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Fish otoliths from the Pliocene Heraklion Basin (Crete Island, Eastern Mediterranean)§

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ABSTRACT

The Pliocene Eastern Mediterranean fish record is revealed through the study of a 60-m thick stratigraphic sequence near the village Voutes (Heraklion, Crete). Forty-two species belonging to twenty families are identified. Calcareous nannoplankton biostratigraphy places the studied sequence within the biozone MNN16a (latest Zanclean). The stratigraphic distribution of 31 species is modified. Among these, 12 species are reported for the first time in the Eastern Mediterranean Zanclean, while 19 species are first reported outside the Ionian Sea. The Voutes fish fauna presents a diversified benthic and benthopelagic assemblage filling a significant gap in the fossil record.

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1. Introduction

Fish otoliths, the aragonitic incremental structures within the teleostean fish’s inner ear, present taxon-specific morphology, which enables fossil fish assemblage reconstruction, since they are highly frequent in sediments of various environmental settings, ranging from lake to deep-sea deposits, and they are generally well preserved (Nolf, 1985). In addition, numerous studies have illustrated their value as palaeoecologic and palaeobathymetric indicators, providing very detailed and accurate palaeobiological and palaeoclimatic information.

The Pliocene Mediterranean fish fauna comprised typical tropical and subtropical taxa, which mostly inhabited the basin following its reconnection to the Atlantic Ocean, after the Messinian Salinity Crisis (Landini and Sorbini, 2005). Pliocene fish remains have been identified through several studies in the Western Mediterranean realm (Nolf and Martinell, 1980; Nolf and Girone, 2006; Girone, 2007). However, few studies have been performed in the eastern sub-basin, almost all currently available information coming from fish skeletal remains. New Zanclean otolith-based fish fossil data for the Eastern Mediterranean basin are presented here for the first time, through the systematic study and analysis of the Zanclean fish otolith assemblages of the Voutes section (Heraklion, central Crete).

2. Geological setting

The Crete Island originated during the late Miocene through the N-S and E-W extensional deformation of the south Aegean, resulting in the formation of multiple tectonic blocks and late Miocene to Pleistocene sedimentary basins (Meulenkamp et al., 1988; Van Hinsbergen and Meulenkamp, 2006). The Neogene sediments overlie a pile of alpine nappe substratum, which includes the metamorphic Plattenkalk and Phyllites–Quarzites Units followed by the Tripolis and Pindos–Ethia, as well as other minor units (Zachariasse et al., 2011).

The presently emerged area of the Heraklion Basin is a Pliocene graben structure located at the northern part of the central Crete Island, in the southern segment of the Hellenic Arc, between the mountains Psiloritis and Dicti. The alpine basement formations contain a rich mélangé of Triassic to Eocene sedimentary and metamorphic rocks, overlain by Neogene and Quaternary sedimentary deposits, recording a great diversity of environments and ecosystems (Symeonidis and Konstadinitis, 1967). The Pliocene Heraklion Basin occurred in a region marked by a great number of successive paleogeographic Miocene frameworks, in the vicinity of the Messara basin. In the latest Tortonian the activation of the E-W-oriented Agia Varvara fault differentiated the two realms, which evolved separately since that time (Delrieu et al., 1991). The Pliocene deposits of the Heraklion Basin are the most extensive ones in the Island. The marine sediments of the lowermost Pliocene generally overlie the late Messinian deposits (Delrieu et al., 1991;
Meulenkamp et al., 1979, 1994), and consist of whitish marls and marly limestones of deep-water origin, reflecting the Pliocene flooding which followed the lago-mare episode immediately after the Mediterranean Salinity Crisis.

The studied Voutes section is located southwest of the village Voutes in central Crete, south of Heraklion city. Geologically it is situated in the western section of the Heraklion Basin (Fig. 1). The section sediments may be placed within the Finikia lithostratigraphic group of Benda et al. (1974) and Meulenkamp et al. (1979); they include more than 60 m of marls and sandy marls (Figs. 2–4). On the lower part of the section, strong gravity flows have formed a series of sand lenses with distinctive sedimentological attributes and characteristic fauna (Fig. 5). The upper part of the section presents three diatomite horizons.

3. Material and methods

Overall, nine sediment samples were taken; 25 kg each, along the Voutes section (Figs. 2 and 3). Sample 1 was taken from the uppermost diatomite horizon, which is bare of other faunal remains. Sample 2 was collected from the uppermost marls, which present a rather rich macro-invertebrate fauna, including

![Fig. 1. Location of the study area. A. Geological map of the Heraklion area (simplified after Fassoulas, 2001), indicating the Voutes village. B. Map of the Eastern Mediterranean including the major circulation patterns. Grey sea areas denote deep-water formation regions. C. Photograph of the study area (obtained from Google Earth). The square marks the extent of the Voutes outcrop.](image-url)
nuculoids, pectinids and limids. Samples 3 and 4 were taken from the second and third diatomite horizons, respectively, which present a poor macro-invertebrate fauna of deep-water bivalves. Sample 5 was taken from the blue marls, at the middle part of the section, where pteropods, nuculoids, thin pectinids and Cadulus were also identified. Sample 6 comes from marly sands, mostly gravity flows, with pectinids and gastropods. Sample a was collected from sandy marls with Neopycnodonta navicularis, pectinids and gastropods. Sample b was taken from one of the sand gravity lenses observed at the lower part of the outcrop (Fig. 5), which also include macrofossils such as naticids, pectinids, venerids, cardiids, turritellids and cerithiids. At the lowermost part of the section, sample c was collected from the marls underneath and around the sand lenses, in which the macroscopic examination showed no evidence of other faunal remains. The microscopic examination of this lowermost bed revealed the presence of bathyal mollusc elements such as Kelliella miliaris, Limopsis spp., and Ledella sp. The samples were washed and sieved in plain water, using a 250 μm-diameter sieve. The otoliths were then handpicked from the sediment under a stereoscope.

The fish otoliths were identified based on the morphological characteristics described by Nolf (1985); lapilli were described and identified based on Assis (2005). The species’ taxonomic position follows Nelson’s (2006) scheme. Many recent fish species were already identified in the Mediterranean Pliocene, but in several cases, specific assignment could not be unequivocally decided, as indicated by the abbreviation “aff.” inserted between the name of the genus and the name of the group species. The abbreviation “cf.” was used whenever the condition of preservation of the otolith did not allow conclusive specific identification. Moreover, several taxa appear in open nomenclature at the species level due to...
insufficient knowledge of related recent species or because the fossil material is too limited or too poorly preserved to decide. Selected otoliths from each taxon were photographed using the scanning electron microscope JEOL JSM-6360 of the Department of Historical Geology and Paleontology of the University of Athens. The identified material is stored at the Athens Museum of Paleontology and Geology.

The relevant chronostratigraphic framework (Fig. 2) for the evaluation of the results was provided through calcareous nannoplankton biostratigraphy, based on Rio et al.’s (1990) bioziation scheme as incorporated in the magnetobiocronologic framework of Lourens et al. (2004) in Gradstein et al. (2004). Numerical ages of biozone boundaries follow Lourens et al. (2004) and Raffi et al. (2006). In addition, the relative abundance of Discoaster spp. was measured in order to further specify the stratigraphic interval under study.

The palaeobiogeographic distributions of the identified Teleostei were compared to equivalent assemblages across the Mediterranean realm in order to fill gaps in the fossil record as well as to identify ichthyofauna differences and similarities.

4. Systematic palaeontology

Altogether, 42 taxa from 20 families were identified in the Voutes section sediments (Fig. 6). Specific notes on their identifications and systematic placement are made below wherever necessary.

Class ACTINOPTERYGII Klein, 1885
Order ANGUILLIFORMES Berg, 1940
Family CONGRIDAE Kaup, 1856
Genus Pseudophichthys Roule, 1915
Pseudophichthys spp.

**Remarks:** Two specimens are placed within this genus, based on the ostium portion of the sulcus, which is only very shallow and consequently poorly definable, in contrast to other congrids. One specimen is unequivocally comparable to the extant Atlantic Pseudophichthys splendens, also already reported from the Western Mediterranean Pliocene (Nolf and Girone, 2006; Girone, 2007), while the other (Fig. 7(3)) is better placed under the fossil species Pseudophichthys escavarietens, also known from the Pliocene of Southern France (Schwarzhans, 1986; Nolf and Cappetta, 1988). These two Pseudophichthys specimens noticeably differ in the placement of the postero-dorsal angle. Moreover, *P. escavarietens* has a more rounded posterior margin and a more regularly-curved dorsal margin than *P. splendens*.

Genus Rhynchoconger Jordan and Hubbs, 1925
Rhynchoconger pantanelli (Bassoli and Schubert, 1906)

**Remarks:** The otoliths placed under this fossil Mediterranean species are well distinguished from *Conger conger* and *Pseudophichthys* spp. by the closed sulcus, connected to the periphery only through a well-marked and rimed ostial channel almost vertical to the sulcus and the dorsal margin. The Voutes specimens are very similar to the otoliths of the fossil species *Rhynchoconger* (Hildebrandia) *pantanelli*, also known from the Pliocene sediments of Northern Italy and Southern France (Nolf and Cappetta, 1988; Girone, 2007).

Order AULOPIFORMES Rosen, 1973
Family CHLOROPHTHALMIDAE Jordan, 1923
Genus Chlorophthalmus Bonaparte, 1840
Chlorophthalmus agassizi Bonaparte, 1840

**Remarks:** The unique specimen found in Voutes sediments is the only known Pliocene record of this species. Previously this genus has been referred with the species *Chlorophthalmus costamagnai* Schwarzhans, 1986 from the early Pliocene of Le Puget (Southern France; Nolf and Cappetta, 1988) and Papiol (Spain; Nolf et al., 1998), and with *Chlorophthalmus cf. agassizi* from the Middle Pleistocene of Kephallonia (Eastern Ionian Sea; Agiadi et al., 2010). The Voutes specimen exhibits all the morphological characteristics of the modern Mediterranean species *C. agassizi* much better than the Kephallonia specimen. Namely, the Voutes specimen has an elongated shape with almost parallel dorsal and ventral margins, a long linear cauda and a much smaller ostium, which open antero-dorsally. The anterior and posterior dorso-ventral areas are almost equal, in contrast to both *C. costamagnai* and *C. cf. agassizi*.
Order MYCTOPHIFORMES Regan, 1911
Family MYCTOPHIDAE Gill, 1893
Genus Diaphus Eigenmann and Eigenmann, 1890

Diaphus spp.

Fig. 7(5–7, 11, 12, 14)

Remarks: Overall, six Diaphus species are recognized in the Voutes material. Diaphus otolith morphology is known to vary greatly with fish age and as such, specific identification can be unequivocally made only with adult specimens of good preservation (Brzobohaty and Nolf, 2000). The otoliths of Diaphus holti (Fig. 7(7)) and D. rafinesqui (Fig. 7(14)) are both characterized by a strongly denticulate ventral margin, well-developed rostrum and a salient postero-dorsal angle. However D. rafinesqui is notably longer than D. holti; the latter has a greater height/length ratio. In addition, the sulcus of D. holti has a nearly rounded caudal colliculum, while it is elongate in D. rafinesqui. Six otoliths can be compared with those of the recent Atlantic Diaphus taaningi (Fig. 7(11)), characterized by a subquadranquadrangular shape and a wide predorsal angle. This species is represented here only by juvenile and young adult specimens, slightly more elongate than recent material. A similar observation is made in the adult and juvenile specimens of D. taaningi from the Early Pleistocene of Montalbano (Western Ionian) and the Early-Middle Pleistocene of Archi (Western Mediterranean; Girone et al., 2006). However, the revision of this taxon proposed by Brzobohaty and Nolf (2000) pointed out that the Pliocene specimens tend to be slightly more elongate than the studied recent material. The same authors also observed such an elongate morphology in specimens from the Early Pliocene of Dar Bel Hamri, Atlantic Morocco. Several specimens present great similarity with the small and medium-sized specimens from Northern Italy (Nolf and Gironne, 2006), which were identified as Diaphus aff. adenomus (Fig. 7(6)).

Order PERCIFORMES Bleeker, 1859
Family ACROPOMATIDAE Gill, 1893
Genus Parascombrops Alcock, 1889

Parascombrops mutinensis Bassoli, 1906

Fig. 7(18–21)

Remarks: The three otoliths of this species described here share the same morphological characteristics with all the Pliocene and Pleistocene material described from Western Mediterranean (Nolf and Martinell, 1980; Nolf and Gironne, 2006). P. mutinensis specimens from the Early Pleistocene Eastern Ionian basin (Agiadi et al., 2010) had a considerably underdeveloped antero-ventral area. Two specimens in the Voutes material are from adult individuals, and both exhibit a well-developed antero-ventral area. However, the third specimen, belonging to a smaller individual, is undoubtedly smaller in this part, being similar to the Akrotiri specimens (Eastern Ionian). Through direct comparison with the Akrotiri specimen and small and large specimens from Palione river (Di Geronimo et al., 2003), it becomes evident that this difference is within the ontogenetic variability of the species; the antero-dorsal area seems to develop in later stages.

Family GOBIIDAE Cuvier, 1816

Fig. 8(13–20, 24)

Remarks: The members of this family have otoliths with very similar morphological characteristics. The most significant diagnostic characters are the size, shape and placement of the central or off-central sulcus and the overall shape of the otolith. The otoliths of Aphia minuta (Fig. 8(19)) are very small, oval-shaped, with a concave inner surface. The sulcus is also small and undivided, while the dorsal margin is irregularly curved. Twelve specimens, even if partially eroded, may be safely identified as Deltentosteus quadrimaculatus otoliths. However the Voutes specimens show greater similarity with the otoliths of D. aff. quadrimaculatus described from the Early Pleistocene of Northern Italy (Nolf and Gironne, 2000; Gironne, 2007), which has a more blunt antero-ventral angle than D. quadrimaculatus. The specimen identified here as Gobius sp.1 (Fig. 8(13)) strongly resembles Gobius sp. from the Pliocene and Pleistocene sediments of Northern Italy (Nolf and Gironne, 2000, 2006). In addition, one gobid specimen exhibits a very characteristic morphology, but cannot be specifically identified, and is referred here to genus “Gobidarum” sp.1 (Fig. 8(20)). This is a small square otolith; the posterior and anterior rims are angled outwards. The sulcus is also small and resembles that of Aphia minuta, exhibiting a concave inner face.

Order GADIFORMES Goodrich, 1909
Family GADIDAE Rafinesque, 1810

Fig. 8(4)
All the Gadidae identified in the present material undoubtedly belong to the fossil Mediterranean species *G. labiatus*. In addition several lapilli are present in the samples (Fig. 8(4)). These exhibited similar morphological characteristics, so they were grouped together. Through comparison with the descriptions given by Assis (2005), these can safely be placed within Gadidae, with no further identification possible at this time. The specimens were thick, square-shaped with rounded margins. A strong, almost square voluminous protuberance is clearly contained within the otolith margin, when observed from the ventral view.

5. Discussion

5.1. Biostratigraphy

In the Voutes section, the nannoflora assemblage is dominated by discoasterids, which provide important biostratigraphic markers in the Pliocene. Discoasters are relatively well diversified and contain *Discoaster adamanteus*, *D. assymetricus*, *D. tamalis*, *D. surculus*, and very sporadic *D. pentaradiatus* and *D. brouweri*.

Placoliths are represented mainly by very abundant *Pseudoemiliания lacunosa*. *Helicosphaera sellii* is also significantly contributing to nannofossil assemblages. *Reticulofenestra pseudoumbilicus* (> 7 µm) and sphenolithids are practically absent. The high abundance of both *D. tamalis* (15–35%) and *D. surculus* (15–50%) implies correlation with nannofossil zone MNN16 (Rio et al., 1990). Moreover, the nearly absence of *D. pentaradiatus* supports the recognition of the paracme interval of this species. Therefore the studied interval from the Voutes section is assigned to the bionzone MNN16, above the highest occurrence of *R. pseudoumbilicus* and
### Sphenolithus spp. following the MNN14/15-MNN16 boundary

(3.84 Ma, Lourens et al., 2004; Raffi et al., 2006) and just below the top of D. pentaradiatus paracme (3.61 Ma, Lourens et al., 2004), within the latest Zanclean.

#### 5.2 Stratigraphic and biogeographic affinities

This study represents the first fish-based reconstruction of the Zanclean fish paleofauna in the Eastern Mediterranean. The following table presents the geographic and stratigraphic distribution of the identified benthic and benthopelagic fish taxa:

<table>
<thead>
<tr>
<th>Family</th>
<th>Genus and Species</th>
<th>Western Mediterranean</th>
<th>Eastern Mediterranean</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Miocene</td>
<td>Pliocene</td>
</tr>
<tr>
<td>Congridae</td>
<td>Pseudophichthus splendidus</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Pseudophichthus excursuatenteresis</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rhynecoconger pantanensis</td>
<td>+</td>
<td>+</td>
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<tr>
<td>Chloryphthalumidae</td>
<td>Chlorophthalum eqialis</td>
<td>+</td>
<td></td>
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<tr>
<td>Morididae</td>
<td>Laemonemus sp.</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Gadidae</td>
<td>Gadilus libatius</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Bythitidae</td>
<td>Gymnogobius ater</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Campidae</td>
<td>Echidodon dentatus</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Atherinidae</td>
<td>Atherina boyeri</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Agonidae</td>
<td>Agonon sp. (ref. A. loxanosi)</td>
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<td></td>
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<tr>
<td>Epigonidae</td>
<td>Epigonus aff. denticulatus</td>
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<td></td>
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<tr>
<td>Acropomatidae</td>
<td>Paracromobrya mutinensis</td>
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<tr>
<td>Sparidae</td>
<td>Oblada melanura</td>
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<tr>
<td>Cepalidae</td>
<td>Cepola macrophthalmus</td>
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</table>

**References**

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stratigraphic and geographic distributions of the identified taxa are presented in Figs. 9 and 10. Overall, the stratigraphic distribution of 31 species is significantly extended. In particular, 12 species are reported for the first time in the Zanclean of the Eastern Mediterranean realm, while 19 species are reported for the first time in the Eastern Mediterranean outside the Ionian Sea. They illustrate a teleost fauna including both neritic and oceanic fishes.

The only previous reference to fossil fish otoliths in the Pliocene of the Eastern Mediterranean, outside the Ionian Sea, is the short note by Markopoulos-Diakontani and Kagiouzis (2001). Unfortunately, the material examined in that paper is not available for re-evaluation. Revisiting the Rethymnon section, outside the village Prassies, allowed the identification of the outcrop where the Late Miocene and Early Pliocene sediment samples were presumably taken by these authors. Systematic identification of the studied specimens could only be evaluated through the provided figures and photographs. As such, the specimens referred to Diaphus spp. can be positively identified at the generic level, Cenotocopsus maderensis may be safely considered to be present, Bregmaceros albiy should best be referred to as Bregmaceros sp. due to the lack of data on the otolith morphological characteristics of the present-day species, and the specimens identified as Gobius vicinalis is better considered to belong to Lesueurigobius sp. based on their description and figures.

A significant observation made on Figs. 9 and 10 is that the Middle–Upper Pleistocene fish distribution is almost completely unknown. This is caused by lack of data due to the practical difficulty in finding appropriate specimens for this period.

Overall, the Pliocene Eastern Mediterranean ichthyofauna, as preserved in the Voutes area, presents a rich pelagic and a rather diverse benthopelagic and benthic component. The pelagic taxa include members of four families: Myctophidae, which is the most abundant and diverse, Sternopygidae, Phosichthyidae, and Bregmacerotidae. The pelagic fish fauna does not present any striking differences neither from the western sub-basin fauna, nor from the Messinian fauna (Fig. 9).

Gobids are by far the most diverse and abundant benthic fish family in the studied assemblages (Fig. 10). Six, out of the nine species identified, inhabit the Eastern Mediterranean coasts until today. Lesueurigobius sanzi may only be found today in the Atlantic Ocean and the western sub-basin, although it was present in both Mediterranean sub-basins prior to the Messinian salt crisis. Gobids generally appear to be quite resilient to the various environmental disturbances, persisting until today. The very limited data on the Eastern Mediterranean fish fauna is the most likely reason behind the striking gobid absence from the Miocene assemblages. Judging from the state of the Western Mediterranean record however, it may be safely assumed that D. quadrimaculatus, G. paganelis, L. friessi and L. sueri are indeed Pliocene-introduced species.

In addition, the sparids Oblada melanura and Pagellus erythrinus first seem to enter the Mediterranean after the Messinian/Zanclean boundary. Furthermore, the presence of Chlorophthalmus agassizi in the Zanclean Eastern Mediterranean basin is notable since this very abundant extant species has only been recorded before, in the Middle Pleistocene sediments of the Ionian Sea (Agiadi et al., 2011). So far, Grammomus ater has only been found in the eastern sub-basin from the Gelasian-Calabarian Ionian Sea (Girone and Varola, 2001). Finally, this is also the first post-Messianian Salinity Crisis Eastern Mediterranean record of the presently abundant species Athirina boyeri (Girone et al., 2006, 2010).

The Voutes fish fauna comprises both Messinian relics, as well as Pliocene introductions. When examining the stratigraphic distribution of the various fish taxa identified in this section, it is perceived that few are those Miocene species which seem to persist into the Pliocene, but do not last until today; these are D. cavallonis, M. fitchi, S. pliccinicus, G. labiatus, Apogon spp., P. mutinus. Apart from Apogon spp., these are presently extinct taxa. In addition, it becomes more evident that some species were indeed first introduced to the Mediterranean after the salinity crisis, and maintained their place in the ecosystem until the present day; these are V. poweriae, C. maderensis, H. benoiti, C. agassizi, G. ater, E. dentatus, E. denticulatus, O. melampra, P. erythrinus, D. quadrimaculatus, G. paganelis, L. friessi, L. sueri, and C. linguatula. The present-day distributions of these latter species are either circum-global or Atlantic. The previously reported Indo-Pacific affinity of the Pliocene Mediterranean fauna (Gaudant, 2002) does not seem to apply in the case of the Voutes assemblages.

6. Conclusion

The added value provided through the examination of the Voutes fish fauna lies in the fact that this is the first systematic study of the evolution of the fish paleofauna in the Eastern Mediterranean. Indeed, Chlorophthalmus agassizi, an extant circum-global species very abundant in the Eastern Ionian Sea today, is documented for the first time outside the Ionian basin and in the Early Pliocene. This significantly affects any preconceptions regarding the Eastern Mediterranean deep-dwelling faunas, which may not be as much affected by climatic regimes, but rather more by other paleoceanographic factors such as circulation patterns, as already proposed by Agiadi et al. (2011). In addition, several systematic remarks are made on the otoliths of selected taxa. Finally, notable is the great diversity of the neritic benthic component, mostly comprised of gobids, presumably reflecting locally different sea bottom conditions, but also of the mesopelagic myctophids. It can be safely assumed that the Voutes area offered several diverse habitats for different faunal components, but also that the environmental perturbations did not permit for a few species to competitively overwhelm others and dominate.

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