped for analysis. In this review, the term “variable” was used to describe a single measurement, such as “wind”, “salinity”, or “maturity”. The term “metric” is used to describe a specific measure for quantifying a variable, e.g. “wind speed” or “wind force”, or “life stage” or “ocular index”. Details on grouping categories from the metadata can be found in Supplementary Information 2 Tables S5 – S8.

### Review of current knowledge

The web-based search identified 1,189 articles, which following the screening process left 14 articles for review. Citation chasing from these 14 articles resulted in an additional 643 articles. Screening these left an additional 22 articles, giving a total of 36 articles for review (Fig. 1). Further details of the bibliographic search results can be found at <https://>

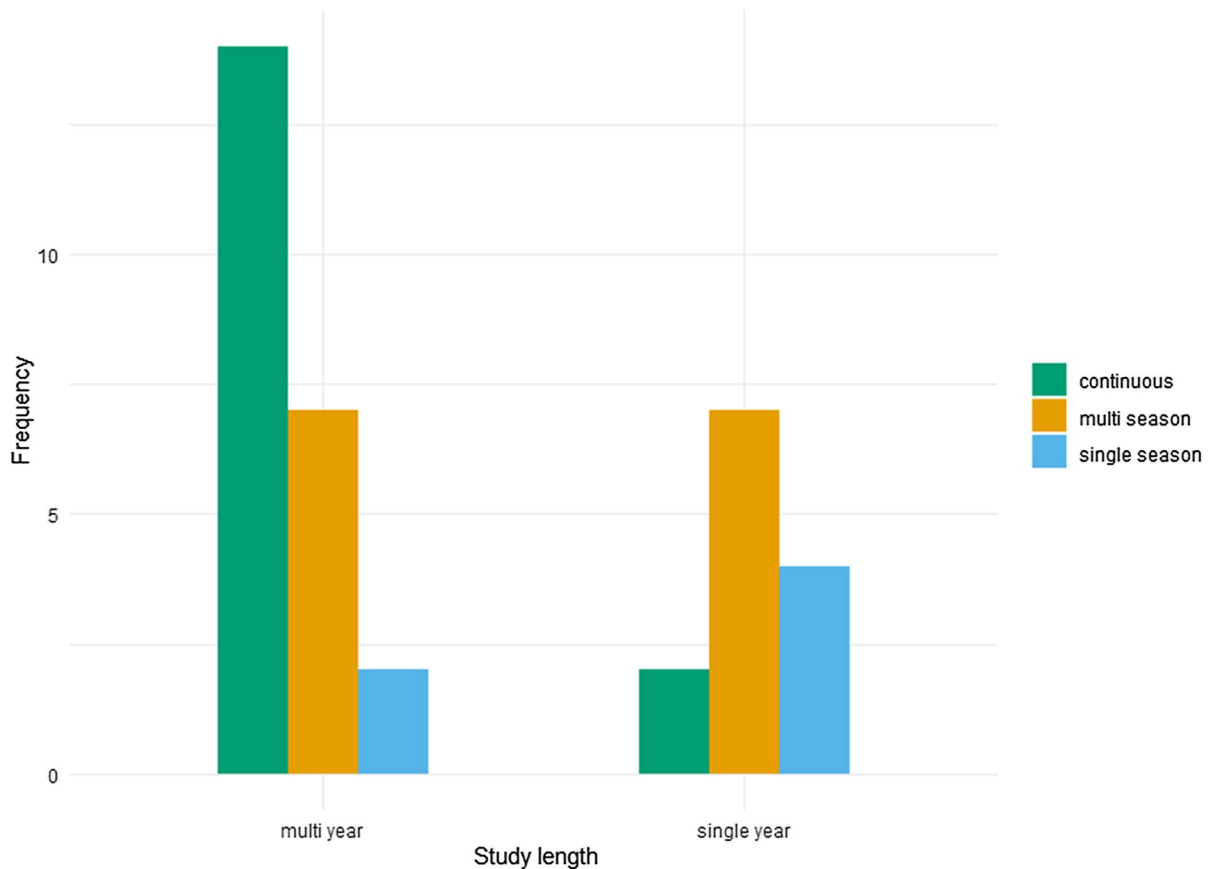
[sysrev.com/u/6827/p/116118](https://sysrev.com/u/6827/p/116118) and metadata extraction database (Supplementary Information 3).

Reviewed articles were published from 1975 to 2022. Journal articles formed the majority ( $n=35$ ) of the final reviewed articles, with one MSc thesis. Movement ecology was the primary research focus ( $n=27$ ), but also habitat ecology ( $n=4$ ), distribution ( $n=3$ ) and demographics ( $n=2$ ).

This section presents an overview of investigations into the movement ecology of anguillid eels in lentic water bodies. It includes a summary of the geographical and taxonomic focus, as well as details of the intrinsic and extrinsic variables used within the reviewed articles.

### Geography, taxonomy and conservation status

Study sites were primarily located in Europe ( $n=18$ ) or New Zealand ( $n=12$ ), with a handful in North America ( $n=3$ ) and Asia ( $n=3$ ). Of the 19 species/subspecies of Anguillid eel (Righton et al. 2021), only 5 [European eel (*A. anguilla*), shortfin (*A. australis*), New Zealand longfin (*A. dieffenbachii*), Japanese eel (*A. japonica*) and American eel (*A. rostrata*)] were represented in reviewed articles, and were all from temperate or subtropical/temperate regions (Jacoby et al. 2015; Righton et al. 2021). The species studied covered a range of IUCN threat categories, including Near Threatened, NT (*A. australis*), Endangered, EN (*A. dieffenbachii*, *A. japonica*, *A. rostrata*), and Critically Endangered, CR (*A. anguilla*). It is worth noting that although *A. australis* is differentiated into two sub species [*A. australis australis* and *A. australis schmidtii* (Righton et al. 2021)], none of the articles where *A. australis* was identified as a study species made this distinction.



**Fig. 2** Frequency of study duration categories across the 36 reviewed articles

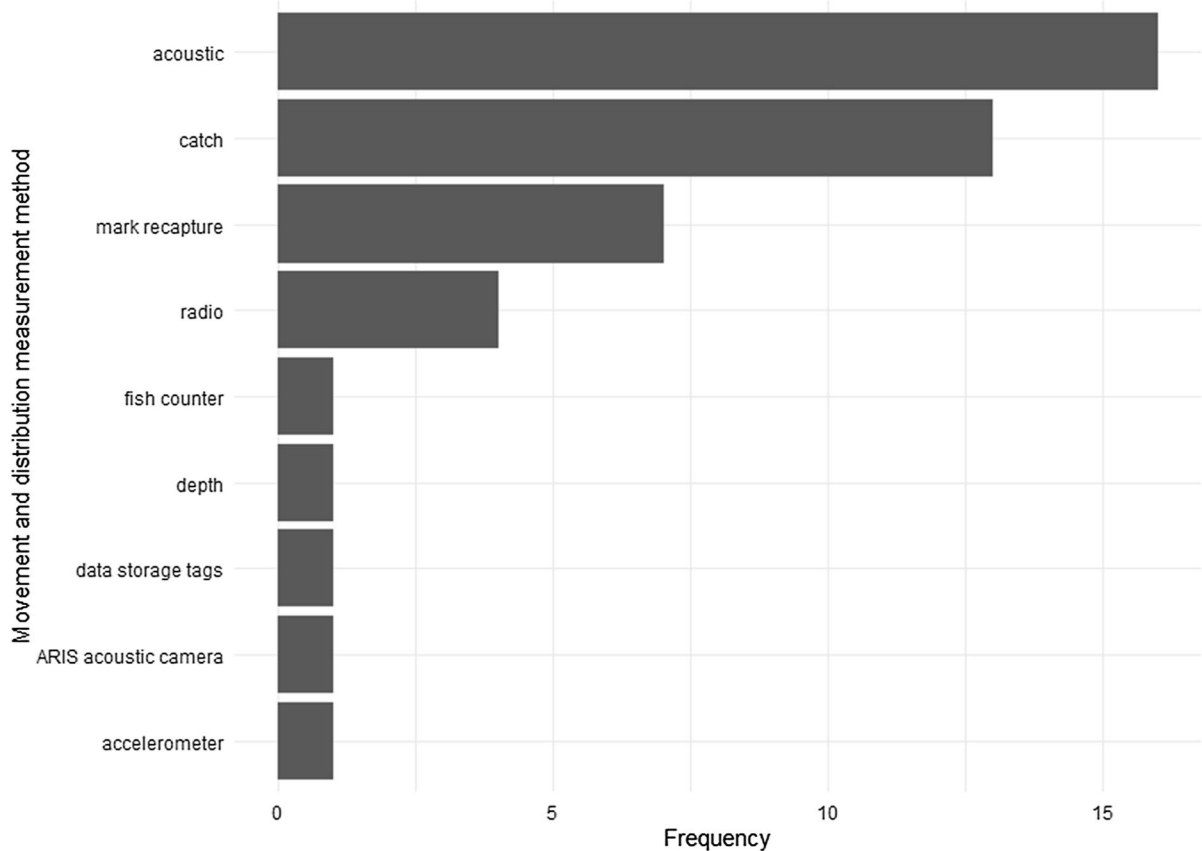
### Life stage and morphology

Life stage data were presented in 75% of studies, using a variety of terminologies including silver, yellow, elver, glass eel, as well as quantitative categories such as < 20 cm, 20–50 cm, > 50 cm, < 300 mm and > 300 mm total length. For our analysis we grouped these into three categories; matured adult; immature adult; and juvenile. Typically, silver was designated as matured adult, yellow as immature adult, and elvers and glass eels as juvenile. For size categories, this designation was led by terminology within the study (e.g. if a quantitative size category was referred to as juvenile or matured adult) and with the species descriptions because anguillid species mature at different sizes and have different maximum lengths. Most studies focused on matured adult and/or immature adult eels (24 out of 27) with five studies including juveniles.

Length data were presented in 69% of articles and mass data in 44% (Table 1). Eleven articles (31%) gave information on the sex of the study animals, with only one addressing male eels.

### Study length and season

Full definitions of study length categories can be found in Supplementary Information 2 Table S5. Articles most commonly collected data across a mix of seasons and years, with continuous multiyear studies the most frequent ( $n=14$ ), followed by multi season multiyear ( $n=7$ ) and multi season single year ( $n=7$ ) (Fig. 2). There was a relatively even spread of seasons covered (summer,  $n=32$ , followed by autumn,  $n=29$ , winter,  $n=22$ , spring,  $n=21$ ). Length of study duration (days) was presented in 19 of the 36 reviewed articles and ranged from 2 to 1161 days (median 329 days).



**Fig. 3** Frequency of movement and distribution measurement methods found in the reviewed articles

### Capture, movement data collection, and movement metrics

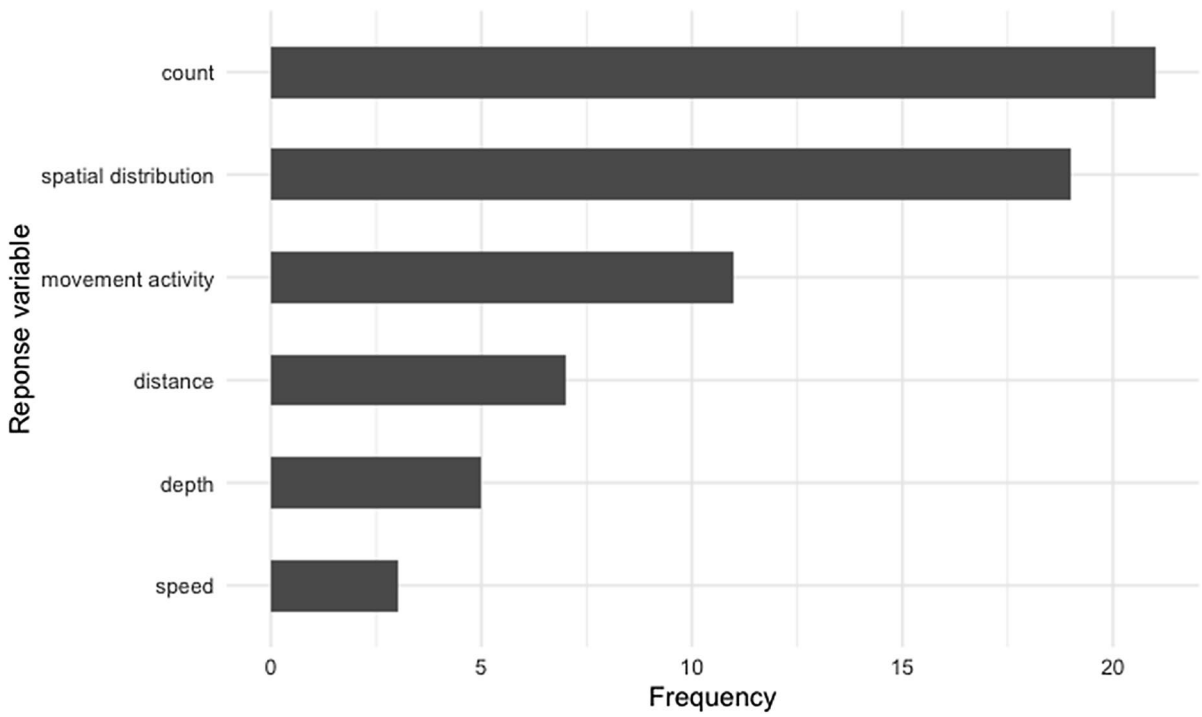
A variety of methods were used to capture anguillid eels in the reviewed papers, including fyke nets ( $n=21$ ), traps ( $n=9$ ), electrofishing ( $n=4$ ), pond nets ( $n=2$ ), trawls ( $n=2$ ) and long lines ( $n=1$ ). Data on capture method was unavailable in only one article. Of the nine techniques employed to collect movement and distribution data, acoustic telemetry ( $n=16$ ), catch data ( $n=13$ ) and mark recapture (e.g. PIT, floy, streamer and carlin tags, and dye) ( $n=7$ ) were the most prevalent (Fig. 3). Among the six response variables used monitor movement activity in the studies, count and spatial distribution metrics were the most common ( $n=21$  and  $n=19$ , respectively) (Fig. 4). Although detailed data on movement, such as home range size and movement extent, could be of value for conservation of

anguillid eel, the focus of this research was on the drivers of different movement metrics, and as such metadata on movement metrics were not collected.

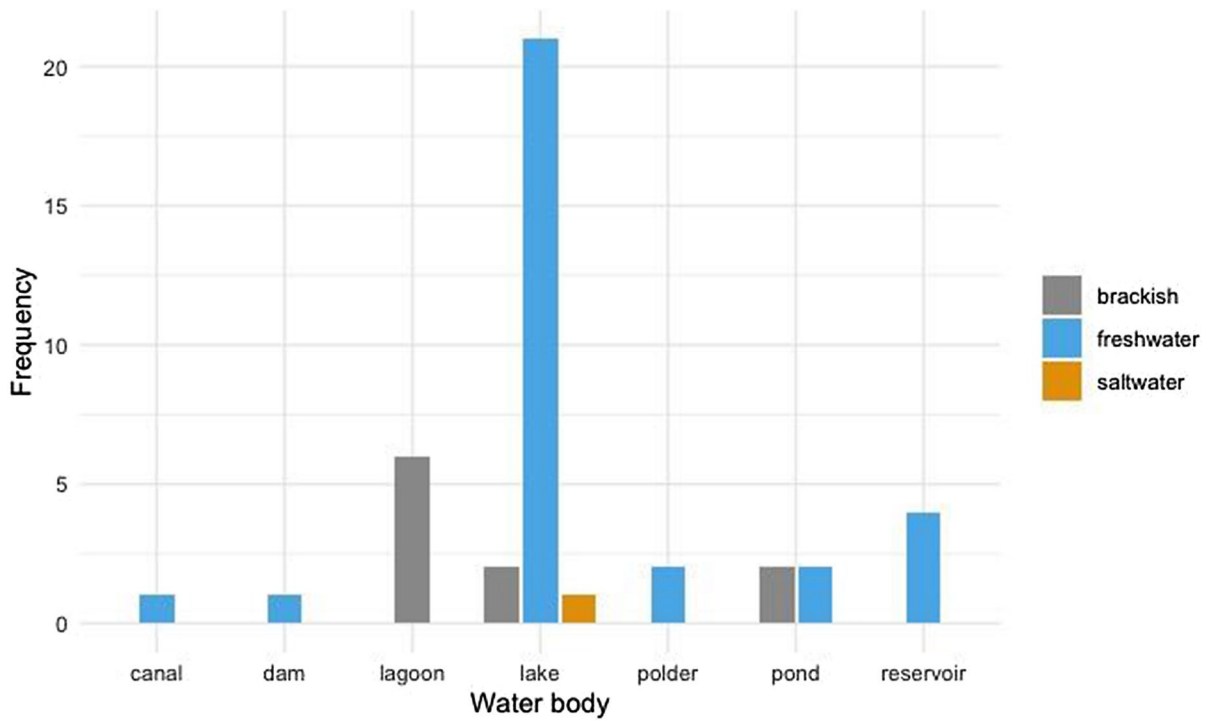
### Water body characteristics

Seven types of lentic systems were studied within the 36 articles, with data collected from a total of 42 individual water bodies including freshwater ( $n=31$ ), brackish ( $n=10$ ) and saltwater environments ( $n=1$ ) (Fig. 5). These ranged in size and depth from 1.2 to 114,000 ha (median 646 ha) and from 1.2–444.0 m (median 5 m), respectively. Data on 9 and 12 of the 42 water bodies was unavailable for size and depth, respectively. Only 1 of the 42 water bodies was a closed system with no feasible route of eel immigration or emigration (Bašić et al. 2019).

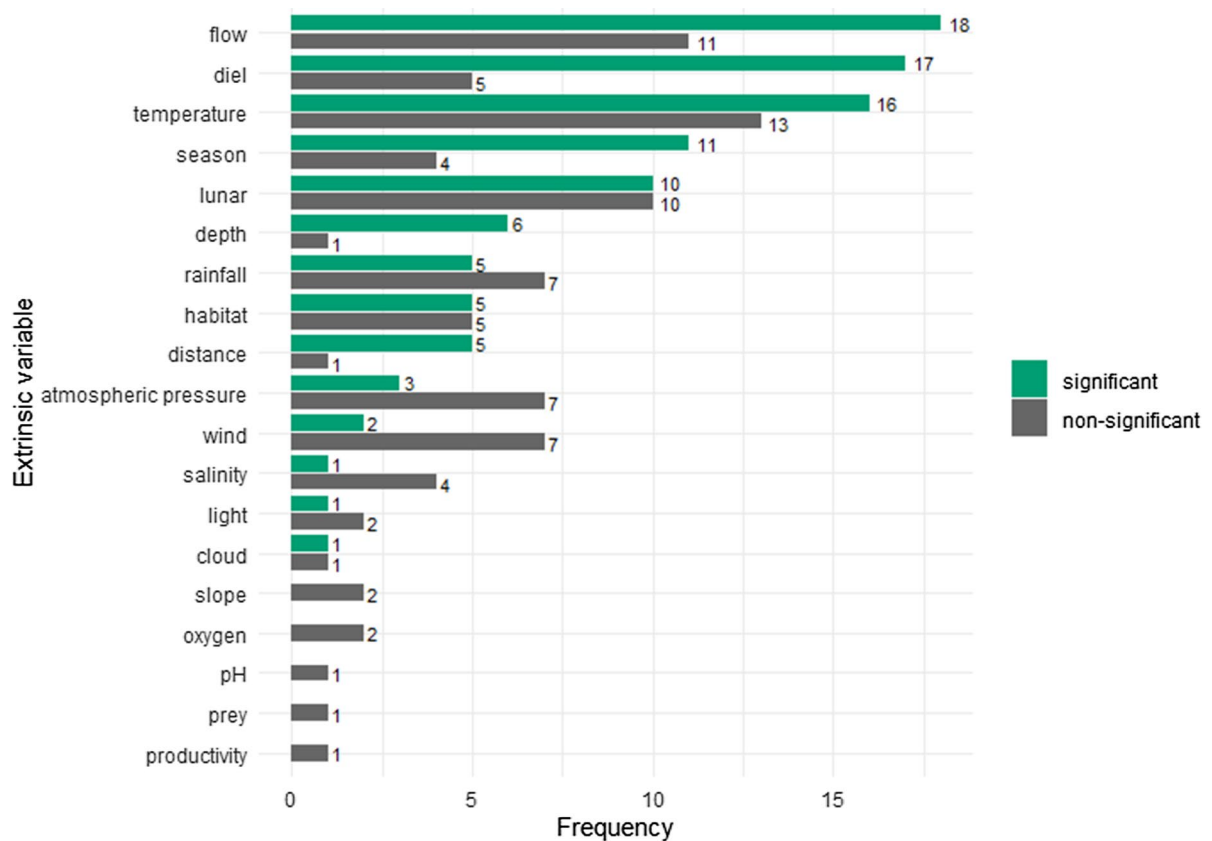




**Fig. 4** Frequency of response variables used to measure movement in the 36 reviewed articles



**Fig. 5** Types of different lentic study systems across the 36 reviewed studies, by water type



**Fig. 6** Frequency of extrinsic factors used as explanatory variables to investigate drivers of Anguillid eel movement in the 36 articles reviewed. Variables are ranked by the number of studies that identified a significant relationship

### Extrinsic and intrinsic drivers of eel movement

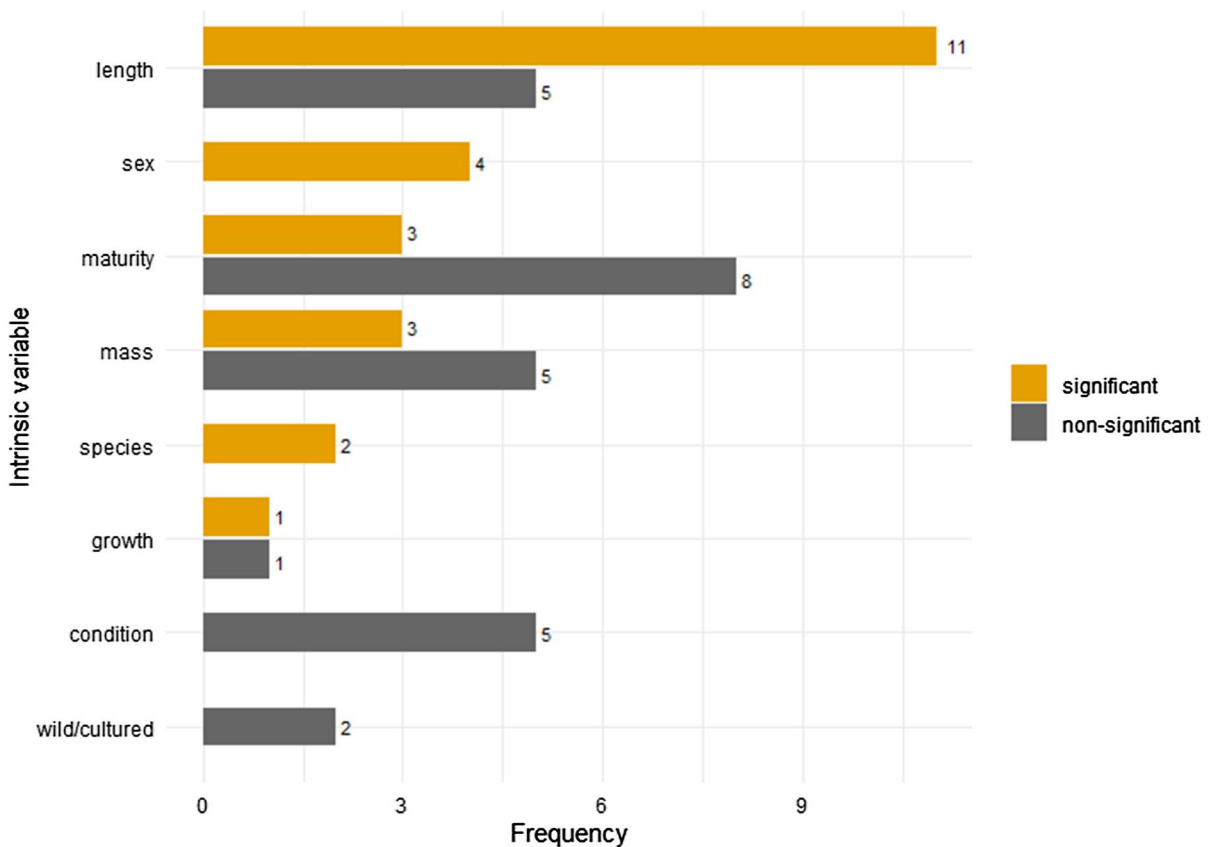
All 36 reviewed studies included extrinsic variables in their investigations, with metrics of temperature ( $n=29$ ), flow ( $n=29$ ), diel period, ( $n=23$ ), lunar cycle ( $n=20$ ), and season ( $n=15$ ) the most common (Fig. 6). Overall, these five variables were found to be the most significant drivers of anguillid movement in lentic systems (Fig. 6).

Intrinsic factors were included in 24 articles. In some anguillid eel species, length and mass can be proxies of maturity and body condition, respectively. However, individuals mature at a wide range of different lengths and masses depending on the latitude/temperature of the rearing environment and species studied (Kotake et al. 2007; Hagihara et al. 2012; Wakiya et al. 2019). As such, mass is generally not a good proxy for body condition or maturity (Bevacqua et al. 2011a, b) and therefore length, mass, and

body condition were kept as separate categories. Metrics of length ( $n=16$ ) were the most frequent intrinsic variables used (Fig. 7), followed by maturity (e.g. life stage, eye index, age) ( $n=11$ ) and mass ( $n=8$ ). These three metrics, along with sex ( $n=4$ ), were also found to be the most significant intrinsic drivers of anguillid eel movement (Fig. 7).

### Discussion

The movement ecology of anguillid eels has primarily been studied in lotic rather than lentic systems (Béguet-Pon et al. 2018a, b). In this section, we evaluate our findings of the most important extrinsic and intrinsic drivers of eel movement in lentic systems in the context of evidence from lotic systems.



**Fig. 7** Frequency of intrinsic factors used as explanatory variables to investigate drivers of Anguillid eel movement in the 36 articles reviewed. Variables are ranked by the number of studies that identified a significant relationship

### Extrinsic drivers

Diel and seasonal metrics, and temperature, flow and lunar cycle were found to be the most frequent and most significant extrinsic drivers of anguillid eel movement in lentic systems. This matches what is understood about extrinsic drivers of movement in lotic systems and indicates that despite variables, such as flow, being minimised in lentic waterbodies (Haro 2003; Piper et al. 2020; Trancart et al. 2020), the key drivers of movement are similar.

#### *Diel period and seasonality*

Sixteen of the 36 reviewed articles explicitly included diel period as an explanatory variable in their analyses, and in 88% of cases it was found to be a significant driver of anguillid eel movement. Movements of eel in lentic systems have a specific daily pattern

with activity much more frequent at night (Jellyman and Chisnall 1999; Barry et al. 2016; Verhelst et al. 2018a, b; Noda et al. 2021), mirroring findings from lotic systems (Edeline et al. 2009; Hedger et al. 2010; Stein et al. 2016), and is thought to indicate foraging activity (Dou and Tsukamoto 2003; Barry et al. 2016). This may also be associated with low light conditions because movement activity has been linked to lunar phase and increased cloud cover (Edeline et al. 2009; Stein et al. 2016; Béguer-Pon et al. 2018a, b). However, interestingly, light level was not a common extrinsic variable, used in just three articles in the systematic map, and therefore light level should be integrated further to assess this.

Seasonality (e.g. month, date and season) was also a key driver of movement, with significance reported in 79% of the 14 articles that addressed it. Seaward migration of adults from lentic systems generally peaked during autumn in European eel (Verhelst et al.

2018a, b; Verhelst, Reubens, et al., 2018), American eel (Winn et al. 1975) and Japanese eel (Noda et al. 2019, 2021), and late summer in shortfin and New Zealand longfin eel (Jellyman and Unwin 2017; Stuart et al. 2019). A seasonal pattern for non-migratory movements is also seen but this may be more variable between location and species. For example, Ovidio et al. (2013), found movement distance and range of resident yellow European eel highest during the spring, while Jellyman and Unwin (2017) found swimming activity greatest during the summer months. Seasonality drives movement in many animal species (Winkler et al. 2014) and is another important temporal driver of anguillid eel movement in lotic systems (Haro 2003; Riley et al. 2011; Hanzen et al. 2021). Migration is often during a specific seasonal window, typically during summer for the upstream migration of juvenile eels, and autumn for the downstream migration of silver eels (Feunteun et al. 2003; Haro 2003; Tesch 2003; Jellyman and Arai 2016), and typically linked to seasonal changes in environmental variables such as temperature and water discharge (Marohn et al. 2014; Matondo and Ovidio 2016; Stein et al. 2016; Sandlund et al. 2017; Arevalo et al. 2021). However, this can vary, both within and between species (Haro 2003; Bruijs and Durif 2009; Righton et al. 2016; Arai 2022b). Seasonal differences in movement activity and home ranges are also found across anguillid eel species in lotic systems (Baras et al. 1998; Feunteun et al. 2003; Mélanie Bégue-Pon et al. 2015a, b; Itakura et al. 2018). Knowledge of seasonal patterns of movement is valuable to inform conservation measures. For example, implementing seasonal shutdowns of hydroelectric dams can significantly reduce mortality in maturing eel (Eyler et al. 2016), while targeted spillway opening at key periods facilitates downstream passage and seasonal operation of barrier mitigation measures, such as eel lifts, aids upstream movements (Eyler et al. 2016; Santos et al. 2016; Knott et al. 2020). Given that eel in lentic systems apparently display a similarly strong seasonality in their movements, further study of these relationships should deliver comparable conservation benefits through optimising the timing of management interventions.

### *Temperature*

Metrics of temperature were the second most frequent extrinsic variables found in our systematic map and were significant in 67% of the studies that addressed them. Decreases in temperature were an important trigger for migration by eel in lentic systems (Acou et al. 2008; Jellyman and Unwin 2017; Noda et al. 2021), and higher temperatures were correlated with both greater movement activity (Boubée et al. 2008; Ovidio et al. 2013; Verhelst, Reubens, et al. 2018; Bašić et al. 2019) and utilisation of shallower depths (Westerberg & Sjöberg 2015; Bašić et al. 2019). Seasonal decreases in water temperature, combined with increased river discharge, are similarly important triggers for anguillid eel metamorphosis and migration in lotic systems (Marohn et al. 2014; Matondo and Ovidio 2016; Stein et al. 2016; Sandlund et al. 2017; Arevalo et al. 2021). This is potentially due to water temperature influencing the physiological and morphological state of anguillid eels, and, accordingly, their ability to migrate (Sandlund et al. 2017; Arevalo et al. 2021). In addition, because eels are ectotherms, water temperature can impact oxygen consumption, metabolic rates and feeding motivation (Wan Soo et al. 2002; Hori et al. 2019), all of which influence movement activity. There was no significant relationship between air temperature or change in water temperature and eel movement, although the sample size was low. Lentic water bodies tend to experience reduced fluctuations and variability in water temperature compared to lotic water bodies (Hieber et al. 2002; Jones 2010; Prescott and Eason 2018). Despite this, it seems temperature is an important driver of movement in both lentic and lotic systems. It may be, however, due to differences in stability and variability between lentic and lotic water bodies that temperature thresholds for movement vary between systems, which will be an interesting avenue for future research. Increases in water temperature over time, due to climate change, has been shown to alter timings of migration patterns across fish species (Quinn and Adams 1996; Tamario et al. 2019). Knowledge of the temperatures that cause migration in lentic systems is still not well known, but will be important to inform conservation and management policies, such as timings of eel pass openings and ‘trap and transport’.

### Flow metrics

Although temperature regulates eel metamorphosis ahead of migration, flow velocity and volume of water facilitate downstream migration toward the sea (Arevalo et al. 2021). Of the 36 reviewed articles, 29 metrics of flow were used as explanatory variables of anguillid eel movement from 17 different studies. As with metrics of temperature, significance varied from study to study, with 62% of 29 flow metrics ( $n=18$ ) found to be significant. Increased flow is an important driver of eel migration in reservoirs as it enables eel to pass over and negotiate dam crests (Acou et al. 2008; Besson et al. 2016; Jellyman and Unwin 2017). Further, flow velocity and direction drive non-migrant eel movement in coastal lagoons (Lagarde et al. 2021). In lotic systems, discharge, and variation in discharge, can be an important trigger of migration across anguillid eel species (Boubée et al. 2001; Drouineau et al. 2017, 2018; Teichert et al. 2020). In rivers, downstream moving individuals preferentially select routes where water velocity and flow are highest (Piper et al. 2013, 2015, 2017). In areas such as estuaries, currents and tide have a greater impact (Sudo et al. 2017). In common with our findings from lentic systems, water level can also be a significant predictor of eel movement in lotic systems (McCarthy et al. 2008; Bruijs & Durif 2009; Piper et al. 2013), but its effect varies according to location, species and system (Jellyman 1979; Jellyman and Sykes 2003; Bruijs and Durif 2009). In summary, despite the intermittent or reduced metrics of flow in lentic water bodies, they often exert a significant influence on anguillid eel movement in these systems.

### Lunar phase

Lunar phase was frequently used as an explanatory variable in the articles but was found to be significant on only 50% of occasions. Downstream migration from lentic water bodies is linked to lunar phase with migration numbers peaking greatest during dark lunar phases between full and new moons (Winn et al. 1975; Todd 1981; Trancart et al. 2018a, b; Noda et al. 2021). In addition, eel movement activity in lentic systems, for foraging and other non-migratory behaviours, is also linked to darker lunar phases (Lamothe et al. 2000; Barry et al. 2016; Bašić et al. 2019). It

has been suggested that the effect of lunar phase on movement is most likely a direct effect of light, rather than any periodic effects (Hain 1975). If light level is the true force driving anguillid eel movement, this may explain the variable results found in this review, as changing conditions such as cloud cover may alter lighting conditions, thereby minimising variance between different lunar phases. Lunar phase is linked to both upstream, downstream and vertical migration in several anguillid species (Hain 1975; Schabetsberger et al. 2013; Chow et al. 2015; Welsh et al. 2015; Cresci 2020). Glass eels in lotic systems are sensitive to the lunar cycle and may use lunar cues for movement orientation during migration (Cresci et al. 2021). Given its demonstrated significance in 50% of studies, lunar phase, along with light level, should be included as explanatory variables in future investigations on anguillid eel movement.

### Intrinsic drivers

Several intrinsic drivers were utilised across the 36 articles, including length, maturity, body condition, mass and sex. In line with many studies of movement ecology, intrinsic drivers of movement were less frequently studied than extrinsic drivers (Holyoak et al. 2008; Joo et al. 2020). This may be due to the difficulty of obtaining life-history data, such as age or sex, on animal species compared to environmental data, or alternatively because these studies were undertaken by ecologists, the aim of which is to investigate relationships between organisms and the environment (Joo et al. 2020).

### Length

Optimal environmental conditions for growth and survival can differ across body sizes (Gutowsky et al. 2016), and the ability to undertake different movements may change with size (Busch and Mehner 2011; Afonso and Hazin 2015; Noda et al. 2016; Andrzejczek et al. 2019). Length was found to be a significant driver of eel movement in lentic systems in 69% ( $n=11$ ) of articles where it was investigated, with increased body length related to increased home range (Barry et al. 2016; Bašić et al. 2019), and different sizes of eel utilising differing habitat types (Chisnall 1996; Carss et al. 1999; Jellyman and Chisnall 1999). The median size of the water bodies

studied was 646 ha, therefore relatively large and potentially containing multiple different habitats, which likely contributed to the finding that length is an important driver in these systems. In lotic systems, movement may also be strongly associated with body length, with upstream migration undertaken by generally smaller individuals, and larger individuals exhibiting more residency and home ranging movements (Brujls and Durif 2009; Imbert et al. 2010; Cresci 2020; Kume et al. 2020). Body length and size can also be a trigger for downstream migration, but often in combination with other extrinsic and intrinsic drivers (Tsukamoto 2009). As mirrored in our results on lentic systems, body size and length are linked to distribution and habitat preferences across eel species in lotic systems (Hanzen et al. 2021).

### Maturity

Maturity and life stage are important drivers of movement across many species, and different life stages may be associated with distinct movement patterns (Pittman et al. 2014). Interestingly, where maturity metrics (Supplementary Information 2, Table S8) were used as an explanatory variable of anguillid eel movement, they were only found to be significant drivers of movement in 27% of articles ( $n=3$ ), but where significant were linked to home range (Bašić et al. 2019) and depth use (Yokouchi et al. 2009). In lotic systems, maturity is linked with migration, particularly downstream migration (Jessop et al. 2008; Palstra et al. 2009; Tsukamoto 2009; Hagihara et al. 2012). Different stages of maturation have different goals, and therefore, may have different movement patterns or behaviours (Laffaille et al. 2005; Edeline et al. 2009; Stein et al. 2016). Maturity as a driver of movement can vary with location (Burnet 1969; Jessop 1987) and may not be enough to trigger movement patterns on its own, but only in conjunction with other factors such as length, behavioural drive and the appropriate extrinsic factors (Tsukamoto 2009; Trancart et al. 2013; Sandlund et al. 2017). As such, the lack of inclusion as interactions with extrinsic variables in our reviewed articles may be driving the non-significance found between maturity and movement. Maturity can be difficult to measure in anguillid eels; several difference indices exist (Cottrill et al. 2002; Acou et al. 2006; Okamura et al. 2007, 2009) and the reviewed studies may not have been able to sample a

range of sizes. It is also notable, that sample size was low with less than one third of the articles including maturity as an explanatory variable, hence the influence of maturity of eel movement in lentic systems warrants further investigation.

### Body condition

Movement strategies are often linked to metrics of body condition, from foraging to dispersal to migration (Goossens et al. 2020). Just five metrics of body condition were included in four reviewed articles, and none of these were found to significantly influence eel movement in lentic systems. In lotic systems, a decrease in body condition in migrating glass eel switches behaviour from migration to more localised, home ranging, and settlement movements, to reduce energetically expensive migration behaviours (Edeline et al. 2006, 2009; Cresci 2020). Body condition can also be an important trigger of downstream migration, as it is an indicator of energy reserves, which are essential for migration (Jessop 1987; Gradín et al. 2014). Habitat selection, movement patterns and movement responses to disturbance may also be influenced by body condition (Itakura et al. 2015; Purser et al. 2016). Conversely, body condition may be shaped by eel movement frequency, as eels in habitats with reduced connectivity and movement opportunities have been found to have lower body condition (Lasne et al. 2008). Body condition may be a more relevant driver of movement to specific life stages, and may define migration or dispersal ability (Hays et al. 2016; Goossens et al. 2020; Blake et al. 2021). Routine inclusion of body condition as an intrinsic variable within future studies will help elucidate this.

### Mass

Like other intrinsic drivers, body mass can have variable impacts on animal movement, depending on both location and also species (Sekercioglu 2010; Tucker et al. 2014; Ofstad et al. 2016; Giroux et al. 2021). There were mixed findings around the importance of body mass on movement of eels in lentic water bodies, with 38% of papers finding it a significant driver. Mass of female *A. dieffenbachii* significantly decreases over the migratory season (Jellyman and Unwin 2017), greater mass is correlated with greater

home range in of *A. anguilla* (Barry et al. 2016) and there may be inter-annual variation in the average mass of migrating in *A. anguilla* (Carss et al. 1999). Likewise, there is a mixed influence of body mass on eel movement in lotic water bodies. Hanzen et al. (2021) found a significant relationship between body mass and home range in *A. bengalensis* but not in *A. marmorata*. Bultel et al. (2014) found that directional migratory speed was significantly correlated with body mass but not body condition in *A. anguilla*. Conversely, Pedersen et al. (2012) found no-influence of body mass on downstream migration progression rate in the same species, while Trancart et al. (2018a, b) found no significant difference in body mass between migratory and non-migratory individuals. This suggests the relationship between mass and movement may be location specific, and therefore should be included in analyses where feasible.

### Sex

Although rarely used across our 36 studies, sex was found to be significant in 100% ( $n=4$ ) of cases. Its low inclusion rate is probably due to difficulties in sexing eels quickly in situ, as well as sexual dimorphism which can lead to females being preferentially selected for tagging studies (Béguer-Pon et al. 2018a, b) and female biased preferences for lentic, lacustrine habitats (Oliveira et al. 2001; Hagihara et al. 2018; Harwood et al. 2022). Where investigated, monthly and seasonal variance are seen between the timing of movement behaviours between male and female eels (Todd 1981; Stuart et al. 2019; Lagarde et al. 2021). Anguillid eels have sex-biased differences in migration strategies, causing differences in movement patterns in lotic systems (Oliveira 1999), as well as both habitat and latitude sex-biased distributions (Magurran and Garcia 2000; Oliveira et al. 2001; Maes and Volckaert 2007; Hagihara et al. 2018; Wakiya et al. 2019). Sex differences in movement patterns are seen across many marine and freshwater species (Bansemer and Bennett 2011; Nifong et al. 2015; Widmann et al. 2015; Gutowsky et al. 2016; Williamson et al. 2021). If feasible, sex should be integrated in investigations into anguillid eel movement because, given the differences migration strategies between sexes, there are likely to be important implications for conservation and management plans.

### Summary of drivers of eel movement in lentic systems

In our systematic map, a wide variety of extrinsic variables were identified for investigating movement ecology of eel in lentic water bodies. Despite marked differences in environmental conditions between lentic and lotic systems, such as minimised flow (Prescott and Eason 2018; Mochek and Pavlov 2021) and less variability and fluctuations in temperature (Hieber et al. 2002; Jones 2010; Prescott and Eason 2018) in lentic waterbodies, our results suggest the extrinsic factors driving eel movements are similar, particularly temperature, flow, diel period, lunar cycle, and season. A possible inference is that drivers of movement are innate in anguillid species and highly sensitive to changes in environmental conditions, and, as such, even the small and subtle changes in variables in lentic systems may trigger changes in movement patterns. This is supported by the success of ‘trap and transport’, where adult eels captured and translocated to a location with seaward connectivity, such as estuaries, undertake migration at similar rates to wild eels despite not experiencing the environmental conditions that are thought to trigger migration (Béguer-Pon et al. 2018a, b; Piper et al. 2020). Temporal impacts of extrinsic variables may vary across species. Some variables may result in immediate movement responses while other variables may have impacts over longer time periods, and result in seasonal patterns of activity (Shaw 2016; Andrzejczek et al. 2019). Similar findings may occur with eel in lentic systems with short term changes in variables such as flow driving movement responses, whilst variables such as temperature and day length require change over long periods to drive movement, and further research in this area is required.

Interestingly, only metrics of length and sex were consistently found to be significant intrinsic drivers of anguillid eel movement in lentic systems. Other intrinsic variables such as body condition, maturity and mass had little effect on eel movement, other than perhaps through association with specific extrinsic variables (Tsukamoto 2009; Trancart et al. 2013; Sandlund et al. 2017). This is different to lotic systems, where relationships between movement and intrinsic variables are more defined. The low impact of many of the intrinsic drivers found across the reviewed studies could be a combination of low

sample size, the high variability of the impact of intrinsic variables from location to location, and the lack of integration of these variables with extrinsic data in analyses. As such, further studies investigating the role of intrinsic variables, such as maturity, on eel movement in lentic systems are required.

### Gaps in knowledge and opportunities for further research

This section highlights specific research gaps identified by our review, and potential opportunities for investigating movement ecology of anguillid eels in lentic systems.

#### Restricted species and geographical area

Despite anguillid eels comprising of 19 different species and sub species, with ranges that span many of the world's continents and oceans (Jacoby et al. 2015; Jellyman 2022), the 36 articles addressed just five, solely temperate, species, and a small number of geographical regions. Tropical species and important areas of anguillid eel habitat, such as south-east Asia, Australia, and southern Africa, were not covered. This evident geographic gap could be due to several reasons including funding, availability and costs of equipment, geopolitical factors and search criteria and language in the systematic map (Orrell and Hussey 2022). However, this geographic bias, mirrors that of other papers that review monitoring of movement and behaviour in aquatic environments (Hussey et al. 2015; Williamson et al. 2019; Butcher et al. 2021; Orrell and Hussey 2022).

The five species studied were primarily located in the global north, and include the three species (*A. anguilla*, *A. japonica* and *A. rostrata*) most commercially important and those most threatened by extinction (Righton et al. 2021; Jellyman 2022). Although there is a general paucity of data on tropical compared to temperate species (Righton et al. 2021), tropical eels are increasingly exploited by the aquaculture industry, as a substitution for the declining temperate eels (Jacoby et al. 2015; Arai 2022a). Lentic and lacustrine water bodies are shown to be important for the growth and development of tropical, as well as temperate, eels (Schabetsberger et al. 2013; Arai and Abdul Kadir 2017; Arai et al. 2020), hence

the research gap on the movement ecology of tropical species in lentic systems should be addressed.

#### Limited data on males and juveniles

It is typically difficult to sex anguillid eels from morphology alone, especially during early life history. Where sex of individuals was noted, study animals were almost exclusively female. This bias can be explained by researchers selecting females, which are larger than males, to minimise the impacts of tag implantation (Béguer-Pon et al. 2018a, b). It could also be explained by sex differences in habitat preference. Females tend to inhabit the higher reaches and lacustrine areas of freshwater systems, with males preferring fluvial habitats and lower reaches (Oliveira et al. 2001; Hagihara et al. 2018). Considering the importance of sex as a driver of movement, such as with sex biased dispersal (Lawson Handley and Perrin 2007; Arlt and Pärt 2008; Shaw 2020), and sex differences in foraging strategies (Johns et al. 2010; Beerman et al. 2016; Austin et al. 2019), further studies on male movement in lentic systems will be beneficial for conservation and management. In addition, movement of juveniles in lentic systems was rarely investigated. Adults tend to be the primary focus of many tagging studies (Orrell and Hussey 2022), as was found across our review, probably because maturing and adult individuals primarily inhabit lentic water bodies, and juveniles may be too small for tagging. However, coastal lentic lagoons can provide important habitat for juvenile eels (Bevacqua et al. 2011a, b; Leone et al. 2016) and movement in these regions should be investigated further. New techniques in ultrasonography to sex eels in the field (Bureau du Colombier et al. 2015) and progressive tag miniaturisation (Hays et al. 2016; Chung et al. 2021; Hellström et al. 2022) will facilitate the advancement of knowledge on movement ecology of both male and juvenile anguillid eels.

#### Limited understanding of eel maturation in lentic water bodies

The maturation process of anguillid eel is still not fully understood with all species exhibiting plasticity in age at maturity in relation to latitude and temperature. The maturation of immature adults (yellow stage) to matured adults (silver stage) in preparation



for migration, occurs in anguillid eel in lentic as well as lotic water bodies (Pankhurst 1982; Piper et al. 2020), with temperature and season potentially driving this transition in both (Haro 2003; Tesch 2003; Righton et al. 2021). In closed lentic water bodies, such as reservoirs however, escapement may rarely occur. Maturation from immature adult to mature adult requires several physiological changes, including an increase in eye diameter, degeneration of the gut and phenotypic changes to skin colouration from brown/yellow to grey/silver (Pankhurst 1982; Durif et al. 2005). Should these morphological changes occur without migration it is unknown if these changes persist, which may have detrimental impact to the individual, or whether the process may reverse. Closed lentic systems, with the potential for recapture, offer an opportunity to further understand these processes in anguillid eel species.

#### Limited data on saltwater or brackish lentic water bodies

Most studies were undertaken in freshwater systems (Fig. 5). Anguillid eels are facultative, rather than obligate, catadromous species (Jacoby et al. 2015; Righton et al. 2021; Jellyman 2022). As such, although freshwater systems are important habitats for growth and development, anguillid species do not necessarily need a freshwater phase and may spend their entire growth phase in coastal marine habitats (Tsukamoto and Arai 2001; Jessop et al. 2008; Arai 2020). Salt or brackish lentic water bodies are therefore likely to prove important habitats for the growth and development of anguillid eel species and should be included as study systems when investigating the drivers of eel movement.

#### Heterogeneity in extrinsic and intrinsic drivers assessed

A wide range of intrinsic and extrinsic variables were assessed as drivers of anguillid movement across the 36 studies but their frequency of studied varied substantially (Figs. 6, 7). Although some metrics such as time of day or season, temperature, length and maturity metrics were commonly assessed, others, including prey, sex, dissolved oxygen and productivity, were infrequently used. Other potentially relevant variables, such as olfactory cues and magnetic fields,

were not studied at all. Overall, papers were less likely to include intrinsic variables in their analyses compared to extrinsic. The pattern of inclusion of variables for study likely reflects, at least in part, differences in the difficulty, and potential cost, of data collection. For example, regular prey surveys at comparable resolutions to telemetry data can be costly in both time and money. Through increased open access remote sensing (Woodcock et al. 2008; Williamson et al. 2019; Topp et al. 2020) and low-cost sensors (Murphy et al. 2015; Chan et al. 2021), the cost of collecting environmental variables such as temperature and chlorophyll-*a* has decreased over recent years. However, other variables, such as pH and dissolved oxygen, are, currently, harder to acquire from remote sensing methodologies and in situ monitoring can still be costly (Gholizadeh et al. 2016; Kim et al. 2020). Likewise, intrinsic variables such as sex and body condition may not be regularly collected due to the costs and difficulty of obtaining this information in the field (Bureau du Colombier et al. 2015). Consequently, there are still substantial gaps in knowledge on how important intrinsic and extrinsic variables drive eel movement in lentic systems. However, the development of new and existing technologies, such as portable ultrasonography (Ruiz-Fernández et al. 2020; Sassoè-Pognetto et al. 2022), low-cost sensors (Demetillo et al. 2019; Wang et al. 2019) and remote sensing techniques (Japitana et al. 2019; Kim et al. 2020; Pereira et al. 2020) will facilitate the integration of currently underutilised variables into movement analyses in anguillid eels.

#### Social drivers of eel movement

Many life stages of eels aggregate (Sorensen 1986; Tesch 2003), and may do so before and during both upstream and downstream migration (Todd 1981; Bruijs and Durif 2009; Tsukamoto 2009; Burgerhout et al. 2013; Schabetsberger et al. 2013; Sandlund et al. 2017; Noda et al. 2021). Despite this, social cues are rarely investigated as drivers of eel movement (Sandlund et al. 2017; Calabrese et al. 2018). Many species occur in social groups at various temporal scales, and social cues may play a role in the coordination of movements for feeding events (Gales et al. 2004; Webster and Laland 2012; Visser et al. 2014; Baracchi et al. 2017), migration (Noyce and Garshelis 2014; Nagy et al. 2018; Torney et al.

2018) and habitat selection (Fletcher 2007; Buxton et al. 2020). Evidence in other diadromous fish such as salmon, suggests that social interactions between individuals may play an important role in migration (Berdahl et al. 2016), and conspecific attraction and social cues are important for habitat selection across a wide range of fish species (Buxton et al. 2020). As such, investigations into the social drivers of movement in eel is an important next step for this field.

Many closed lentic water bodies, such as reservoirs, hold significant populations of anguillid eel (Bašić et al. 2019; Piper et al. 2020) which provide an opportunity as closed experimental systems to investigate questions on anguillid eel ecology. One exciting avenue for study is the influence of sociality on movement and space use. Acoustic telemetry can be a useful tool for monitoring social interactions and networks of aquatic organisms (Villegas-Ríos et al. 2022). By recording co-occurrences of tagged individuals, information on the social interactions between them can be inferred (Mourier et al. 2017; Heupel et al. 2018). In addition, new technologies such as high-resolution acoustic telemetry systems can record precise, direct, associations between individuals (Aspillaga et al. 2021; Villegas-Ríos et al. 2022). These data sets can be used to construct social networks within populations (Jacoby and Freeman 2016; Mourier et al. 2018) which can help inform the social ecology, connectivity, and drivers of movement, as well as aiding research into population structure, spatial management and connectivity, fisheries, aquaculture, and disease management (Villegas-Ríos et al. 2022). As seen in this study, acoustic telemetry is regularly used for monitoring movements of anguillid eels, and as such, the tools to investigate social cues of movement are available to researchers but are currently underutilised. Using these tools could greatly aid our understanding of movement of eel in both lentic and lotic systems, as well as increase knowledge on the social drivers of movement ecology more generally, which are currently poorly understood (Calabrese et al. 2018).

#### Pertinent questions for future research

Based on this review we provide a list of what we believe to be the most pertinent questions that require answering to enable the effective management and conservation of anguillid eel within closed lentic

systems. Further, these data are required to facilitate the extradition of land-locked eel populations with high potential to contribute to the wider panmictic spawning stock:

1. Are there sex differences in movement patterns in anguillid eels?
2. Can eels in closed lentic systems, with no escapement, fully mature?
3. Can anguillid eels reverse the silvering/maturation process?
4. How does maturation stage influence eel movement in lentic waterbodies?
5. What size do anguillid eels mature/silver in lentic systems?
6. Do eels aggregate, or socialise, in lentic systems?
7. If eels do aggregate, what are the drivers of such behaviours?
8. If eels do aggregate, what is the social structure of eel aggregations?

#### Conclusions

To our knowledge this is the first systematic map of the drivers of anguillid eel movement in lentic water bodies. Lentic waterbodies are important habitat for anguillid eels and also offer opportunities as experimental systems to advance our knowledge of eel ecology. Many of the lentic water bodies where significant populations of anguillid eels occur are closely managed by stakeholders, such as water companies or the state (Noga and Wolbring 2013; Bašić et al. 2019; Loftus et al. 2019; Piper et al. 2020). To be effective, conservation plans must be formulated with the engagement of such stakeholders and be founded on firm scientific evidence. In depth knowledge of wildlife movements, and the drivers of movement, is essential to inform conservation management and policy of threatened species (Ogburn et al. 2017; Fraser et al. 2018). Only by understanding the extrinsic and intrinsic drivers of anguillid eel movement, will the spatial (e.g. what regions) and temporal scales (e.g. what time periods) required for optimal and targeted management decisions be revealed. Such an evidence-based approach maximises the benefits of limited funds and time to undertake conservation and management plans, and minimises impacts to stakeholder interests (Allen and Singh 2016). Information

on movement ecology will also allow managers to identify alternative management actions, should primary action plans clash with stakeholder interest or other conservation measures, as well as allowing managers to develop trade-off scenarios that balance conservation needs with land-use practices (Allen and Singh 2016). For anguillid eels this information will inform optimal temporal and spatial scales for mitigation techniques such as trap and transport (Béguér-Pon et al. 2018a, b; Piper et al. 2020), the location of eel passes (Calles et al. 2012; Pecorelli et al. 2019), or timings of pump shutdown to reduce eel mortality (Eyler et al. 2016; Baker et al. 2020), all of which can have a significant impact to the conservation and management of this threatened family.

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**Data availability** All data generated or analysed during this study are included in this article and its additional files. RIS files from all search engine results are available from the Zenodo Digital Repository: <https://zenodo.org/record/7250310#.Y1g6zHZKjDc>

## Declarations

**Conflict of interest** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** All the authors mentioned in the manuscript have agreed for authorship, read, and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.

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