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REVIEWS

Improving conservation outcomes for seadragons: data, knowledge gaps, and future directions

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Abstract Seadragons are charismatic fishes endemic to Australia's Great Southern Reef and are flagships for marine biodiversity. Due to their unique appearances and behaviors, seadragons are of interest for both scientific research and broader conservation purposes. However, studies on wild seadragon populations are challenging to implement, and peer-reviewed data on population demographics, life histories, and other aspects of seadragon biology and ecology are currently limited. Seadragon habitats, including kelp-covered reefs and seagrass meadows, have declined in various areas of the southern Australian coast, spurring concerns that seadragon abundances may also be contracting. The lack of range-wide baseline data on seadragon populations has precluded a robust understanding of their vulnerability to extinction, and further conservation-focused research has been recommended by past studies. Here, we summarize existing research on the three known seadragon species: common, leafy, and ruby seadragons, with the aim of improving future conservation outcomes for seadragons. Range-wide population size estimates and trends in abundance data are key knowledge gaps preventing accurate extinction risk assessments. Lack of data about basic ecological and biological factors such as longevity and reproduction further hinder effective conservation actions. We describe developing research methodologies including citizen science, machine learning, habitat mapping, and molecular methods that show promise for improving outcomes for these iconic fishes and the habitats they rely on.

Keywords Australia · Flagship species · Great Southern Reef · IUCN Red List · Marine conservation · Syngnathid · Syngnathidae · *Phycodurus* · *Phyllopteryx*

Introduction

Syngnathidae is a diverse and charismatic family of pipefishes that includes seadragons. Species in this

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family display a range of distinctive morphological traits, including long, tube-like snouts, reduced fins, prehensile tails, and bodies armored in bony plates (Browne et al. 2008). Many of the physical characteristics typical of syngnathids are intricately adapted to their habitats and provide camouflage for feeding and avoiding predation (Hamilton et al. 2017). Brooding of offspring (male pregnancy) is another notable characteristic shared by all syngnathids (Hamilton et al. 2017; Whittington and Friesen 2020). Because of these unique adaptations, syngnathids act as valuable models for studying the evolution of various biological traits, including sex roles and even pregnancy in vertebrates (Wilson et al. 2003; Whittington and Friesen 2020). Syngnathids are frequently utilized as flagship species for marine conservation due to their captivating appearances and behaviors, combined with the fact that multiple species are considered at risk for extinction (Pollom et al. 2021). Charismatic flagship species have the potential to engage public attention and concern for environmental issues as well as motivate action to protect threatened habitats (e.g., Smith and Sutton 2008, but see Batt 2009).

Despite their high cultural and scientific value, there is concern about the extinction risk for many syngnathid species, with 18 species currently considered threatened by the International Union for the Conservation of Nature's (IUCN) Red List (De Brauwer and Burton 2018; Pollom et al. 2021). Species listed as data deficient are of additional concern as these might be equally at risk without necessary conservation efforts to prevent extinction. The Red List currently categorizes 97 of approximately 300 known species of syngnathids as 'data deficient', indicating there is insufficient data to assess their extinction risk, although threats to the species' habitats or other risk factors might be known or suspected (IUCN 2012; Pollom et al. 2021). Another 183 syngnathid species have been assessed as 'least concern', a designation indicating that they have been evaluated against the IUCN Red List criteria and have not qualified for a threatened listing, even if data on their population demographics was limited (IUCN 2012; Pollom et al. 2021). Data gaps are concerning given modern threats to syngnathids and their habitats, which include overfishing, pollution from development, and rising ocean temperatures associated with climate change (Lawson et al. 2017; Monteiro et al. 2023).

Australia's Great Southern Reef (GSR), an interconnected temperate rocky reef system that spans the southern coast from northern New South Wales to central Western Australia (Fig. 2), harbors a highly diverse assemblage of syngnathid fishes (Bennett et al. 2015; Hamilton et al. 2017). The GSR is home to many endemic syngnathid species, including all three known species of seadragons. Two species of seadragons live in shallow coastal waters, the common seadragon (*Phyllopteryx taeniolatus*, (Lacepède 1804)) and the leafy seadragon (*Phycodurus eques*, (Günther 1865)). Both common and leafy seadragons are popular subjects for SCUBA divers to observe and photograph along Australia's southern coast. A third species, the ruby seadragon (*Phyllopteryx dewysea,* Stiller et al. 2015), was recently discovered in deeper water beyond recreational SCUBA diving limits (Stiller et al. 2015; Rouse et al. 2017).

The ecosystem services provided by the biodiversity in the GSR add significant value to both the ecology and economy of Australia, but the reef system faces myriad challenges from human impacts, including climate change and degradation from pollution (Bennett et al. 2015). The GSR also suffers from a lack of public awareness about its importance for Australian society (Bennett et al. 2015). Charismatic animals such as seadragons have the potential to garner attention and support for this valuable ecosystem.

Common and leafy seadragons are the state marine emblems for Victoria and South Australia respectively and are popular species to observe while diving or snorkeling. In addition to their local popularity, they are enjoyed by ocean enthusiasts worldwide in aquariums. Both common and leafy seadragons meet criteria to make effective environmental flagships, including endemism to regions of interest, cultural relevance to communities (such as expression in local artwork), distinctive appearances recognizable by target audiences, and existing uses as regional symbols by organizations (Bowen-Jones and Entwistle 2002; Vincent et al. 2011). These characteristics combined with the common seadragon's GSR-wide distribution and the leafy seadragon's representation of important GSR habitats in the south and southwest indicate that both species are likely to continue functioning well as flagship species for the GSR.

Despite their iconic status and value as ambassadors for marine conservation, baseline information about seadragon biology and ecology remains surprisingly limited. Published research on wild seadragons remains sporadic at best, with less than 20 peer-reviewed publications over the past 25 years. Both common and leafy seadragons are difficult to study in the wild due to their excellent camouflage, and in the case of leafy seadragons, relatively few known populations (Connolly et al. 2002a). Ruby seadragons are even more challenging to study as they live at greater depths than the other two species (Stiller et al. 2015; Rouse et al. 2017). Although some projects have monitored local populations of common or leafy seadragons (Connolly et al. 2002a, b; Sanchez-Camara et al. 2011; Baker et al. 2020), researchers still lack robust baseline datasets for seadragon populations across their entire distribution. There is increasing concern that both common and leafy seadragon populations are declining, principally due to habitat loss (Allan et al. 2022a; Edgar et al. 2023; Qu et al. 2023). The data needed to inform conservation planning for seadragons is limited, and comprehensive long-term monitoring is needed to better understand trends in their population numbers, lifespans, and reproductive habits.

This review summarizes the past 30 years of research on the biology and ecology of the three seadragon species with a focus on their conservation. To improve the clarity of relationships between the various topics covered, we have added 'signposts' after some sections indicating connections to later, related sections, such as conservation concerns, research gaps, and developing methods. We have not included all possible concerns, gaps, or methods but have prioritized those that we believe will be most useful for supporting evidence-based next steps in seadragon conservation. To that end, conservation concerns highlight existing knowledge around seadragon vulnerability to extinction. Research gaps focus on knowledge that is missing but needed to inform conservation planning and assessments such as the IUCN Red List. Developing methods focus on tools that could be useful for addressing research gaps (e.g. expanding population monitoring) and assisting management (e.g. predicting suitable habitat).

Taxonomy, distribution, and phylogeography

Taxonomy of the three seadragon species

Seadragons originated in temperate Australasia (Santaquiteria et al. 2021), and the three accepted seadragon species are readily distinguished by their morphologies and genetic differences. The species belong to two genera: *Phyllopteryx* (*P. taeniolatus* and *P. dewysea*) and the monotypic genus *Phycodurus* (*P. eques*) (Table 1).

The common seadragon (*P. taeniolatus*) is also often referred to as the 'weedy' seadragon. Herein, we use 'common' seadragon in accordance with the standard common name for the species (Yearsley et al. 2006; Rees et al. 2022), but we acknowledge that, particularly on the east coast of Australia, they are referred to as 'weedies'. Common seadragons tend to range from brown to orange in color with vertical blue bars and intricate spot patterns across their bodies (Fig. 1). These spot patterns extend to their heads, snouts, and sometimes appendages (Fig. 1), and their colors and sizes can

Table 1 Overview of taxonomy, distributions, and main habitat types for common, leafy, and ruby seadragons

Scientific name	Common name	Distribution	Main habitat types	Depth range	Sources
Phyllopteryx taeniolatus Lacepède (1804)	Common seadragon (also, weedy seadragon)	Northern New South Wales to central Western Australia, including Tasmania	Rocky reefs covered in macroalgae, sandy edges of reefs, seagrass beds	1 m–50 m	Edgar (2000), Sanchez-Camara et al. (2006), Wilson et. al (2017), Allan et al. (2022a)
Phyllopteryx dewysea Stiller et al. (2015)	Ruby seadragon	Southern Western Australia	Mixed sponge and invertebrate reef and sandy habitat	+50 m	Stiller et al. (2015), Rouse et al. (2017)
Phycodurus eques Günther (1865)	Leafy seadragon	South Australia to southern Western Australia	Rocky reefs covered in macroalgae, sandy edges of reefs, seagrass beds	4 m–30 m	Edgar (2000), Kuiter (2003), Connolly et al. (2002b), Baker (2009), Stiller et al. (2017)

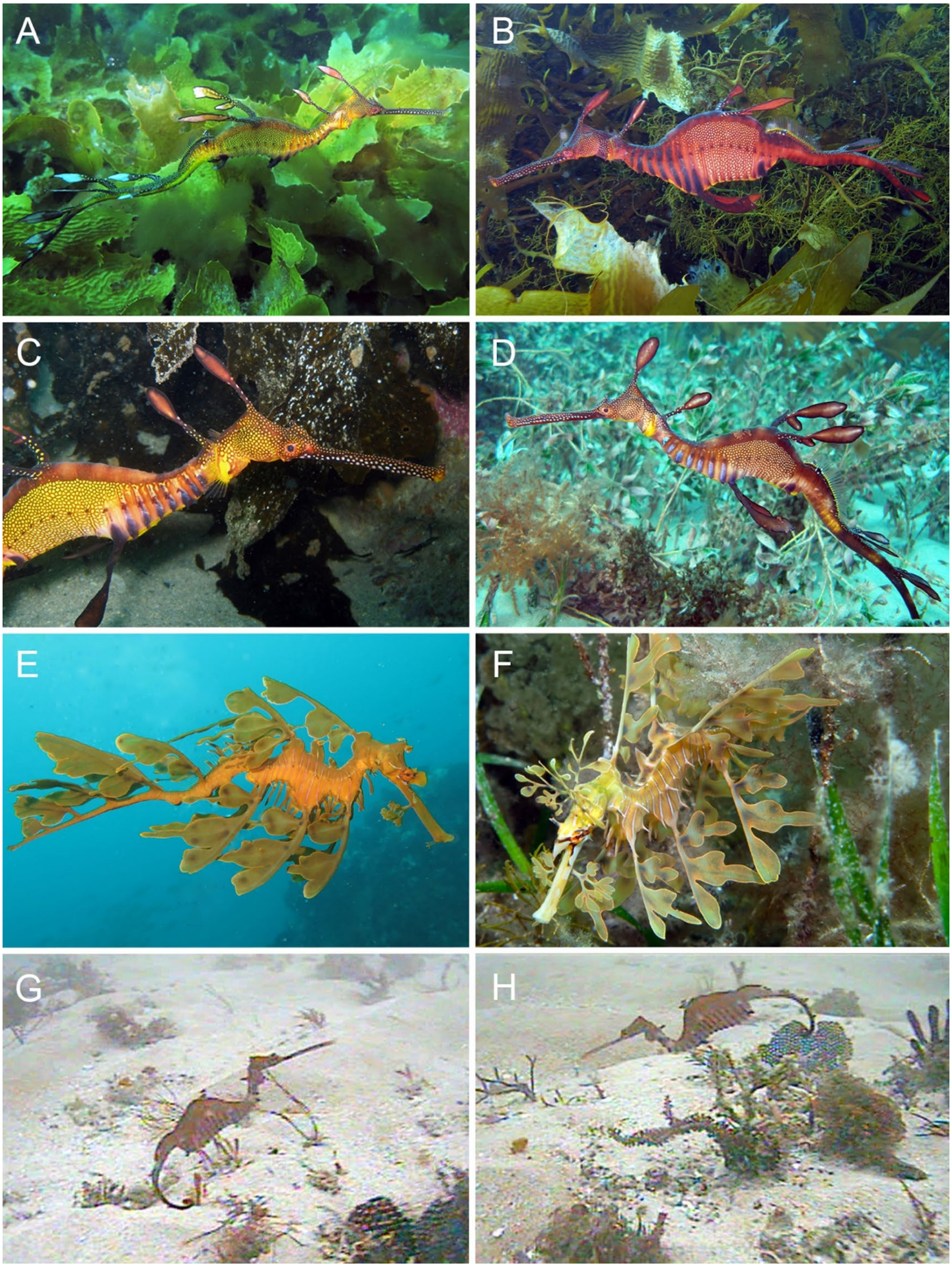

Fig. 1 Examples of the three seadragon species from different regions in Australia **A** common seadragon (this individual missing ventral appendages) in Western Australia **B** common seadragon in Tasmania **C** common seadragon in New South Wales **D** common seadragon in Victoria **E** leafy seadragon in Western Australia **F** leafy seadragon in South Australia **G**, **H** ruby seadragon in Western Australia from Rouse et al. 2017

vary in relation to habitat and food sources (Kuiter 2003). They have smaller leaf-like dermal appendages than leafy seadragons, although the size and shape of these can also vary with environmental factors (Kuiter 2003). Leafy seadragons (*P. eques*) are typically golden in color with white stripe or bar patterns on their faces and bodies and longer, more macroalgae-like appendages (Fig. 1). Those living in deeper habitats are often darker or more reddish-colored (Kuiter 2003). Ruby seadragons (*P. dewysea*) are uniformly red in color with pink vertical bars on their bodies and white stripe or bar patterns on their faces. They appear to lack the dermal appendages of the other two species (Fig. 1). Ruby seadragons may have prehensile tails, although common and leafy seadragons do not (Stiller et al. 2015; Rouse et al. 2017).

Historically, the ribboned pipefish or ribboned seadragon (*Haliichthys taeniophorus,* (Gray 1859)) found around mid-Western Australia to Queensland, has been considered a northern seadragon, with Kuiter (2003) suggesting it was 'related to the genus *Phycodurus*'. An alternative view came from Whitley and Allan (1958), who pointed out differences in tail ridge morphology between common and leafy seadragons and inferred that while common seadragons had likely descended from a pipefish species like *H. taeniophorus,* leafy seadragons had a different ancestor. In 2010, Wilson and Rouse found that common and leafy seadragons formed a well-supported clade and were not closely related to *H. taeniophorus*. Their study suggested that despite differences in tail ridge morphology, the appendages of common and leafy seadragons evolved from a common ancestor in relation to their algae association (Wilson and Rouse 2010). The ruby seadragon was later found to be the sister-species to the common seadragon, and the leafy seadragon is sister-species to the clade formed by the other two (Stiller et al. 2015). Together, all three species of seadragons form a well-supported clade (Stiller et al. 2015, 2023), using *Solegnathus* (spiny pipehorses) as an outgroup (Stiller et al. 2022).

Distribution

All three seadragon species are endemic to Australia's Great Southern Reef (Bennett et al. 2015). The documented range of common seadragons includes New South Wales, Victoria, Tasmania, South Australia, and Western Australia (Fig. 2). The northernmost established population of common seadragons on the east coast seems to be at Broughton Island near Nelson Bay, New South Wales (Allan et al. 2022b). Geraldton has historically marked the northern limit of common seadragons on the west coast (Hutchins and Swainston 1986; Edgar 2000; Baker 2009), although no live sightings substantially north of Perth have been reported for the past two decades.

Leafy seadragons have a more limited range and are found only in South Australia and Western Australia (Fig. 2). They have been documented as far north as the Abrolhos Islands off the coast of Western Australia in 2000 (Sue Morrison pers. Comm., formerly WA Museum), and sightings around Perth are rare. There are persistent but usually unsubstantiated reports of leafy seadragons in Victoria and two reports of leafy seadragons in Tasmania from over a decade ago (Baker 2009), however these are likely to be rare vagrants rather than established populations.

The distribution of *P. dewysea* is only known to include southern Western Australia but is little-studied and potentially more extensive than currently understood (Fig. 2) (Stiller et al. 2015; Rouse et al. 2017).

Related sections:

- Conservation concerns- habitat loss, restricted ranges, and high site fidelity
- Research gaps- range-wide population size estimates, trends in abundances, and distribution limits
- Developing research methodologies- environmental DNA for detecting populations

Genetic connectivity, diversity, and management units for conservation

Patterns observed in the genetic structure and diversity of seadragons raise concerns about their resilience to environmental pressures, particularly given their endemism, limited mobility, lack of dispersal, and known anthropogenic threats to their habitats. Defining management units is critical for effective conservation planning, and an understanding of genetic structure can inform this process. Common seadragons show strong genetic structure between three main groups in the western, central, and eastern

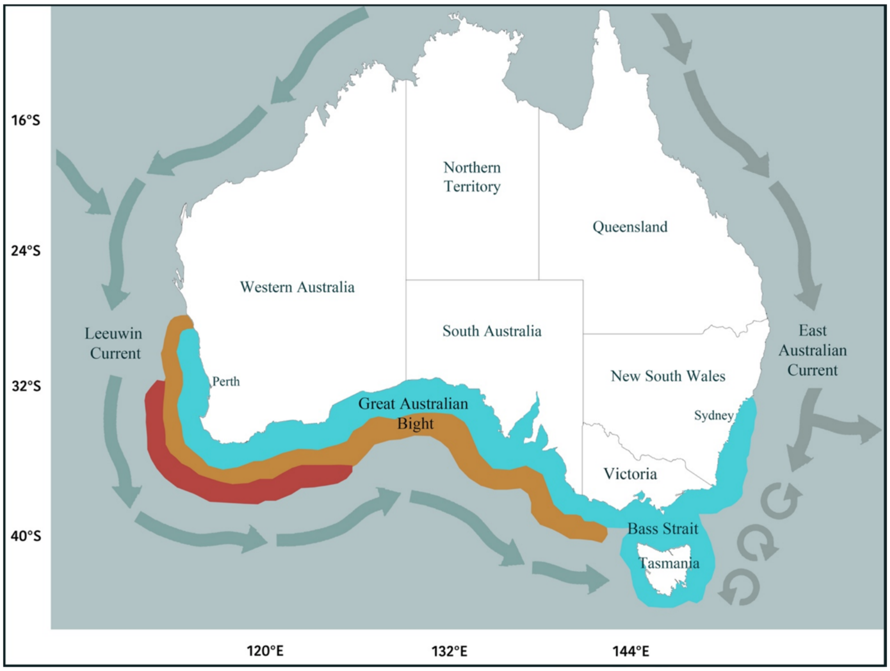

Fig. 2 Ranges of the three seadragon species: common (blue), leafy (gold), and ruby (red). The Great Southern Reef generally aligns with the distribution of the common seadragon. Current patterns are broadly summarized from Ridgway and Hill 2009 and Berthot et al. 2007

parts of their range along the southern coast with substructure in each of those groups, likely linked to their low dispersal capacity (Stiller et al. 2023). These patterns of structure include notable differences across the Bass Strait (Fig. 2) (Wilson et al. 2017; Klanten et al. 2020; Stiller et al. 2023). Klanten et al. (2020) suggested that this structure could reflect a Victorian subspecies which might require separate management from populations in New South Wales and Tasmania. Because past glacial periods resulted in repeated emergences of the Bassian Isthmus, seadragon populations east and west of that barrier experienced periods of temporary separation (10,000–40,000 years ago), which resulted in differences between those populations as they continued to develop. However, genomic data across the complete range of common seadragons demonstrated that the differences observed between populations east and west of Bass Strait are consistent with other structured areas of the common seadragon's range, reinforcing the single species concept (Stiller et al. 2023). There is evidence of genetic exchange between those populations following periods of isolation (Stiller et al. 2023), contrasting with the much deeper, enduring divergences between the three established seadragon species (common, leafy, and ruby) (Stiller et al. 2023).

Farther west, common seadragons show well-defined structure on each side of the Great Australian Bight (GAB) (Fig. 2) (Wilson et al. 2017; Stiller et al. 2023), though analyses using nuclear data indicate that western and central populations are less divergent than previously inferred from mitochondrial data alone (Stiller et al. 2023). This could suggest that the populations diverged relatively recently (< 0.63 mya), in accordance with changing sea levels and ensuing geographic shifts (Stiller et al. 2023). The GAB represents a sampling gap due to challenging accessibility, so it remains unclear whether the common seadragon clades east and west of it might connect gradually across that region (Wilson et al. 2017; Stiller et al. 2023). Generally, the limited dispersal potential of seadragons makes it unlikely that there is significant gene flow between geographically distant groups (Wilson et al. 2017; Stiller et al. 2023).

Range-wide, the genetic diversity of common seadragons decreases from the center to the western and eastern edges of their distribution (Wilson et al. 2017; Stiller 2023). As with structuring, this pattern has likely resulted from geological changes and range expansions over time, with more stable habitat in the center of the range providing a refuge from which other populations dispersed east and westward (Stiller et al. 2023). The highest genetic diversity is seen at sites located in South Australia and the southern part of Western Australia, tapering from those areas to the eastern and western coasts (Wilson et al. 2017; Stiller et al. 2023). The more variable ocean temperatures along those coasts may have caused seadragon populations to repeatedly shift their ranges, expanding, contracting, and ultimately resulting in less diversity (Stiller et al. 2023). The populations with lower genetic diversity in New South Wales, Tasmania, and the Perth area of Western Australia are likely at greater risk of local extinction- a risk compounded by climate change impacts expected on the western and eastern coasts (Wilson et al. 2017; Klanten et al. 2020; Stiller et al. 2023). For example, the predicted weakening of the Leeuwin Current and the strengthening of the East Australian Current (Fig. 2) will likely significantly impact environmental conditions and habitats on both coasts (Pattiaratchi and Buchan 1991; Feng et al. 2003; Ridgway 2007; Sun et al. 2012; Wijeratne et al. 2018; DeWoody et al. 2021).

Like common seadragons, leafy seadragon populations show high levels of genetic structuring, but within their smaller distribution they show only two main clades located in the western and central parts of the southern Australian coast (Larson et al. 2014; Stiller et al. 2017, 2021). Notable substructure is seen in the central region of southern Australia, which is the eastern limit of the species distribution (Stiller et al. 2017, 2021). As with common seadragons, the GAB constitutes a sampling gap, and connectivity across that region remains unclear (Stiller et al. 2017, 2021). Phylogeographic studies show that geological change over time has significantly influenced genetic structuring of leafy seadragon populations (Stiller et al. 2021). The central region of southern Australia encompasses large, shallow bays with extensive seagrass and kelp meadows that were flooded around 14,000 years ago, at the end of the Last Glacial Maximum (LGM) (Stiller et al. 2021). Following flooding, each bay was colonized by one or two lineages of leafy seadragons, evidenced by the genetically distinct populations living there today (Stiller et al. 2021).

Genetic diversity of leafy seadragon populations differs significantly between the western and central parts of the Australian coast but is low overall (Larson et al. 2014; Stiller et al. 2017, 2021). Some locations are more concerning than others, for example, the central region Spencer Gulf populations show relatively high diversity in the context of a species-wide comparison, while Bremer Bay in the west shows particularly low diversity (Stiller et al. 2017). In Western Australia, the genetic diversity of leafy seadragon populations continues to decrease moving westward (Stiller et al. 2021). If habitat loss during the LGM caused local extinctions of westerly seadragon populations, a source population of leafy seadragons likely recolonized those regions from the east after the LGM (Stiller et al. 2021). That population would have only brought a subset of the genetic diversity of the original group (Stiller et al. 2021). While central lineages would have expanded into large bays and continued differentiating, the west would have seen a pattern of removal and recolonization, resulting in more diverse and structured populations centrally, and less diverse, less structured populations moving across a westward gradient (Stiller et al. 2021).

Genomic analyses and population-level questions have not yet been addressed for the ruby seadragon due to a lack of available samples (NGW pers. comm.). The ruby seadragon's phylogenetic placement positions it as sister to the common seadragon, the two lineages having diverged about 3.72 mya (Stiller 2023). The most recent common ancestor of all three species has been dated to about 6.80 mya (Stiller 2023).

Related section:

- Conservation concerns- low genetic diversity and limited connectivity

Ecology and biology

Feeding mechanisms and diet composition

Members of the family Syngnathidae share a variety of unique morphological traits, including tube-like snouts used for suction-feeding. Syngnathids demonstrate high levels of trophic specialization linked to their snout morphologies (Manning et al. 2019), with common and leafy seadragons belonging to the longer-snouted group (Kendrick and Hyndes 2005; Kendrick and Hyndes 2005). A longer snout (relative to other syngnathid species) allows seadragons to strike at prey that are farther away from the mouth and to reach that prey more quickly (Kendrick and

Hyndes 2005), however the trade-off is a lower success rate for capturing prey (Van Wassenbergh et al. 2011). Seadragons also possess larger gape sizes (relative to other long-snouted syngnathids) that allow them to ingest larger prey, and common and leafy seadragons' appendages enable them to remain camouflaged while floating above seaweed patches- areas where their preferred prey tend to aggregate (Kendrick and Hyndes 2005). Researchers have observed ruby seadragons making feeding strikes in the wild through video taken by a remotely operated vehicle; the activity occurred mostly near the sandy bottom (Rouse et al. 2017).

All syngnathid species feed primarily on small crustaceans, with variations in diet likely due to local abundances and availability of prey items (Currie and Sorokin 2010b; Manning et al. 2019). Common seadragons feed mainly on mysid shrimp—swimming crustaceans that are relatively larger and quicker than other types of syngnathid prey—that can make up more than 80% of their diets (Kendrick and Hyndes 2005). In captivity, leafy seadragons can subsist on mysid shrimp (Branshaw 2005), and examination of the gut contents of two wild leafy seadragons revealed that they had consumed a combination of isopods, prawns, and Leptostraca (leaf-like shrimps) (Currie and Sorokin 2010a). The diet of the ruby seadragon is not currently known. Overall, the feeding ecology of seadragons emphasizes the degree to which their morphologies (including snout morphology and camouflage) are highly adapted for successful predation in temperate reef habitats.

Habitat use and preferences

Common and leafy seadragons depend strongly on the macroalgal habitats found in the GSR and live in close association with sargassum, kelp, and seagrass around rocky reef and sandy habitats (Edgar 2000; Connolly et al. 2002b; Baker 2009; Sanchez-Camara et al. 2006; Allan et al. 2022a; Qu et al. 2023). Both species are seen within a depth range of <5 m up to 30 m, and common seadragons have been observed at depths up to 50 m (Edgar 2000). Live specimens of the ruby seadragon have been observed or trawled from 51 to 54 m depth, indicating a preference for deeper habitat than the other two species (Stiller et al. 2015; Rouse et al. 2017). Seadragon habitat associations appear to be influenced by environmental factors including substrate type, swell, and tidal action (Sanchez-Camara et al. 2004). Common seadragons are most frequently found in macroalgae habitats but are also known to use seagrass habitats in locations such as the Mornington Peninsula in Victoria, the Gulfs in South Australia, and southern Western Australia (Elek and Woodfield 2003; Kuiter 2009). Although leafy seadragons are commonly associated with macroalgae, radio-tracked individuals around West Island in South Australia showed a notable preference for *Posidonia* seagrass habitat (Connolly et al. 2002b). Little is known about habitat preferences of the ruby seadragon as only two individuals have been observed in the wild thus far, occurring over a mixed sand and sponge habitat (Rouse et al. 2017).

Seadragons of all life stages depend on the excellent camouflage provided by their coloration, patterning, and algae-like appendages for both hunting and escaping predation (Forsgren and Lowe 2006; Sanchez-Camara et al. 2006). It is likely that seadragons have more success capturing prey when they are camouflaged in vegetated areas while still near the high concentrations of mysid shrimp in more exposed areas (Allan et al. 2022a). Therefore, one of the main trade-offs seadragons face in terms of habitat use is between the camouflage afforded by macroalgal cover and the locations of mysid swarms, which are often found in more open water over soft sediment substrates (Allan et al. 2022a). Common seadragons surveyed in Botany Bay, New South Wales preferred habitat that maximized both the amount of kelp cover and the presence of mysid shrimp. Specifically, those seadragons strongly preferred a minimum of 40% *Ecklonia radiata* cover but would utilize sandy habitat as well if the density of mysid shrimp swarms were higher there (Allan et al. 2022a). Both the home ranges and breeding timelines of seadragons correlate strongly with mysid abundances (Kuiter 2009; Sanchez-Camara et al. 2006; Allan et al. 2022b), and as mysid abundances are correlated with the health of kelp forests and seagrasses as well as levels of pollutants (Edgar et al. 2000; Sanchez-Camara et al. 2004), it is essential that these factors are considered when designing management areas for seadragon populations.

Related sections:

- Conservation concerns- habitat loss, restricted ranges, and high site fidelity
- Developing research methodologies- tools for predicting suitable habitat

Site fidelity

Few studies have documented the individual ranges of seadragons, but those that have done so observed well-defined, small home ranges for both common and leafy seadragons. Common seadragons tracked in New South Wales for just over one year were found to be highly site-attached, with home ranges measuring 50–150 m long and <50 m wide (Sanchez-Camara et al. 2004). In general, the individuals studied did not change sites and were not observed outside their home areas, apart from pregnant males and some females moving into shallower waters at the end of the breeding season (Sanchez-Camara et al. 2004). These movements might have facilitated the hatching of young into more favorable environmental conditions, as the largest concentrations of mysid prey were observed near the male seadragons in those shallow areas (Sanchez-Camara et al. 2004). Near West Island in South Australia, individual leafy seadragons studied over the course of about one year had home ranges that were typically less than 2 ha (or 100 m by 200 m) in size (Connolly et al. 2002b). Within their ranges, the seadragons studied fluctuated between long sedentary intervals and short bursts of movement (Connolly et al. 2002b). The periods of movement did not appear to correlate with summer–winter or day-night rhythms (Connolly et al. 2002a, 2002b), although other observations from Rapid Bay in South Australia and Bremer Bay in Western Australia have indicated that some individuals might move seasonally towards deeper water (Baker et al. 2020, Craig Lebens pers. comm.). Both common and leafy seadragons move horizontally and vertically within their home ranges for purposes such as feeding and reproduction (Connolly et al. 2002a; Connolly et al. 2002b; Sanchez-Camara et al. 2004; Baker et al. 2020). Based on studies of common seadragons in Sydney and leafy seadragons in South Australia, males, females, and juveniles tend to overlap in their ranges and do not demonstrate territorial behavior (Connolly et al. 2002a; Sanchez-Camara et al. 2004).

While there have been no systematic studies of seadragon dispersal, some examples of seadragons moving outside of the small home ranges mentioned above have been documented. A tagged male common seadragon at a study site in New South Wales (NSW) was observed to move 550 m during a 2004 study, a markedly greater distance compared to other tagged seadragons in the same study (Sanchez-Camara 2004). This anomalous large-scale movement occurred at the end of the breeding season and was thought to be related to reproductive purposes (Sanchez-Camara 2004). An even larger movement was documented when a common seadragon initially tagged as a juvenile in Botany Bay was observed 3 years later and 1.3 km away at Bare Island, NSW (Sanchez-Camara 2004). The movement of this individual was thought likely to be storm-related (DJB pers. comm.). Although most leafy seadragons tracked in South Australia occupied home ranges smaller than 2 ha in size, one individual behaved in a more transient way, covering 88 ha of habitat within the study site (Connolly et al. 2002b). This fish might have had a very large home range, might have been relocating to a new home range, or might have had territorial interactions with other seadragons that influenced the transient behavior (although this was not observed) (Connolly et al. 2002b). Larger movements and larger home ranges appear anomalous in the context of past studies but indicate that seadragons are occasionally capable of covering larger distances, although the purpose behind such movements is unknown.

Related sections:

- Conservation concerns- habitat loss, restricted ranges, and high site fidelity
- Developing research methodologies- tools for predicting suitable habitat

Reproduction

Knowledge about seadragon breeding behavior, reproductive periods and outputs, as well as the early lives of newly hatched juveniles is limited to a few localized studies in the wild and observations in aquaria. Male and female seadragons engage in elaborate courtship rituals to facilitate the transfer of eggs from the female's cloaca to the brood patch under the male's tail (Forsgren and Lowe 2006; Quong 2017). Both males and females ascend and descend in the water column as part of courting behavior and egg transfers (Forsgren and Lowe 2006; Quong 2017). The actual egg transfer during mating has been elusive to observe, both in the wild and in captivity. Male seadragons incubate their eggs for 30—42 days before the young are hatched directly from the brood patch on the tail (Fig. 3) (Forsgren and Lowe 2006; Sanchez-Camara et al. 2006). Male common seadragons have been observed moving to more shallow or sheltered areas in the later stages of brooding as their embryos become closer to hatching (Sanchez-Camara et al. 2004). Juvenile seadragons are independent just after hatching (Fig. 3), feeding on their yolk sacs for several days before beginning to hunt (Kuiter 2003; Forsgren and Lowe 2006). They develop pigmentation during their larval stage that likely provides necessary camouflage during both incubation and their early days of life after hatching (Forsgren and Lowe 2006). Young are hatched into their immediate surroundings and lack a dispersive larval phase (Kuiter 2003; Forsgren and Lowe 2006).

Wild common seadragons at study sites in New South Wales were documented having up to two broods per breeding season (Sanchez-Camara et al. 2005) of around 250 eggs each (Kuiter 1988), a lower reproductive output compared to many seahorse and pipefish species (Gronell 1984; Matsumoto and Yanagisawa 2001; Foster and Vincent 2004). The size of the male brood patch may be a limiting factor in reproductive output (Forsgren and Lowe 2006). Male leafy seadragons at Rapid Bay in South Australia were also observed brooding one or two clutches of eggs during one breeding season (Baker et al. 2020). Reproductive output has not been quantified for most areas where common and leafy seadragons live.

Reproductive timelines have been documented for some populations of common seadragons in New South Wales and leafy seadragons in South Australia. In the populations observed, brooding male common seadragons were seen from June-January (Sanchez-Camara et al. 2005), and most brooding male leafy seadragons were seen during October-January (Baker et al. 2020). The majority of brooding male common seadragons were observed toward the end of their breeding season, correlating with higher water temperatures and resulting in juveniles born into warmer conditions (Sanchez-Camara et al. 2005). Growth rates of juvenile seadragons are faster during the warmer temperatures of the summer and autumn months, slowing during the cooler seasons (Sanchez-Camara et al. 2005). However, warmer conditions beyond the expected range (as in a climate change scenario) would likely have a deleterious effect on seadragons. As ectothermic animals, fishes are acutely impacted by temperature changes, which can cause inefficiencies in their metabolic processes and reduce the energy they have available for investment in functions like reproduction (Little et al. 2020).

Common seadragons living in cooler water at higher latitudes seem to grow more slowly than those living at lower latitudes, though latitudinal trends in adult body sizes remain unclear. In New South Wales, common seadragons showed higher early growth rates and standard lengths at 6 months and 1 year of age (Sanchez-Camara et al. 2005), when compared to Victorian animals (Kuiter 1988). Common seadragons in Tasmania have also been estimated to have slower growth and smaller lengths compared to New South Wales seadragons (Sanchez-Camara et al. 2011). More recent work has not clarified geographic patterns in seadragon sizes but has highlighted issues with sexual dimorphism (Klanten et al. 2020). It appears that sexual dimorphism is not consistent in seadragons across their range, complicating measurements and interpretations of body sizes.

Related section:

- Research gaps- comprehensive data on lifespans and reproductive outputs

Lifespans

Longevity data for seadragons are limited, but it appears likely that their lifespans vary according to location and environmental conditions. About a decade ago, two mark-recapture studies in the eastern part of the common seadragon's range provided baseline longevity estimates of around 6 years for New South Wales populations and over 10 years for Tasmanian populations (Martin-Smith 2011; Sanchez-Camara et al. 2011). The colder waters of Tasmania appeared to correlate with slower growth rates and longer lifespans (Martin-Smith 2011; Sanchez-Camara et al. 2011). Leafy seadragons remain even less studied, with only one report

Fig. 3 Life stages of common and leafy seadragons **A** common seadragon early brood **B** common seadragon mature brood **C** common seadragon juvenile **D** common seadragon subadult **E** leafy seadragon early brood **F** leafy seadragon mature brood **G** leafy seadragon juvenile **H** leafy seadragon subadult

documenting repeated sightings of individuals over 6–7 years at Rapid Bay in South Australia (Baker et al. 2020). In captivity, seadragons have been known to live over 10 years (Kuiter 2003), with a recent study from aquaria reporting lifespans up to 9 years for common seadragons and over 8 years for one leafy seadragon (Pauly et al. 2022).

Generally, predation on syngnathids is not considered a significant factor in their survival, likely due to their excellent camouflage combined with low nutritional benefits (Browne et al. 2008; Kleiber et al. 2011). Documented predation events on a variety of syngnathid species have suggested that such events are uncommon and appear to be opportunistic; syngnathids do not seem to be main targets for predators (Kleiber et al. 2011, but see Harasti et al. 2014). Scattered reports of predation upon seadragons agree with this view, including evidence of common seadragon remains found in dietary analyses of Tasmanian devil scat- clearly an opportunistic scavenging encounter (McLennan et al. 2022). In another example of opportunism, photographs and reports on social media show kangaroos (in locations where they scavenge on beaches) eating seadragon remains (Facebook-SeadragonSearch). Reports of seadragon predation in the ocean include common seadragon remains found in the stomach contents of breaksea cod (Shayne Starr pers. comm.) and snapper (Elaine Lek, Craig Lebens pers. comm.).

Related sections:

- Research gaps- comprehensive data on lifespans and reproductive outputs
- Developing research methodologies- genetic methods using DNA methylation to determine lifespans

Individual level monitoring and population demographics

Past seadragon monitoring studies have utilized tagging techniques including visual implant fluorescent elastomer tags with common seadragons (Sanchez-Camara et al. 2011) and ultrasonic telemetry (radio tracking) with leafy seadragons (Connolly et al. 2002b). Both methods monitored the movements of individual fish and provided data on population parameters from specific locations (Connolly et al. 2002b; Sanchez-Camara et al. 2011). However, physical tagging is effort-intensive and challenging to scale up range-wide, in addition to raising ethical considerations around handling animals. SCUBA surveys completed by researchers and citizen scientists have offered less invasive methods for collecting data about seadragon populations. Surveys completed by researchers have used fixed search patterns employing transects to document seadragon observations (Connolly et al. 2002a; Sanchez-Camara et al. 2011), while surveys by citizen scientists have been focused within the boundaries of general search areas without strict search patterns (Baker et al. 2020). In both cases, survey observations have been useful for documenting seadragons' presence, behavior, and habitat associations, in addition to supplementing data from physical tagging (Connolly et al. 2002a; Sanchez-Camara et al. 2011; Baker et al. 2020). However, surveys lack the precision to reliably identify and track individual fish.

During studies that surveyed and sometimes photographed common and leafy seadragons, researchers noted that it was possible to identify specific individuals based on their unique facial markings or appendage patterns (Connolly et al. 2002a; Sanchez-Camara et al. 2011). Further investigation confirmed that analyzing stable markings and appendage patterns on adult common and leafy seadragons in photographs is a reliable method for tracking individual fish and monitoring populations over time (Martin-Smith 2011; Baker et al. 2020). Unique markings stabilize at 6—7 months of age for common seadragons (Forsgren and Lowe 2006) and adulthood for leafy seadragons (Connolly et al. 2002a), enabling consistent individual identification of adults for both species. While photo-tracking through pattern-matching is a viable monitoring strategy for both common and leafy seadragons, the image analysis process has traditionally been too effort-intensive to scale up beyond local projects (Martin-Smith 2011; Baker et al. 2020). Methods that increase the efficiency of both data collection and pattern-matching analyses are currently in use (http://www.seadragonsearch.org) to expand the scope of monitoring both in terms of time scale and geographic range.

Related sections:

- Conservation concerns- population declines and low densities
- Research gaps- range-wide population size estimates, trends in abundances, and distribution limits
- Developing research methodologies- combining citizen science and machine learning tools for expanded population monitoring

Conservation issues and actions- looking towards a Red List reassessment

Extinction risk status

Over the past two decades, both common and leafy seadragons have moved between several categories on the International Union for the Conservation of Nature's (IUCN) Red List, which assesses extinction risk for wild species (Connolly 2006a, b; Pollom 2017a, b). Both species were originally assessed for the Red List as data deficient in 1996 due to their little-studied abundance trends and basic ecology (IUCN 1996). However, both were reassessed in 2006 and moved to the category 'near threatened' (Connolly 2006a, b), denoting that they did not meet the criteria for a threatened categorization at that time but were evaluated as likely to be moved to a threatened category in the future (IUCN 2012). An assessment of 'near threatened' does not indicate the absence of extinction risk, but the absence of evidence needed to meet the criteria for higher risk categories (IUCN 2012). The 2006 reassessments were spurred by the availability of new information about each species, mainly focused on geographic ranges and known threats to seadragon habitat. Data on population sizes, abundance trends, and life histories for each species were lacking, and more thorough monitoring of seadragon populations was called for to address these data gaps and complete more robust future assessments (Connolly 2006a, b).

Common and leafy seadragons were both most recently reassessed in 2017 as 'least concern', although the assessments acknowledged that their population numbers appeared to be declining (Pollom 2017a, b). A main concern for seadragon populations' future resilience was habitat degradation near urban centers. Because moderate proportions of the understood ranges for common and leafy seadragons occurred away from urban centers, the designation of 'least concern' was deemed most appropriate for each species (Pollom 2017a, b). However, it is well understood that seadragons depend strongly on habitats that are declining due to a variety of human impacts. Furthermore, they exhibit ecological traits that increase their vulnerability to both local and range-wide extinctions, including low densities, low fecundity, restricted home ranges, lack of a dispersive larval phase, and low emigration rates (Sanchez-Camara et al. 2004). To better identify conservation priorities and inform management actions, future seadragon research should aim to address knowledge gaps related to IUCN Red List assessment criteria, including reductions in population size and geographic range.

Ruby seadragons were assessed for the Red List in 2016 and categorized as 'data deficient' due to the species being newly described in 2015 with little known about its ecology or distribution (Aylesworth and Pollom 2016). To date, no new population-level information has become available that would necessitate a reassessment.

Conservation actions to date

Common, leafy, and ruby seadragons (along with all syngnathids) are protected in their entire range throughout Australian waters by the Australian Environmental Protection and Biodiversity Conservation Act (1999). Common seadragons are protected in state waters by the Fisheries Management Act 1994 (New South Wales), the Fisheries Act 1995 (Victoria), the Fisheries Act 1982 (South Australia), the Fish Resources Management Act 1994 (Western Australia), and the Tasmanian Living Marine Resources Management Act 1995 (Tasmania). Leafy seadragons are protected in state waters by the Fisheries Management Act 2007 (South Australia) and the Fish Resources Management Act 1994 (Western Australia). Limited collection of seadragons for aquaria is currently allowed with permitting. A 2006 study concluded that the numbers of individuals collected from the wild for aquaria were low enough to be sustainable for conservation purposes, particularly when compared with threats such as habitat loss (Martin-Smith and Vincent 2006). Researchers have questioned how meaningful current protections for seadragons are without also considering threats to their habitat (Sanchez-Camara et al. 2011). There is no species-specific or international trade legislation in place for the three seadragon species (Aylesworth and Pollom 2016; Pollom 2017a, b). A comprehensive and evidence-based national conservation strategy for seadragons is still lacking.

Captive breeding for conservation

Captive breeding programs could theoretically be beneficial for conserving seadragons but at present remain intermittently successful, small-scale, and costly to implement (Forsgren and Lowe 2006). Common seadragons have transferred, brooded, and hatched eggs in aquaria on various occasions, though successful breeding has been challenging to achieve (Koldeway 2005). Available information indicates that most captive common seadragons have been sourced from Victoria (Klanten et al. 2020), populations with reasonable amounts of genetic variation (Stiller et al. 2023). Leafy seadragons have yet to breed successfully in captivity, and captive numbers are decreasing; at the time of writing, there are only 5 leafy seadragons in 3 aquariums worldwide (Jeremy Brodt, Leslee Matsushige pers. comm.). In the past, attempted egg transfers between leafy seadragons in captivity have been observed, but in each case the male dropped the eggs before embryo development was underway (Koldeway 2005). The barriers to captive breeding are unclear but could potentially be related to limited mate choices for females, limited tank depths, or factors related to light and temperature (Koldeway 2005). Various diseases associated with captivity pose further challenges to keeping seadragons in aquaria, even as established adults (Nyaoke et al. 2009; Bonar et al. 2013; Denk et al. 2020). While they play important roles in aquaria as flagship species for education and ocean conservation, captive environments do not currently provide enough stability for conserving seadragons in a sustainable manner. This may change, but at present protecting wild populations is critical for all three species.

Conservation concerns- limited connectivity and low genetic diversity

The limited dispersal potential and high levels of genetic structure seen among common and leafy seadragon clades range-wide indicate limited gene flow between distinct populations (Stiller et al. 2017, 2021, 2023; Wilson et al. 2017; Klanten et al. 2020). Limited connectivity between populations increases extinction risk as it inhibits the mixing of gene pools that would increase overall population diversity. A lack of connectivity also indicates that individuals are unlikely to colonize new areas (Wilson et al. 2017). Almost all sampled populations of common seadragons have shown very low genetic connectivity, indicating that if there was a local extirpation, locations would not be quickly recolonized by immigrants from neighboring populations (Wilson et al. 2017). For conservation purposes, researchers have recommended that seadragon populations with potential gene flow, such as those east and west of Bass Strait, should be jointly managed to maintain any existing contact through connecting habitat (Stiller et al. 2021, 2023).

Many common and leafy seadragon populations have low genetic diversity, so preserving the diversity they do have is critical (Stiller et al. 2017, 2021, 2023; Wilson et al. 2017). Common seadragon populations have lower genetic diversity on the peripheries of their range, which likely puts those populations at higher risk of extirpation (Stiller et al. 2023). Additionally, there has been a series of significant marine heat waves since the most recent genetic sampling for seadragons, raising the question of whether such events have resulted in further loss of genetic diversity (Stiller et al. 2023). Overall, the concerns raised by genetic studies underscore the need for more robust demographic data to inform future extinction risk assessments.

Conservation concerns- habitat loss, restricted ranges, and high site fidelity

Habitat degradation is a leading cause of decline in syngnathids and is considered a key risk factor for extinction as well as a focus for conservation efforts (De Brauwer et al. 2020; Pollom et al. 2021). Common and leafy seadragons are dependent on macroalgal habitats, have evolved camouflage specific to those habitats, and demonstrate high site fidelity and limited mobility (Connolly et al. 2002b; Sanchez-Camara et al. 2004; Qu et al. 2023). Researchers have expressed increasing concerns over seadragon resilience in the face of habitat loss (Sanchez-Camara et al. 2004; Qu et al. 2023), as both species' ranges include areas of documented habitat degradation from various causes (Pollom 2017a, b).

Australia's Great Southern Reef (GSR) is home to some of the most exceptional seaweed diversity in the world, including a significant number of endemic species, and many species that act as habitat engineers (Martínez et al. 2018). However, kelp and seagrass habitats Australia-wide are threatened by human impacts, and loss of seaweed cover has been documented along Australia's southern coast in association with increased water temperatures, heat waves, and increased severity of storms (Edyvane et al. 2003; Wernberg et al. 2013; Davis et al. 2022). Both the east and west coasts of the Australian continent have experienced some of the highest rates of ocean warming relative to other parts of the world (Hobday and Pecl 2014), and these physical changes have resulted in range shifts for various species (Martínez et al. 2018; Shalders et al. 2018; Parker et al. 2019, 2021). Climate-related habitat changes will likely cause a retraction in the northern extent of many GSR species, and as shallow water species cannot shift further south beyond the continental shelf, these changes will result in a continuously decreasing range, compounded by a decrease in habitat quality (Parker et al. 2019, 2021).

Habitat loss is not the only reason ranges might decrease. Fishes have some capacity to adjust to changing temperatures, but the limits of those capacities are unknown for many species (Little et al. 2020). It is understood that as heat in the environment increases, the energetic costs of growth and movement become greater for most fishes, compromising their abilities to function normally (Little et al. 2020). The effects of increased competition or predation by warmer-climate species shifting south remains unclear but could further exacerbate extinction risk in temperate species (Shalders et al. 2018). Given the limited dispersal abilities of common and leafy seadragons, as well as their finely tuned adaptations to algal habitats, changing environmental conditions and loss of seaweed cover will likely impact local abundances of both species.

Conservation concerns- population declines and low densities

Past monitoring studies for seadragons have been limited in scope but have provided concerning insights regarding abundance trends. Just over a decade ago in New South Wales, declines were observed in numbers of common seadragons at two out of three study sites (Sanchez-Camara et al. 2011). Those declines were apparent by the year 2007 as compared to baseline population size estimates from 2001–2002, with seadragon numbers at one site reducing from 45–47 to 33–34 individuals, and numbers at the other site declining from 67–69 to 30–34 individuals (Sanchez-Camara et al. 2011). The declines were concurrent with the continued industrialization of Botany Bay. Declines of common seadragon numbers were also observed at the Derwent Estuary, a study site near Hobart, Tasmania, where individual numbers dwindled from about 34 to about 27 individuals over the course of the study (Sanchez-Camara et al. 2011). Martin-Smith (2011) documented a decline in numbers of common seadragons at another location in Tasmania, Kingston Beach, which was estimated to have a population size of 32–34 individuals in 2003–2004 (Sanchez-Camara et al. 2011) but only 9 individuals by 2009–2010. A more recent study assessed population trends for many species across the GSR and found a striking decline of 59% in common seadragons range-wide between 2011 and 2021 (Edgar et al. 2023). However, the population trend analyses in this study utilized survey data that included "zero records" (absence data), complicating the analysis of change (Edgar et al. 2023). Additionally, using absence data can be misleading when survey methods were not designed to detect cryptic species (De Brauwer et al. 2018). The estimated 59% decline range-wide is certainly cause for concern and is an indicator that urgent investigation and robust analyses are required.

There is little data available on leafy seadragon population trends. A non-peer-reviewed report observed numbers of leafy seadragons at Rapid Bay Jetty in South Australia between 2014 and 2019. This report did not calculate absolute abundance estimates, but compared opportunistic sightings documented by citizen scientists to sightings documented by a dive tour operator during the mid-2000s (Baker et al. 2020). The differences in numbers of leafy seadragons observed at the site over time were notable, with approximately 75 individuals documented during the mid-2000s, and only 12 individuals documented during 2013–2014 (Baker et al. 2020). Several months into 2019, divers participating in the project were no longer sighting leafy seadragons at Rapid Bay Jetty, even during seasons that seadragons would normally have been present at the site (Baker et al. 2020). By 2020, a small number of individuals were again observed (Baker et al. 2020). This sequence of observations raised concerns about fluctuating population numbers and the causes of those fluctuations. However, the insights are limited to a single site where leafy seadragons occur, and it is unknown how representative these data are. Overall, declines in leafy seadragon populations are thought to be likely due to habitat degradation (Pollom 2017b).

Population densities for common seadragons have been estimated to be 10–70 seadragons ha^{-1} at New South Wales study sites, 15–34 seadragons ha^{-1} in one Tasmanian study (Sanchez-Camara et al. 2011), and 20–60 individuals ha^{-1} in a second Tasmanian study (Martin-Smith 2011). Overall, these population densities are lower than those established for other syngnathid species across a range of habitats (Foster and Vincent 2004; Moreau and Vincent 2004; Martin-Smith and Vincent 2005; Curtis and Vincent 2006; Sanchez-Camara et al. 2011). In South Australia, leafy seadragon populations have been estimated to have densities of 57 individuals ha^{-1}, similar to the upper ranges for common seadragon densities, although these data are over two decades old (Connolly et al. 2002a). Concerningly, a string of massive climate-related East coast low storms hit southeast Australia in 2022, resulting in over 200 common seadragons washing up dead in the Sydney region (Booth et al. 2025). Syngnathids generally have low fecundity and low population densities, making them less resilient in recovering from impacts that decrease their abundances (Connolly et al. 2002a; Foster and Vincent 2004; Sanchez-Camara et al. 2011). Therefore, two key questions that need to be addressed in future research include establishing current population sizes and whether seadragons are experiencing significant declines across their ranges.

Future directions

Research gaps: comprehensive data on lifespans and reproductive outputs

Lifespans and reproductive outputs for seadragons across their ranges are currently unknown. Longevity estimates from localized studies suggest possible differences in length of life between common seadragons living at different latitudes or within different environmental conditions (Martin-Smith 2011; Sanchez-Camara et al. 2011). Similarly, given correlations observed between physical ocean components, such as temperature, and seadragon breeding behavior, differences may exist between reproductive habits and outputs of seadragons living at different latitudes and/or within different current systems. Developing research methodologies and tools for monitoring seadragon populations across their ranges will help to address these knowledge gaps and the challenges faced by distinct seadragon populations in different regions of Australia.

Research gaps: range-wide population size estimates, trends in abundances, and distribution limits

Localized studies and reports have documented past declines in seadragon numbers (Martin-Smith 2011; Sanchez-Camara 2011; Baker et al. 2020), but a national, species-level context requires range-wide population size data. The only population size estimates for common seadragons are from locations on Australia's east coast and are now over a decade old (Martin-Smith 2011; Sanchez-Camara et al. 2011). The only abundance estimates for leafy seadragons are from West Island, South Australia and are now over two decades old (Connolly et al. 2002a). There are no estimates of population sizes for ruby seadragons. Current estimates are required to understand how seadragon populations are responding to contemporary stressors and to what extent local and regional populations might be threatened. Such estimates would also provide the baseline needed to monitor how abundance trends change or remain stable into the future. Both common and leafy seadragons are well-camouflaged and challenging to locate in the wild even at shallow, accessible dives sites. Due to their cryptic nature, a true census will likely not be possible for either species. Capture-mark-recapture (CMR) methods constitute a more effective method to assess population sizes for these species.

Understanding seadragon population numbers on a range-wide scale will require expanding study sites across their distributions, as well as solidifying our understanding of distribution limits. Recent peer-reviewed studies have focused on common seadragon populations near the perceived northern limit of their range on the east coast (Allan et al. 2022a, b), but other areas away from urban centers continue to represent data gaps. Such regions include the Great Australian Bight (where it is difficult to access coastal waters) and the perceived northern limits of both common and leafy seadragons on Australia's west coast near Geraldton and the Abrolhos Islands. The available records for ruby seadragons, from beach-washed and trawled specimens as well as live observations, indicate that there are populations in the Recherche Archipelago region (Rouse et al. 2017). However, the overall scarcity of records precludes a true understanding of the ruby seadragon's range (Stiller et al. 2015, NGW pers. comm.).

Risk assessments to inform conservation planning for seadragons, such as the IUCN Red List, require current and widespread data on abundance trends to make evidence-based recommendations for the future. Although changes in seadragon numbers have been documented to an extent that has raised concerns about their vulnerability, the available data is not comprehensive enough to clarify the status of seadragons across their ranges, or to identify which populations might be most at risk.

Research gaps: ruby seadragon

Abundance estimates and trends, longevity data, and data on reproductive outputs do not exist for the ruby seadragon, as only a few individuals have ever been observed in the wild (Stiller et al. 2015; Rouse et al. 2017). The ruby seadragon represents similar flagship qualities to common and leafy seadragons, and since so little is currently understood about it, a precautionary principle is recommended going forward (Stiller et al. 2015; Rouse et al. 2017).

Developing research methodologies: environmental DNA for detecting populations

The detection of environmental DNA (eDNA) is an emerging method for monitoring marine species, with promising applications for detecting rare or endangered species (e.g. Bonfil et al. 2021; Nester et al. 2023). Environmental DNA refers to DNA that can be extracted from environmental samples (including soil, water, or air) without knowledge of the original organism (Taberlet et al. 2012). An important benefit of using eDNA methods for detecting potentially threatened species is avoiding the need for capturing or visually observing a target organism (Goldberg et al. 2016). This method may be particularly useful to detect seadragon populations that are difficult to survey due to camouflage or living at sites that are remote or deeper than recreational SCUBA limits, as ruby seadragons do. Specific assays for the detection of syngnathids have been developed and tested on seahorses and critically endangered pipefishes with promising results (Nester et al. 2020, 2023). Applying eDNA methods to detect seadragons could contribute to a better understanding of their distributions and conservation status. These methods of sample collection also offer avenues to include diverse stakeholders including citizen scientists in data collection and to raise public awareness around marine habitats (Larson et al. 2020).

Developing research methodologies: tools for predicting suitable habitat

A recent study investigated the influence of kelp (*Ecklonia radiata*) and mysid shrimp abundances on the habitat preferences of common seadragons and developed a model to predict where seadragons were likely to occur within a given habitat, finding that the most significant predictors of seadragon presence represented a trade-off between mysid presence and percent kelp cover (Allan et al. 2022b). Given these results, combining species modeling for mysid shrimp presence with monitoring of kelp distributions could contribute to a better understanding of where seadragon populations are likely to prosper in the future. Methods for mapping kelp distributions range from the use of long-term biological datasets (Young et al. 2023) to the application of remote sensing tools utilizing satellite imagery to document changes in kelp cover (Hamilton et al. 2020). Some studies have investigated factors driving survival of mysid shrimp (Paul et al. 2013; Ober et al. 2017) and could potentially be expanded to better understand where mysids are likely to persist in the future. Given potential habitat loss for temperate coastal species at the northern extents of the GSR, predicting favorable locations for seadragons under changing ocean conditions could inform planning for spatial protections and connected habitats. Integrated analyses could combine elements of habitat data with other datasets (such as population estimates) in a causal inference framework to gain further insights into suitable habitat for seadragons.

Developing research methodologies: genetic methods using DNA methylation to determine lifespans

Understanding the lifespans of fishes is essential to studying important life history traits such as generational turnover, age of maturity, size of breeding adult populations and ultimately the resilience of a species to disturbances. Fish ageing has traditionally been conducted by studying growth rings in otoliths (ear bones), but while useful for its accuracy, this lethal method is not advised when studying potentially threatened species (Hobbs et al. 2014). Estimates of seadragon lifespans therefore currently rely on repeated long-term observations of single individuals in well-studied field locations or in aquaria. This approach provides estimates rather than exact ages due to ambiguity around individual dates of birth and mortality in the wild. In aquaria, births and deaths can be tracked with greater precision, but artificial conditions might affect captive lifespans in ways that preclude generalization to wild individuals (Boggio-Pasqua et al. 2022).

An emerging, non-lethal methodology to estimate age in fishes by measuring DNA methylation may have future applications for seadragons. This method relies on predictable changes occurring in the DNA of species as they age, allowing researchers to establish "epigenetic clocks" that can be read from small tissue samples such as fin clips (Mayne et al. 2020). Reference genomes are available to support the use of these methods for common and leafy seadragons (Qu et al. 2021; Small et al. 2022). Epigenetic methods have been developed for European sea bass, zebrafish, bottlenose dolphins, killer whales, bowhead whales, pinnipeds, some freshwater fish species, and green turtles, providing non-destructive avenues for accumulating longevity data (Beal et al. 2019; Anastasiadi and Piferrer 2020; Mayne et al. 2020, 2021, 2022; Parsons et al. 2023; Robeck et al. 2023). The success of the age estimation models developed for European sea bass and zebrafish have highlighted the opportunities for using this method with non-mammalian vertebrates (Anastasiadi and Piferrer 2020; Mayne et al. 2020). Future research developing epigenetic clocks for seadragons could provide an increasingly precise way of obtaining longevity data important for conservation planning.

Developing research methodologies: combining citizen science and machine learning tools for expanded population monitoring

Widespread and efficient monitoring of wild seadragons is needed to address a variety of research gaps. Conventionally used methods rely heavily on trained scientific divers to find, survey, and study seadragons, and the logistical and budgetary constraints associated with these methods have resulted in past research being largely restricted to a limited number of locations close to human population centers. One avenue for increasing data collection is to utilize the skill sets of community members outside of scientific institutions.

Inviting members of a community to collaborate with scientists on a research project, usually by assisting with data collection, is termed "citizen science" (Bonney et al. 2016). iNaturalist is one example of a citizen science project that has successfully engaged volunteers in sharing images of wildlife through a digital platform to aggregate research-quality data. Similarly, photos of seadragons can be sourced from SCUBA diving communities to increase the reach of seadragon monitoring projects (Baker et al. 2020). Participants can contribute raw data in the form of photographs without requiring formal scientific training, providing a simple methodology that allows a straightforward definition for what constitutes quality data (e.g. accurate date and location data associated with images). As with any research design, data quality is rooted in sound methodology, and clear, attainable protocols for participants result in more reliable data (Balázs et al. 2021). In addition to providing data, citizen science initiatives have the potential to increase public awareness of and investment in conservation activities by considering not only the biological and ecological but also the social factors that influence successful biodiversity conservation (Wright et al. 2015).

Citizen science methods allow for data collection that is more diverse, efficient, and capable of gathering large volumes of information. However, the resulting challenge is in the scalability of data analysis. Machine learning (ML) tools can complement citizen science data collection by increasing the scale, speed, and accuracy of data analysis (Lukyanenko et al. 2019; Balázs et al. 2021). ML tools learn patterns in data and are then able to make predictions given new inputs. When images are the input data, ML tools can learn to label features in the images and look for similar features when presented with new images (Berger-Wolf et al. 2017; Blount et al. 2020). Such methods have become increasingly popular for ecological studies gathering large volumes of data and requiring efficient analyses that will inform conservation applications. Identifying individual seadragons in photographs is a complex task that is accelerated with the use of ML tools, as evidenced by the citizen science project SeadragonSearch, which has successfully used the Wildbook platform to train an algorithm that expedites identification of individual seadragons with high levels of accuracy (www.wildbook.seadragonsearch.org). Final identifications are determined by researchers, but the machine learning pipeline provides a method for scaling data analysis to accommodate the volume of widely collected citizen science records.

Conclusion

To protect seadragons going forward in an era of accumulating human impacts and changing ocean conditions, it will be necessary to acquire data needed to inform extinction risk assessments and management recommendations. Providing new data to inform a reassessment of common and leafy seadragons for the IUCN Red List would be an impactful initial goal for current research projects. This will require robust and comprehensive information indicating whether individual seadragon populations are declining, whether any observed declines are related to human impacts, and how resilient individual populations are in terms of numbers, reproductive potential, longevity, and distribution limits.

Knowledge gaps for the ruby seadragon are even more extensive and difficult to address with traditional methodologies. Emerging technologies could prove particularly useful for this species, including the potential use of eDNA methods to begin establishing a baseline understanding of the ruby seadragon's distribution. In the absence of comprehensive datasets, a precautionary principle should be followed for all three species and applied when planning spatial protection of seadragon habitat. Future research and developing novel methods can complement long-term monitoring programs to improve our understanding of population dynamics for all three species.

An improved understanding of seadragon population trends at sites Australia-wide combined with projected environmental changes to these habitats would support evidence-based planning for protected areas. Spatial protections are likely to benefit these site-loyal animals, as such protections would reduce the number of concurrent stressors faced by seadragon populations. Declines in seadragon populations may indicate broader ecosystem health problems (Sanchez-Camara et al. 2011), and protections for seadragons could simultaneously benefit habitat engineers such as macroalgae and seagrass, as has been demonstrated with other syngnathids inhabiting seagrass beds (Shokri et al. 2009). Habitat-focused conservation actions could also benefit other fishes and invertebrates dependent on the health of those systems. Habitat protection is an increasingly important focus for national and global biodiversity frameworks, including the United Nations' 30 × 30 initiative to protect 30% of lands and oceans by the year 2030 (Kunming-Montreal Global Biodiversity Framework). Given the striking amount of biodiversity and endemic species found in the GSR, protecting habitat throughout this reef system could be greatly impactful for broader conservation goals.

The value of seadragons as flagship species for the GSR, their potential to act as indicator species for and provide umbrella protections to their habitats, as well as their intrinsic value as Australian endemics all underscore the importance of future research to support evidence-based conservation for these remarkable syngnathid fishes.

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Author contributions CAT wrote the first drafts of the manuscript, implemented edits and additions as it developed, and created the figures. NGW and MDB contributed to writing. NGW, GWR, DJB, and MDB edited and provided feedback on the manuscript as it progressed. All authors read and approved the final version of the paper.

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Declarations

Conflict of interest The authors have no competing interests to declare.

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