
Supplementary information

**Evolutionary lability of a key innovation
spurs rapid diversification**

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1 Supplementary Discussion

1.1 Classification of simple and complex teeth

In this study, we classified tooth complexity as a binary trait. Our binary classification represents a major evolutionary transition, from between simple and complex in any form, that follows the traditional definition of a key innovation and has functional implications. We classified a species as complex if teeth with more than one cusp were present on any dentigerous bones in the oral jaws. Lineages with complex teeth thus include species with teeth that have two (e.g., Loricariidae, Mormyridae) to as many as twelve cusps (e.g., Acanthuridae, Characidae). We recognize that our phylogenetic comparative analyses based on this binary classification ignore any transitions in cusp number within complex species. In other studies of vertebrates, transition rates of the number of cusps were found to be higher within complex lineages; the transition rate from two to three cusps is higher than the rate from one to two cusps in squamates¹. We expect a similar pattern to be true in fishes. Some groups (e.g., Characiformes) have considerable variation in the number of cusps within complex lineages while others (e.g., African cichlids) have only two or three. However, we expect that the effect of a transition within complex lineages (i.e., from three to four cusps) on macroevolutionary processes is considerably weaker than a transition from simple to complex teeth in any form.

1.2 The development of complex teeth

In vertebrates, the process of tooth development and replacement is a conserved process that has given rise to a diversity of dentitions through modification to the same underlying machinery^{2,3}. Formation of complex teeth from a simple, conical ancestral form may require minimal modification to existing tooth development mechanisms⁴. Early experimental studies in mammals implicate extracellular signaling ligands, primarily fibroblast growth factors (FGFs) and bone morphogenetic proteins (BMPs), in controlling cusp number and morphology^{5,6}. The antagonistic actions of these signaling molecules control outcomes at multiple stages of tooth morphogenesis, including tooth formation and position and the formation of the primary enamel knot (EK). BMPs and FGFs secreted from the primary EK can inhibit or promote the development of additional EKs (and as a result, tooth cusps) because the number and spacing of EKs determines the number of cusps⁷⁻⁹. Experimental studies in fishes, including African

cichlids, show that manipulating any single pathway containing candidate activators or inhibitors of cusp development produce changes in the number of tooth cusps^{4,10}. These signaling pathways include BMP, FGF, Hedgehog (Hh), Notch, and Wnt/ β -catenin. This supports the idea that change in tooth complexity in cichlids has a simple genetic basis that can respond rapidly to selective pressure^{11,12}, as activation or inhibition of any single pathway is enough to produce extreme changes in tooth complexity.

The observed ontogenetic change in tooth complexity, from complex to simple, in many African cichlids implies that every individual has the developmental capacity to produce both simple and complex teeth. We suggest this ontogenetic change may play an important role in causing the elevated macroevolutionary transition rates in this clade. The redundancy of development pathways that affect tooth complexity in cichlids¹⁰ provides multiple avenues for significant morphological change to occur. Fine-tuning of gene regulation through ontogeny facilitates trophic innovations in African cichlids¹³. This ontogenetic change might allow tooth complexity to respond rapidly to selection by maintaining a level of phenotypic plasticity. Indeed, cichlids often show plastic responses in trophic morphology^{14–16}. Moreover, we see population-level variation in tooth complexity in putative species complexes at early stages of divergence, particularly in Lake Victoria, that may be linked to diet and microhabitat (N.P. unpublished data,¹⁷). Genetic assimilation may result in the canalization of simple or complex teeth during or following the speciation process¹⁸. We suggest this scenario is consistent with the association between elevated macroevolutionary transition rates and ontogenetic change, and the resulting effect of this lability on speciation rates in this study.

2 Supplementary Tables

2.1 Supplementary Table 1 | Actinopterygian families that contain lineages with complex oral jaw teeth. Within each family, genera that contain at least one species with complex teeth are listed. Orders follow Near and Thacker (2024)¹⁹.

Order	Family	Genera with complex species	Reference
Perciformes	Liparidae	<i>Liparis</i> , <i>Polypera</i> , <i>Crystallichthys</i> , <i>Elassodiscus</i> , <i>Rhinoliparis</i> , <i>Careproctus</i> , <i>Temnocora</i> , <i>Crystallias</i> , <i>Paraliparis</i> , <i>Allocareproctus</i>	20–28
Atheriniiformes	Anablepidae	<i>Jenynsia</i>	29
Atheriniiformes	Poeciliidae	<i>Poeciliopsis</i> , <i>Limia</i> , <i>Poecilia</i>	30–32
Atheriniiformes	Goodeidae	<i>Allodontichthys</i> , <i>Ameca</i> , <i>Ataeniobius</i> , <i>Chapalichthys</i> , <i>Characodon</i> , <i>Goodea</i> , <i>Ilyodon</i> , <i>Skiffia</i> , <i>Xenophorous</i> , <i>Xenotaenia</i> , <i>Xenotoca</i>	33–38
Atheriniiformes	Cyprinodontidae	<i>Aphanius</i> , <i>Cyprinodon</i> , <i>Jordanella</i> , <i>Cualac</i> , <i>Floridichthys</i> , <i>Megupsilon</i>	29,39
Siluriformes	Amphiliidae	<i>Tetracamphilius</i>	40
Siluriformes	Trichomycteridae	<i>Trichogenes</i>	41
Siluriformes	Scoloplacidae	<i>Scoloplax</i>	42
Siluriformes	Astroblepidae	<i>Astroblepus</i>	43
Siluriformes	Sisoridae	<i>Glaridoglanis</i>	44
Siluriformes	Heptateridae	<i>Phenacorhamdia</i>	45
Siluriformes	Mochokidae	<i>Atopochilus</i> , <i>Atopodontus</i> , <i>Euchilichthys</i>	46–48
Siluriformes	Loricariidae	<i>Brochiloricaria</i> , <i>Dasylicaria</i> , <i>Farlowella</i> , <i>Furcodontichthys</i> , <i>Harttia</i> , <i>Harttiella</i> , <i>Hemiodontichthys</i> , <i>Ixinandria</i> , <i>Lamontichthys</i> , <i>Limatulichthys</i> , <i>Loricaria</i> , <i>Loricariichthys</i> , <i>Metaloricaria</i> , <i>Paraloricaria</i> , <i>Pseudoloricaria</i> , <i>Pterosturisoma</i> , <i>Ricola</i> , <i>Rineloricaria</i> , <i>Spatuloricaria</i> , <i>Sturisoma</i> , <i>Sturisomatichthys</i> , <i>Delturus</i> , <i>Hemipsilichthys</i> , <i>Lithogenes</i> , <i>Microplecostomus</i> , <i>Hirtella</i> , <i>Isbrueckerichthys</i> , <i>Neoplecostomus</i> , <i>Pareiorhaphis</i> , <i>Pareiorhina</i> , <i>Acestridium</i> , <i>Hypoptopoma</i> , <i>Otocinclus</i> , <i>Corumbataia</i> , <i>Curculionichthys</i> , <i>Epactionotus</i> , <i>Hisonotus</i> , <i>Microlepidogaster</i> , <i>Otothyris</i> , <i>Otothyropsis</i> , <i>Parotocinclus</i> , <i>Gymnotocinclus</i> , <i>Plesiopoma</i> , <i>Rhinolekos</i> , <i>Acanthicus</i> , <i>Ancistrus</i> , <i>Andeancistrus</i> , <i>Araichthys</i> , <i>Baryancistrus</i> , <i>Chaetostoma</i> , <i>Cordylancistrus</i> , <i>Corymbophanes</i> , <i>Dekeyseria</i> , <i>Dolichancistrus</i> , <i>Exastilithoxus</i> , <i>Hemiancistrus</i> , <i>Hopliancistrus</i> , <i>Hypancistrus</i> , <i>Lasiancistrus</i> , <i>Leporacanthicus</i> , <i>Lithoxus</i> , <i>Megalancistrus</i> , <i>Micracanthicus</i> ,	49–78

		<i>Neblinichthys, Panaqolus, Panaque, Parancistrus, Paulasquama, Pseudacanthicus, Pseudancistrus, Pseudolithoxus, Pseudoqolus, Scobinancistrus, Soromonichthys, Spectracanthicus, Transancistrus, Yahuwak, Aphanotorulus, Hypostomus, Isorineloricaria, Pterygoplichthys, Pogonopoma, Pseudorinelepis, Rhinelepis, Ancistomus, Cryptancistrus, Guyanancistrus, Leptoancistrus, Peckoltia, Peckoltichthys, Nannoplecostomus</i>	
Osteoglossiformes	Mormyridae	<i>Boulengeromyrus, Brienomyrus, Brevimyrus, Campylomormyrus, Gnathonemus, Hippopotamyrus, Hyperopisus, Isichthys, Ivindomyrus, Marcusenius, Mormyrops, Mormyrus, Paramormyrops, Pollimyrus, Stomatorhinus, Cryptomyrus, Petrocephalus</i>	46,79–87
Myctophiformes	Myctophidae	<i>Diogenichthys</i>	88
Blenniiformes	Mugilidae	<i>Agonostomus, Chaenomugil, Chelon, Joturus, Mugil, Neomyxus</i>	89–95
Atheriniformes	Atherinopsidae	<i>Atherinops, Colpichthys</i>	96
Atheriniformes	Exocoetidae	<i>Cypselurus</i>	97
Atheriniformes	Hemirhamphidae	<i>Arrhampus, Chriodorus, Euleptorhamphus, Hemiramphus, Hyporhamphus, Oxyporhamphus</i>	98–102
Centrarchiformes	Girellidae	<i>Girella</i>	103
Acanthuriformes	Pomacanthidae	<i>Apolemichthys, Centropyge, Chaetodontoplus, Genicanthus, Holacanthus, Paracentropyge, Pomacanthus, Pygoplites</i>	104, observation of specimens
Centrarchiformes	Terapontidae	<i>Helotes</i>	105
Acanthuriformes	Ephippidae	<i>Platax, Proteracanthus, Rhinoprenes, Tripteron, Zabidius</i>	106
Acanthuriformes	Scatophagidae	<i>Scatophagus, Selenotoca</i>	107
Cichliformes	Pomacentridae	<i>Abudefduf</i>	observation of specimens
Acanthuriformes	Siganidae	<i>Siganus</i>	observation of specimens
Acanthuriformes	Acanthuridae	<i>Acanthurus, Ctenochaetus, Prionurus, Paracanthurus, Zebrasoma</i>	observation of specimens
Scombriformes	Nomeidae	<i>Psenes</i>	108
Scombriformes	Ariommatidae	<i>Ariomma</i>	109
Scombriformes	Stromateidae	<i>Pampus, Peprilus</i>	110,111
Gobiesociformes	Gobiesocidae	<i>Diademichthys, Acyrtops, Acyrtus, Derilissus, Gobiesox, Tomicodon, Sicyopterus, Sicydium, Cotylopus, Lentipes, Akihito, Parasicydium, Stiphodon, Awaous, Tridentiger, Evorthodous, Apocryptodon, Apocryptes, Boleophthalmus</i>	112–133
Gobiiformes	Oxudercidae	<i>Belonophago, Congocharax, Distichodus, Dundocharax, Eugnathichthys, Hemigrammocharax, Ichthyborus, Mesoborus, Microstomatichthyborus,</i>	134–166
Cithariniformes	Distichodontidae		167

		<i>Monostichodus, Nannaethiops,</i>	
		<i>Nannocharax, Neolebias, Paradistichodus,</i>	
		<i>Paraphago, Phago, Xenocharax</i>	
Cithariniformes	Citharinidae	<i>Citharinidium, Citharinops, Citharinus</i>	167
Characiformes	Alestiidae	<i>Alestes, Alestopetersius, Arnoldichthys,</i>	168
		<i>Bathyaethiops, Brachypetersius, Brycinus,</i>	
		<i>Bryconaethiops, Hemigrammopetersius,</i>	
		<i>Ladigesia, Micralestes, Nannopetersius,</i>	
		<i>Petersius, Phenacogrammus,</i>	
		<i>Rhabdalestes, Tricuspidaletes</i>	
Characiformes	Acestrorhynchidae	<i>Acestrorhynchus, Gilbertolus,</i>	observation of
		<i>Gnathocharax, Heterocharax,</i>	specimens
		<i>Hoplocharax, Roestes</i>	
Characiformes	Anostomidae	<i>Abramites, Anostomoides, Anostomus,</i>	169–174
		<i>Gnathodolus, Hypomasticus, Laemolyta,</i>	
		<i>Leporellus, Leporinus, Megaleporinus,</i>	
		<i>Petulanos, Pseudanos, Rhytiodus, Sartor,</i>	
		<i>Schizodon</i>	
Characiformes	Bryconidae	<i>Brycon, Chilobrycon, Henochilus</i>	175–177
Characiformes	Chalceidae	<i>Chalceus</i>	178
Characiformes	Characidae	<i>Acrobrycon, Amazonspinter, Argopleura,</i>	179–227
		<i>Astyanax, Bryconamericus, Carlastyanax,</i>	
		<i>Ceratobranchia, Cheirodon,</i>	
		<i>Chrysobrycon, Compsura, Coptobrycon,</i>	
		<i>Corynopoma, Creagrus, Ctenobrycon,</i>	
		<i>Deuterodon, Diapoma, Eretmobrycon,</i>	
		<i>Erythrocharax, Gephyrocharax,</i>	
		<i>Glandulocauda, Gymnocorymbus,</i>	
		<i>Hasemania, Hemibrycon, Hemigrammus,</i>	
		<i>Heterocheirodon, Hollandichthys,</i>	
		<i>Hyphessobrycon, Inpaichthys, Jupiaba,</i>	
		<i>Knodus, Kolpotocheirodon, Lepidocharax,</i>	
		<i>Leptagoniates, Lophiobrycon, Markiana,</i>	
		<i>Microchemobrycon, Mimagoniates,</i>	
		<i>Moenkhausia, Myxiops, Nematobrycon,</i>	
		<i>Odontostilbe, Oligosarcus, Petitella,</i>	
		<i>Phenacogaster, Piabina, Planaltina,</i>	
		<i>Poptella, Prionobrama, Pristella,</i>	
		<i>Probolodus, Prodonotocharax,</i>	
		<i>Protocheirodon, Pseudochalceus,</i>	
		<i>Rhinobrycon, Serrapinnus, Stethaprion,</i>	
		<i>Stygichthys, Tetragonopterus, Thayeria</i>	
Characiformes	Chilodontidae	<i>Caenotropus</i>	172,228
Characiformes	Crenuchidae	<i>Ammocryptocharax, Crenuchus,</i>	179,229–231
		<i>Poecilocharax</i>	
Characiformes	Gasteropelecidae	<i>Carnegiella, Gasteropelecus,</i>	232
		<i>Thoracocharax</i>	
Characiformes	Hemiodontidae	<i>Argonectes, Bivibranchia, Hemiodus</i>	233
Characiformes	Iguanodectidae	<i>Iguanodectes</i>	204
Characiformes	Lebiasinidae	<i>Lebiasina, Nannostomus</i>	234,235
Characiformes	Parodontidae	<i>Apareiodon, Parodon, Saccodon</i>	236–238
Characiformes	Serrasalminidae	<i>Colossoma, Mylesinus, Myleus, Ossubtus,</i>	239–249
		<i>Pristobrycon, Pygocentrus, Pygopristis,</i>	
		<i>Serrasalmus, Tometes, Utiaitichthys</i>	
Characiformes	Triportheidae	<i>Clupeacharax, Triportheus</i>	250,251
Blenniiformes	Cichlidae	See Supplementary Table 12	

2.2 Supplementary Table 2 | Estimated number of transitions between each state under the MAP ancestral state reconstruction of tooth complexity for 11,508 species of ray-finned fishes. Low and high refer to the two hidden states in the model, reflecting differences in lability. The number of transitions are reported for five different prior transitions (50 / 150 / 200 / 250 / 400). The results under the prior of 200 (in bold) are reported in the main text.

From	To	Transition type	Number of transitions
simple-low	complex-low	gain complex teeth	6 / 6 / 8 / 7 / 8
simple-low	simple-high	increase lability	31 / 36 / 16 / 48 / 24
simple-low	complex-high	gain complex teeth, increase lability	1 / 0 / 1 / 3 / 9
complex-low	simple-low	lose complex teeth	0 / 24 / 27 / 26 / 27
complex-low	simple-high	lose complex teeth, increase lability	1 / 3 / 0 / 1 / 3
complex-low	complex-high	increase lability	3 / 10 / 11 / 22 / 28
simple-high	simple-low	decrease lability	17 / 119 / 113 / 101 / 60
simple-high	complex-low	gain complex teeth, decrease lability	2 / 5 / 8 / 12 / 10
simple-high	complex-high	gain complex teeth	58 / 65 / 78 / 242 / 362
complex-high	simple-low	lose complex teeth, decrease lability	1 / 0 / 0 / 5 / 36
complex-high	complex-low	decrease lability	3 / 56 / 62 / 71 / 83
complex-high	simple-high	lose complex teeth	64 / 60 / 83 / 248 / 374

2.3 Supplementary Table 3 | Comparison of discrete character evolution models fit over the ray-finned fish phylogeny (n=11,508 species). Bayes factors (BF) are reported in comparison to the best-fit model, HR2-ARD (in bold). A second set marginal likelihood estimation under the same power posterior analysis and stepping sampler is shown in parentheses to demonstrate that the marginal likelihood estimates are stable using 10 stones.

Model	Marginal likelihood	ln BF	BF
ER	-1116.615 (-1116.688)	273.5266	6.1815E+118
ARD	-949.2979 (-950.1362)	106.2095	1.33721E+46
HR-variable	-873.8059 (-872.8403)	30.7175	2.18998E+13
HR2-ER	-844.9976 (-846.8524)	1.9092	6.747688488
HR2-ARD	-843.0884 (-843.0934)	-	-

2.4 Supplementary Table 4 | Mean estimated transition rates between simple and complex teeth across ray-finned fishes under 5 priors. The relative difference in rates reported as the ratio of the rate of loss to the rate of gain.

	low gain	low loss	high gain	high loss	ratio-low	ratio-high
50	0.000050788	0.0004784	0.0095337	0.013	9.42	1.36
150	0.00003964	0.001698	0.0243	0.0495	42.84	2.04
200	0.000034685	0.0017515	0.0715	0.0897	50.5	1.25
250	0.00002683	0.001542	0.2606	0.2309	57.47	0.89
400	0.000023939	0.001759	0.4535	0.4062	73.48	0.9

2.5 Supplementary Table 5 | Transition rates between simple and complex teeth across ray-finned fishes under a HiSSE model fit using the ‘castor’ R package under a Bayesian HR2-ARD model in RevBayes.

Transition type	rate (HiSSE with ‘castor’)	rate (HR2-ARD)
gain complex teeth – low lability	0.1657	0.00003
lose complex teeth – low lability	72.1088	0.00175
gain complex teeth – high lability	136.0097	0.0715
lose complex teeth – high lability	107.7286	0.0897

2.6 Supplementary Table 6 | Tooth complexity and diet classifications for Cichlidae, covering all genera from Africa, Madagascar, and South Asia. If genera contain species with both simple and complex teeth, both are listed. For genera that contain species of multiple different diet classifications, all diets within that genera are listed.

Genus	Tooth complexity	Diet	Tooth complexity references	Diet references
<i>Abactochromis</i>	Complex	Zoobenthivore	252	253
<i>Alcolapia</i>	Complex	Herbivore	254	255,256
<i>Asprotilapia</i>	Complex	Herbivore	257,258	259
<i>Cheilochromis</i>	Complex	Zoobenthivore	260	255
<i>Chetia</i>	Complex	Piscivore, Zoobenthivore	261,262	255,262,263
<i>Chindongo</i>	Complex	Herbivore, Omnivore, Zooplanktivore	253,264	253,255,265,266
<i>Coelotilapia</i>	Complex	Herbivore	267	255
<i>Congolapia</i>	Complex		268	
<i>Coptodon</i>	Complex	Herbivore, Omnivore, Zooplanktivore	269,270	255,269,270
<i>Ctenochromis</i>	Complex	Omnivore	258,271	272
<i>Cunningtonia</i>	Complex	Zooplanktivore	257,258	255
<i>Cyathochromis</i>	Complex	Herbivore	273	255,266
<i>Cyclopharynx</i>	Complex	Herbivore	274	255
<i>Danakilia</i>	Complex	Herbivore	254	255
<i>Docimodus</i>	Complex	Carnivore specialist	260,275	255,266
<i>Eclectochromis</i>	Complex	Zoobenthivore	276	255
<i>Etia</i>	Complex	Zoobenthivore	277	278
<i>Etroplus</i>	Complex	Herbivore	279	255
<i>Fossorochromis</i>	Complex	Zoobenthivore	276	255
<i>Genyochromis</i>	Complex	Carnivore specialist	273	255
<i>Gobiocichla</i>	Complex	Herbivore	257	255
<i>Heterotilapia</i>	Complex	Omnivore	280	278
<i>Interochromis</i>	Complex	Herbivore	258	255
<i>Iodotropheus</i>	Complex	Omnivore	253	253
<i>Iranocichla</i>	Complex	Herbivore	281,282	255
<i>Katria</i>	Complex		279	
<i>Konia</i>	Complex	Zoobenthivore	283	255
<i>Labeotropheus</i>	Complex	Herbivore	253	253,255
<i>Lichnochromis</i>	Complex	Piscivore	260	273
<i>Limnotilapia</i>	Complex	Omnivore	258	255,284
<i>Lithochromis</i>	Complex	Herbivore	285	285
<i>Maylandia</i>	Complex	Herbivore, Zooplanktivore, Zoobenthivore	264,286	253,255,265,266
<i>Mbipia</i>	Complex	Herbivore, Omnivore	285	255
<i>Mchenga</i>	Complex	Zooplanktivore	276,287	255,288
<i>Melanochromis</i>	Complex	Herbivore, Omnivore, Piscivore, Carnivore specialist	253	253,255
<i>Naevochromis</i>	Complex	Carnivore specialist	260	255
<i>Neochromis</i>	Complex	Herbivore, Omnivore	285	255,285
<i>Orthochromis</i>	Complex	Herbivore, Omnivore	289–291	255

<i>Oxylapia</i>	Complex		279	
<i>Pelmatolapia</i>	Complex	Herbivore	292	255
<i>Petrochromis</i>	Complex	Herbivore	293	294
<i>Petrotilapia</i>	Complex	Herbivore, Omnivore	273,295	253,255,295
<i>Pharyngochromis</i>	Complex		296	
<i>Pseudetroplus</i>	Complex	Omnivore	279	255
<i>Pseudocrenilabrus</i>	Complex	Omnivore, Zoobenthivore	291,297	255
<i>Pseudosimochromis</i>	Complex	Herbivore	294	259,294
<i>Pseudotropheus</i>	Complex	Herbivore, Omnivore, Zooplanktivore, Zoobenthivore	276	253,255
<i>Ptychochromis</i>	Complex	Omnivore, Zoobenthivore	279	255
<i>Ptychochromoides</i>	Complex	Omnivore	279	255
<i>Sarotherodon</i>	Complex	Herbivore, Omnivore, Zoobenthivore	254	255
<i>Schwetzoichromis</i>	Complex	Herbivore	274	255
<i>Simochromis</i>	Complex	Herbivore	258	259
<i>Taeniolethrinops</i>	Complex	Zoobenthivore	260	255
<i>Thoracochromis</i>	Complex		291	
<i>Tilapia</i>	Complex	Herbivore	257,270	255,298,299
<i>Tropheops</i>	Complex	Herbivore	264	253,264
<i>Tropheus</i>	Complex	Herbivore	258	255
<i>Baileychromis</i>	Simple	Piscivore	300	300
<i>Bathybates</i>	Simple	Piscivore	258	255
<i>Benitochromis</i>	Simple	Omnivore	301	278,302
<i>Boulengerochromis</i>	Simple	Piscivore	303	255
<i>Buccochromis</i>	Simple	Piscivore	260,276	255
<i>Callochromis</i>	Simple	Zoobenthivore	258	255
<i>Caprichromis</i>	Simple	Carnivore specialist	260	255,304
<i>Cardiopharynx</i>	Simple	Zooplanktivore	258	255
<i>Chalinochromis</i>	Simple	Zoobenthivore	305,306	255,284
<i>Champsochromis</i>	Simple	Piscivore	276	255
<i>Chilochromis</i>	Simple	Herbivore	307	278
<i>Chilotilapia</i>	Simple	Zoobenthivore	276	255
<i>Chromidotilapia</i>	Simple	Omnivore, Zoobenthivore	279,308	255
<i>Congochromis</i>	Simple		309	
<i>Corematodus</i>	Simple	Carnivore specialist	276	255,260
<i>Cyathopharynx</i>	Simple	Herbivore	258	255
<i>Cynotilapia</i>	Simple	Zooplanktivore	276	255,266,276
<i>Cyphotilapia</i>	Simple	Piscivore	258	255,284
<i>Cyprichromis</i>	Simple	Zooplanktivore	258	255,284
<i>Cyrtocara</i>	Simple	Zoobenthivore	260	253,310
<i>Dimidiochromis</i>	Simple	Piscivore	260,276	255,266
<i>Diploaxodon</i>	Simple	Piscivore, Zooplanktivore	260	255,311,312
<i>Divandu</i>	Simple	Omnivore	313	255
<i>Ectodus</i>	Simple	Herbivore	258	284
<i>Enigmatochromis</i>	Simple		314	
<i>Eretmodus</i>	Simple	Herbivore	258	255
<i>Exochochromis</i>	Simple	Piscivore	260	260
<i>Gephyrochromis</i>	Simple	Herbivore	276	315
<i>Gnathochromis</i>	Simple	Zoobenthivore, Zooplanktivore	258	316
<i>Grammatotria</i>	Simple	Zoobenthivore	258	255
<i>Greenwoodochromis</i>	Simple	Piscivore	258	284

<i>Haplotaxodon</i>	Simple	Piscivore	258	317
<i>Hemibates</i>	Simple	Piscivore	258	255
<i>Hemichromis</i>	Simple	Zoobenthivore, Piscivore	318	255
<i>Hemitaeniochromis</i>	Simple	Carnivore specialist, Piscivore	260,276	255,260
<i>Hemitalapia</i>	Simple	Herbivore	276	255
<i>Heterochromis</i>	Simple	Zoobenthivore	257	255
<i>Julidochromis</i>	Simple	Zoobenthivore	305	255
<i>Lamprologus</i>	Simple	Zoobenthivore, Piscivore, Zooplanktivore	257	255,284,316
<i>Lepidolamprologus</i>	Simple	Piscivore	319, observation of specimens	255
<i>Lestradia</i>	Simple	Herbivore	258	255,284
<i>Limbochromis</i>	Simple	Herbivore	301	255,278
<i>Limnochromis</i>	Simple	Zoobenthivore	258	316
<i>Lobochilotes</i>	Simple	Zoobenthivore	258	255
<i>Myaka</i>	Simple	Omnivore	283	255,283
<i>Nanochromis</i>	Simple	Omnivore, Zoobenthivore	301	255
<i>Neolamprologus</i>	Simple	Zooplanktivore, Zoobenthivore, Piscivore	305	255,316,320
<i>Pallidochromis</i>	Simple	Piscivore	321	311
<i>Paracyprichromis</i>	Simple	Zooplanktivore	258	255
<i>Parananochromis</i>	Simple	Omnivore	322,323	278
<i>Paratilapia</i>	Simple	Piscivore	279	324
<i>Paretroplus</i>	Simple	Zoobenthivore	279	279,325–327
<i>Pelmatochromis</i>	Simple	Omnivore	257	255,278
<i>Pelvicachromis</i>	Simple	Herbivore, Omnivore	301	278,328,329
<i>Perissodus</i>	Simple	Carnivore specialist	258	317
<i>Plecodus</i>	Simple	Carnivore specialist	258	317
<i>Pterochromis</i>	Simple		301	
<i>Pundamilia</i>	Simple	Zooplanktivore, Omnivore, Zoobenthivore	285	255
<i>Pungu</i>	Simple	Zoobenthivore	283	255,283
<i>Reganochromis</i>	Simple	Zoobenthivore	observation of specimen	255,284
<i>Rhamphochromis</i>	Simple	Piscivore	260,276	255,311
<i>Sargochromis</i>	Simple	Zoobenthivore	262	255,330
<i>Sciaenochromis</i>	Simple	Piscivore	260	255,266
<i>Serranochromis</i>	Simple	Piscivore	262	255,263
<i>Spathodus</i>	Simple	Omnivore	258	255,284
<i>Stigmatochromis</i>	Simple	Piscivore, Zoobenthivore	260,331	255
<i>Stomatepia</i>	Simple	Piscivore, Zoobenthivore	283	283,332
<i>Taeniochromis</i>	Simple	Piscivore	276	255
<i>Tangachromis</i>	Simple	Zooplanktivore	258	255,284
<i>Tanganicodus</i>	Simple	Herbivore	258	259
<i>Teleogramma</i>	Simple	Zoobenthivore	257,333	46,278,333
<i>Telmatochromis</i>	Simple	Herbivore, Zoobenthivore	334,335	336
<i>Thysochromis</i>	Simple	Zoobenthivore	337	278,337
<i>Trematocara</i>	Simple	Zooplanktivore, Zoobenthivore	258	338
<i>Trematochromis</i>	Simple	Piscivore	258	284
<i>Triglachromis</i>	Simple	Zoobenthivore	258	255
<i>Tristamella</i>	Simple	Omnivore, Herbivore	339	255
<i>Tylochromis</i>	Simple	Zoobenthivore, Omnivore	257	255
<i>Tyrannochromis</i>	Simple	Piscivore	260,276	255

<i>Variabilichromis</i>	Simple	Omnivore	258	255
<i>Wallaceochromis</i>	Simple	Omnivore	340	340
<i>Xenochromis</i>	Simple	Zooplanktivore	258	317
<i>Xenotilapia</i>	Simple	Zoobenthivore	258,341	255
<i>Aulonocara</i>	Simple, Complex	Zoobenthivore	260,342,343	255,260
<i>Copadichromis</i>	Simple, Complex	Zooplanktivore	260,276,287,344,345	255,344
<i>Ctenopharynx</i>	Simple, Complex	Zooplanktivore, Zoobenthivore	260,311	255
<i>Haplochromis</i> *	Simple, Complex	Herbivore, Omnivore, Zooplanktivore, Zoobenthivore, Piscivore, Carnivore Specialist	257,274,285,297,307,346–352	255,297,348
<i>Labidochromis</i>	Simple, Complex	Zoobenthivore, Herbivore, Omnivore	353	253,255,353
<i>Lethrinops</i>	Simple, Complex	Zoobenthivore, Herbivore	260,276,354–356	255,355,356
<i>Mylochromis</i>	Simple, Complex	Zooplanktivore, Zoobenthivore	260,276,357	255
<i>Nimbochromis</i>	Simple, Complex	Piscivore	276,311	255
<i>Nyassochromis</i>	Simple, Complex	Zooplanktivore, Herbivore, Omnivore	260	255,344
<i>Ophthalmotilapia</i>	Simple, Complex	Herbivore	358	259
<i>Oreochromis</i>	Simple, Complex	Zooplanktivore, Omnivore, Herbivore, Zoobenthivore	254,257	255
<i>Otopharynx</i>	Simple, Complex	Piscivore, Zoobenthivore, Herbivore, Zooplanktivore, Omnivore, Carnivore specialist	260,276,331,359,360	255
<i>Placidochromis</i>	Simple, Complex	Omnivore, Zoobenthivore, Herbivore	260,276,311	255
<i>Protomelas</i>	Simple, Complex	Zoobenthivore, Carnivore specialist, Herbivore	260,276,344	255,260
<i>Steatocranus</i>	Simple, Complex	Herbivore, Zoobenthivore	46	255
<i>Tramitichromis</i>	Simple, Complex	Zoobenthivore	276	255,266
<i>Trematocranus</i>	Simple, Complex	Zooplanktivore, Zoobenthivore	260,361	255

2.7 Supplementary Table 7 | Comparison of discrete character evolution models fit over the African cichlid phylogeny (n=1,069 species). Bayes factors (BF) are reported in comparison to the best-fit model, HR4-ER (in bold).

Model	Marginal likelihood	ln BF	BF
ER	-662.044	245.9517	6.5383E+106
ARD	-648.3601	232.2678	7.458E+100
HR2-ER	-418.8311	2.7388	15.46841186
HR2-ARD	-424.2223	8.13	3394.799565
HR4-ER	-416.0923	-	-
HR4-ARD	-419.5322	3.4399	31.18383963

2.8 Supplementary Table 8 | Marginal likelihoods of Bayesian state-dependent speciation and extinction (SSE) models, each fit over a subtree of African cichlids. The CID-4 model for the Lake Victoria subtree did not mix properly during the power-posterior analysis. Best-fit models for each subtree are bold.

Model	Rivers/non-rift lakes	Lake Tanganyika	Lake Malawi	Lake Victoria
CID-2	-4724.319	-2559.727	-1576.46	-396.74
CID-3	-2368.919	-1341.914	-1563.757	-469.631
CID-4	-2317.977	-1279.22	-1561.664	*
BiSSE	-2391.691	-1293.066	-1771.429	-511.508
HiSSE-2	-2350.964	-1288.786	-1578.434	-361.792
HiSSE-3	-2370.752	-1286.176	-1568.255	-388.507
HiSSE-4	-2370.671	-1282.403	-1566.829	-343.619

2.9 Supplementary Table 9 | Marginal likelihoods and Bayes factor (BF) for SSE models using lability as a four-state discrete trait (very low, low, high, very high). Both models were fit over the full African cichlid phylogeny (n=1,069). BF's are reported in comparison to the best-fit model, MuHiSSE-4 (in bold). A second set marginal likelihood estimation under the same power posterior analysis and stepping sampler is shown in parentheses.

Model	Marginal likelihood	ln BF	BF
CID-2	-7359.293 (-7359.423)	201.765	4.22E+87
CID-3	-7255.554 (-7216.647)	98.026	3.73E+42
CID-4	-7162.698 (-12177.58)	5.17	175.91
MuHiSSE-2	-7234.33 (-7235.751)	76.802	2.26E+33
MuHiSSE-3	-7181.471 (-7176.844)	23.943	2.5E+10
MuHiSSE-4	-7157.528 (-7156.99)	-	-

2.10 Supplementary Table 10 | Mean speciation, extinction and net diversification (speciation minus extinction) rates estimated for each level of lability (very low, low, high, very high) across four hidden states (A, B, C, D) under the MuHiSSE-4 model for African cichlids. For each speciation and extinction rate mean, the standard deviation is reported in parentheses. Mean rates were taken from the posterior distribution estimated using MCMC.

State	Speciation	Extinction	Net diversification
very low - A	0.0839 (.0091)	0.0173 (.0104)	0.0666
low - A	0.1121 (.0184)	0.0745 (.0589)	0.0376
high - A	0.1816 (.0354)	0.117 (.1254)	0.0646
very high - A	0.2085 (.038)	0.2349 (.1999)	-0.0264
very low - B	0.2095 (.0164)	0.0046 (.0042)	0.2049
low - B	0.2786 (.031)	0.0172 (.0143)	0.2614
high - B	0.4534 (.0813)	0.0323 (.0457)	0.4211
very high - B	0.5205 (.0865)	0.0593 (.0577)	0.4612
very low - C	1.2859 (.195)	0.0081 (.0093)	1.2778
low - C	1.7134 (.3169)	0.0346 (.0461)	1.6788
high - C	2.7284 (.2624)	0.0461 (.0519)	2.6823
very high - C	3.1323 (.2173)	0.0874 (.0795)	3.0449
very low - D	10.4397 (1.885)	0.0785 (.1119)	10.3612
low - D	13.9104 (2.9158)	0.3329 (.5182)	13.5775
high - D	22.1519 (3.0042)	0.5052 (.8237)	21.6467
very high - D	25.3064 (1.5964)	0.9448 (.9306)	24.3616

2.11 Supplementary Table 11 | Mean speciation, extinction and net diversification (speciation minus extinction) rates estimated for each level of lability (very low, low, high, very high) across two hidden states (A and B) under the MuHiSSE-2 model for African cichlids. For each speciation and extinction rate mean, the standard deviation is reported in parentheses. Mean rates were taken from the posterior distribution estimated using MCMC.

State	Speciation	Extinction	Net diversification
very low - A	0.1288 (.0116)	0.0287 (.0174)	0.1001
low - A	0.2676 (.0298)	0.0179 (.0173)	0.2497
high - A	0.2513 (.0425)	0.0168 (.0172)	0.2345
very high - A	1.0263 (.1443)	0.6345 (.1988)	0.3918
very low - B	1.4683 (.2514)	0.2308 (.1887)	1.2375
low - B	3.0516 (.5585)	0.144 (.1627)	2.9076
high - B	2.8098 (.2732)	0.122 (.1178)	2.6878
very high - B	11.4576 (.3818)	4.4766 (.5204)	6.981

2.12 Supplementary Table 12 | Fit of independent and dependent models of character evolution using Pagel's (1994) method across African cichlids (n=1,069 species). Models were fit using two binarizations of herbivory; one that included only strict herbivores, and an alternate that included omnivores and herbivores. Best-fit models are in bold.

Classification	Model	log-likelihood	AIC
herbivores only	Independent	-936.8434	1941.687
	Dependent	-900.7249	1809.45
herbivores and omnivores	Independent	-1038.9674	2081.935
	Dependent	-936.7457	1881.491

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