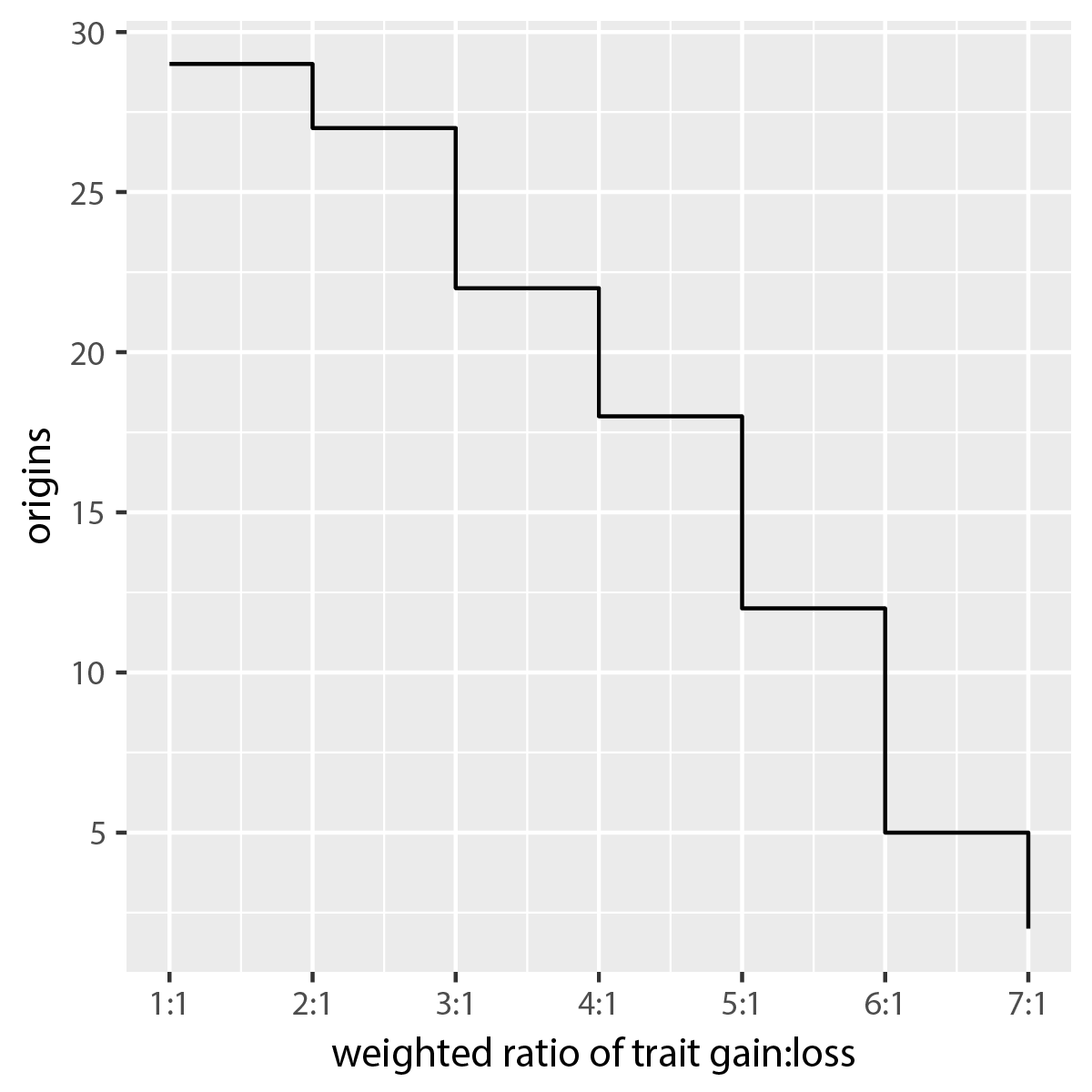
**Multi-level convergence of complex traits and the evolution of bioluminescence**

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**Supporting information**

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**Fig. S1.** Using parsimony-based methods in an ancestral reconstruction of bioluminescence in ray-finned fishes produces independent-origin estimates that are dependent on the hypothesized cost of trait gain:loss. As it becomes more costly to gain bioluminescence in ray-finned fishes, bioluminescence is more likely to be lost than gained, and the number of origins decreases. The R package castor’s asr\_maximum\_parsimony function provided ancestral likelihood calculations for each weighted trait gain to loss ratio and the presented origins for each trait gain:loss represent the most conservative origin estimates (Louca & Doebeli, 2018).

**Table S1.** Table of bioluminescent taxa with information on type of bioluminescence, known luciferins, and number of origins within a taxonomic group.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Kingdom/Phylum** | **Taxon as shown on Fig. 2** | **Bioluminescence type** | **Luciferin** | **No. origins** | **References** |
| Proteobacteria | Bacteria | bacteriogenic a | bacterial | 1 | a Strehler *et al.* (1954) |
| Dinoflagellata | Dinoflagellates | autogenic a | dinoflagellate b | 1 | a Herring (1987)  b Nakamura *et al.* (1989) |
| Radiolaria | Polycystine radiolaria | autogenic a | coelenterazine b | 1 | a Haddock *et al.* (2010)  b Thomson *et al.* (1997) |
| Cercozoa | Phaeodarian radiolaria | autogenic a | unknown | 1 | a Herring (1987) |
| Fungi | Fungi | autogenic a | fungal b | 1 c | a Herring (1987)  b Purtov *et al.* (2015)  c Purtov *et al.* (2015) |
| Porifera | Porifera | autogenic a | coelenterazine a | 1 | a Martini *et al.* (2020) |
| Ctenophora | Ctenophora | autogenic a | coelenterazine b | 1 | a Herring (1987)  b Thomson *et al.* (1997) |
| Cnidaria | Anthozoa | autogenic a | coelenterazine b | 3 c | a Herring (1987)  b Cormier *et al.* (1970);Shimomura & Johnson (1979)  c Bessho-Uehara *et al.* (2020*a*) |
| Hydrozoa | autogenic a | coelenterazine b | 1 c | a Herring (1987)  b Shimomura & Johnson (1979)  c Bessho-Uehara *et al.* (2020*a*) |
| Scyphozoa | autogenic a | coelenterazine b | 2 c | a Herring (1987)  b Shimomura *et al.* (2001)  c Bessho-Uehara *et al.* (2020*a*) |
| Chaetognatha | Chaetognatha | autogenic a | coelenterazine b | 2 b | a Herring (1987)  b Thuesen *et al.* (2010) |
| Mollusca | Decabrachia  Octobrachia | autogenic a  bacteriogenic a | coelenterazine b unknown  bacterial | 10 c | a Herring (1987); Robison *et al.* (2003); Galeazzo *et al.* (2019)  b Herring (1987); Robison *et al.* (2003); Galeazzo *et al.* (2019)  c Sanchez *et al.* (2018) |
| Bivalvia | autogenic a | coelenterazine b | 1 | a Herring (1987)  b Inouye *et al.* (2020) |
| Caenogastropoda | autogenic a | unknown | 1 | a Herring (1987) |
| Heterobranchia | autogenic a | unknown  *Pholas* luciferin b | 4 | a Herring (1987)  b Michelson, (1978); Inouye *et al.* (2020) |
| Nemertea | Nemertea | autogenic a | unknown | 1 | a Kanda (1939) |
| Annelida | Chaetopteridae | autogenic a | unknown | 1 | a Nishi *et al.* (2000) |
| Syllidae | autogenic a | *Odontosyllis* luciferin b | 1 | a Herring (1987)  b Kotlobay *et al.* (2019) |
| Polynoidae | autogenic a | unknown | 1 | a Plyuscheva *et al.* (2009) |
| Tomopteridae | autogenic a | unknown 2,b | 1 | a Gouveneaux *et al.* (2017)  b Thomson *et al.* (1997) |
| Cirratuliformia | autogenic a | unknown | 1 | a Osborn *et al.* (2009); Francis *et al.* (2016) |
| Clitellata | autogenic a | *Diplocardia* luciferin b  *Fridericia* luciferin c  unknown | 2 b,c | a Herring (1987)  b Ohtsuka *et al.* (1976); Petushkov *et al.* (2014)  c Ohtsuka *et al.* (1976); Petushkov *et al.* (2014) |
| Terebelliformia | autogenic a | unknown | 1 | a Kin *et al.* (2019) |
| Nematoda | Nematoda | bacteriogenic a | bacterial | 1 | a Patterson *et al.* (2015) |
| Arthropoda | Pycnogonid | autogenic a | unknown | 1 | a Herring (1987) |
| Centipedes | autogenic a | unknown | 1 | a Anderson (1980) |
| Millipedes | autogenic a | unknown | 1 | a Marek & Moore (2015) |
| Cypridinid ostracods | autogenic a | vargulin | 1 b | a Campbell & Herring (1990)  b Campbell & Herring (1990) |
| Halocyprid ostracods | autogenic a | coelenterazine a | 1 | a Campbell & Herring (1990); Oba *et al.* (2004) |
| Collembola | autogenic a | unknown | 1 | a McElroy *et al.* (1974) |
| Coleoptera | autogenic a | firefly luciferin | 2 b | a Herring (1987)  b Fallon *et al.* (2018) |
| Diptera | autogenic a | unknown 1,b | 2 b | a Herring (1987)  b Watkins *et al.* (2018); Viviani *et al.* (2020) |
| Copepoda | autogenic a | coelenterazine b | 1 | a Herring (1987)  b Campbell & Herring (1990) |
| Decapod shrimp | autogenic a | coelenterazine b | 1 | a Herring (1987)  b Thomson *et al.* (1995) |
| Euphausiacea | autogenic a | euphausiid luciferin b | 1 | a Herring (1987)  b Nakamura *et al.* (1988) |
| Lophogastridan shrimp | autogenic a | coelenterazine b | 1 | a Herring (1987)  b Frank *et al.* (1984) |
| Amphipoda | autogenic a | unknown | 1 | a Bowlby *et al.* (1991) |
| Hemichordata | Hemichordata | autogenic a | *Ptychodera* luciferin b | 1 | a Herring (1987)  b Kanakubo *et al.* (2005) |
| Echinodermata | Crinoids | autogenic a | unknown | 1 | a Herring (1987) |
| Ophiuroidea | autogenic a | coelenterazine b  unknown | 1 | a Herring (1987)  b Shimomura (1986); Herring (1987) |
| Asteroidea | autogenic a | unknown | 1 | a Herring (1987) |
| Holothuroidea | autogenic a | unknown | 1 | a Herring (1987) |
| Chordata | Appendicularia | autogenic a | coelenterazine a | 1 | a Galt & Flood (1998); Haddock *et al.* (2010) |
| Ascidian | autogenic a | unknown | 1 | a Aoki *et al.* (1989) |
| Salp and doliolids | unknown a | unknown | 1 | a Herring (1987) |
| Sharks and rays | autogenic a | unknown | 1 | a Renwart & Mallefet (2013) |
| Anguilliformes | autogenic a  bacteriogenic a | unknown  bacterial | 2 b | a Herring (1987)  b Davis *et al.* (2016) |
| Alepocephaliformes | autogenic a | unknown 2,b | 2 c | a Herring (1972, 1987); Thomson *et al.* (1997)  b Herring (1972, 1987); Thomson *et al.* (1997)  c Davis *et al.* (2016) |
| Clupeiformes | autogenic a | unknown | 1 b | a Herring & Morin (1978); Herring (1987)  b Davis *et al.* (2016) |
| Argentiniformes | bacteriogenic a | bacterial | 2 a | a Davis *et al.* (2016) |
| Stomiiformes | autogenic a | coelenterazine b, unknown | 1 c | a Herring (1987)  b Shimomura *et al.* (1980); Thomson *et al.* (1997)  c Davis *et al.* (2016) |
| Aulopiformes | autogenic a  bacteriogenic a | unknown  bacterial | 4 b | a Herring & Morin (1978); Herring (1987)  b Davis *et al.* (2016) |
| Myctophiformes | autogenic a | coelenterazine b | 1 c | a Herring (1987)  b Duchatelet *et al.* (2019)  c Davis *et al.* (2016) |
| Gadiformes | bacteriogenic a | bacterial | 3 b | a Herring & Morin (1978)  b Davis *et al.* (2016) |
| Beryciformes | bacteriogenic a | bacterial | 2 b | a Herring & Morin (1978)  b Davis *et al.* (2016) |
| Batrachoidiformes | autogenic a | vargulin b | 1 c | a Herring & Morin (1978)  b Tsuji *et al.* (1975)  c Davis *et al.* (2016) |
| Scombriformes | autogenic a | unknown | 1 b | a Herring (1987)  b Davis *et al.* (2016) |
| Gobiiformes | autogenic a  bacteriogenic a | vargulin b  bacterial | 2 4,c | a Herring & Morin (1978); Thacker & Roje (2009)  b Tsuji *et al.* (1971)  c Davis *et al.* (2016) |
| Acanthuriformes | autogenic a  bacteriogenic a | unknown  bacterial | 4 b | a Herring (1987)  b Davis *et al.* (2016) |
| Acropomatiformes | autogenic 3,a  bacteriogenic a | vargulin b, unknown 2,c  bacterial | 3 4,d | a Herring (1987); Bessho-Uehara *et al.* (2020*b*)  b Haneda *et al.* (1966); Thomson *et al.* (1997)  c Haneda *et al.* (1966); Thomson *et al.* (1997)  d Davis *et al.* (2016) |

Superscript letters a–d identify the relevant references.

1 Proposed luciferin structure available.

2 Coelenterazine found in organism but not yet demonstrated to be used in its bioluminescence system.

3 Kleptoprotein bioluminescence (found in *Parapriacanthus ransonneti*).

4 Prior estimate from Davis *et al*. (2016) changed upon conducting parsimony-based ancestral state reconstruction. using updated classifications of autogenic and bacteriogenic bioluminescence.