



## Invited Review



## Palaeontological signatures of the Anthropocene are distinct from those of previous epochs

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## ABSTRACT

The “Great Acceleration” beginning in the mid-20th century provides the causal mechanism of the Anthropocene, which has been proposed as a new epoch of geological time beginning in 1952 CE. Here we identify key parameters and their diagnostic palaeontological signals of the Anthropocene, including the rapid breakdown of discrete biogeographical ranges for marine and terrestrial species, rapid changes to ecologies resulting from climate change and ecological degradation, the spread of exotic foodstuffs beyond their ecological range, and the accumulation of reconfigured forest materials such as medium density fibreboard (MDF) all being symptoms of the Great Acceleration. We show: 1) how Anthropocene successions in North America, South America, Africa, Oceania, Europe, and Asia can be correlated using palaeontological signatures of highly invasive species and changes to ecologies that demonstrate the growing interconnectivity of human systems; 2) how the unique depositional settings of landfills may concentrate the remains of organisms far beyond their geographical range of environmental tolerance; and 3) how a range of settings may preserve a long-lived, unique palaeontological

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record within post-mid-20th century deposits. Collectively these changes provide a global palaeontological signature that is distinct from all past records of deep-time biotic change, including those of the Holocene.

## 1. Introduction

Increasing human interactions with the biosphere over tens of millennia (McNeill, 2011) leave a fossil record (Williams et al., 2022a; Nawrot et al., 2024) that shows the growing geographical spread and technological sophistication of humans. This is evident in patterns of extinction (e.g., Chiba and Cowie, 2016; Wood et al., 2017; Prates and Perez, 2021) and landscape domestication (e.g., Price and Bar-Yosef, 2011; Dong et al., 2020) that extend across major continental areas, into isolated ocean islands (Wood et al., 2017), and into the adjacent coastal zone (e.g., Tomašových and Kidwell, 2017). In this increasingly modified landscape three types of grass, wheat (*Triticum durum*, *T. aestivum*), maize (*Zea mays*) and paddy rice (*Oryza sativa*) are grown in quantities collectively exceeding 2000 million tonnes per year (Wrigley, 2010). There is also a ~five-fold increase in the habitable land under crop over the past three centuries, from ~329 million hectares in 1700 to 1.63 billion hectares in 2023 (Ritchie and Roser, 2019 and updates thereafter). Landscape domestication has left a distinctive and global fossil signature, for example in palynological and diatom records of lakes (e.g., Verschuren et al., 2002; Kiage and Liu, 2009; Wolfe et al., 2013; Wilkinson et al., 2014). In concert with these changes, the mass of domesticated animals increased rapidly during the 20th and early 21st centuries, as global meat consumption doubled per capita (Ritchie et al., 2017) and the number of humans almost tripled since the 1960s (Roser and Ritchie, 2023). Overall, these patterns have decoupled long-term relationships between net primary production (NPP) and mammal biodiversity (Fritz et al., 2016), with human use of energy exceeding the available global NPP by a large margin (at least 40 exajoules/year) as well as regionally in most ecological contexts (Doughty et al., 2016).

A by-product of the concentration of mass in domesticated animals and plants, and the industrialization, globalization, and urbanization that have distanced us from food production (Thyberg and Tonjes, 2016), is that about one-quarter to one-third of all food produced globally is wasted (Bellemare et al., 2017). This includes about 1.3 billion tonnes of the edible part of food products (Gustavsson et al., 2011; Schanes et al., 2018); food waste commonly makes up the largest component of municipal solid waste landfills (e.g., in the USA food waste represents ~25% of total landfill, EPA, 2023). Many food items find their way into landfills, as waste or as the inedible discarded components, and likely will leave a distinctive palaeontological signal (in the form of fossilised bones, shells, seeds, etc.) of the mid-20th century Great Acceleration of population growth, industrialization and globalization (Steffen et al., 2007, 2015), with a notable fraction of organisms having been transported beyond the geographical range of their environmental tolerance.

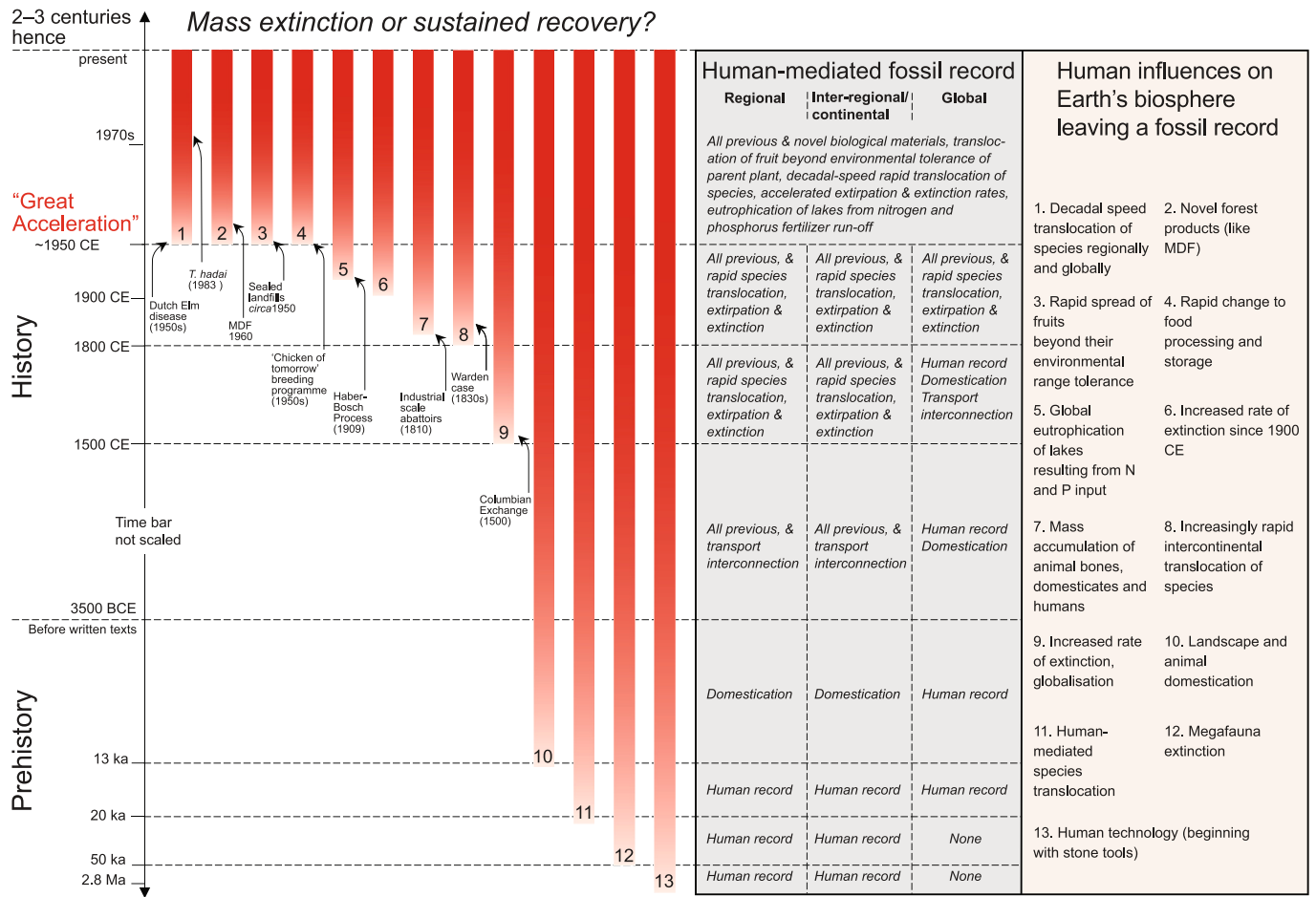
The 20th and early 21st centuries have shown accelerating patterns of interconnectivity between geographical regions, ecosystems and human ecologies that profoundly changed the spatial distribution of species (Seebens et al., 2017, 2018, 2021). Global shipping increased ten-fold from 1955 to 2007 (cargo transported; Rodrigue, 2020) becoming the major vector for transferring organisms via ballast waters and biofouling (Cariton and Geller, 1993; Davidson et al., 2018). Rapidly expanding global road systems (Strano et al., 2017; Meijer et al., 2018) are important conduits for the dispersal of non-native species via the materials carried along them in vehicles and by the colonization of disturbed habitats that border them (Christen and Matlack, 2006; Lavoie et al., 2007). Urban environments, modified river and canal banks, the spread of irrigation systems, and the physical connection of water masses, both land and sea, have also contributed to the spread of non-

native taxa (e.g., Himson et al., 2020). Conversely, the acceleration in the damming of most of the world's rivers since the mid-20th century (Syvitski and Kettner, 2011; Syvitski et al., 2020) has in many cases inhibited the movement of native species through their natural ranges, causing local extirpations and threatening extinction of those species (e.g., certain species of salmon and eels; Vergeynst et al., 2019). All these changes are then coupled with the impacts of climate change on the biosphere, playing out in both marine and terrestrial ecologies.

Here we examine the actual and likely fossil record of these changes with a specific focus on the mid-20th century onset of the Anthropocene epoch as proposed by the Anthropocene Working Group (AWG; Waters et al., 2023). We describe the palaeontological signatures of the Great Acceleration and its attendant globalization, using published archives, including those from the AWG's studies (Waters et al., 2023). We show that the palaeontological signatures from the mid-20th century onwards are already fundamentally different from those of earlier biota and assess the likely long-term (geological) survivability of Anthropocene fossil archives.

## 2. Fossil patterns of the Great Acceleration exemplify growing interconnectivity

Species introductions mediated by humans have occurred since prehistory (Mooney and Cleland, 2001), and since the 15th century CE sea trade has linked the continents into a 'biologically interactive web' (McNeill, 2011). Earlier introductions left a fossil record (summarised in Williams et al., 2022a; also Fig. 1), for example of the spread of maize since the Columbian Exchange (e.g., Kiage and Liu, 2009). The rate of species exchange has increased over the past two centuries, and in the 20th and 21st centuries culminated in rapid translocations of species globally within a few decades, providing abundant biostratigraphic constraints on a mid-20th century boundary level for the Anthropocene (Williams et al., 2022a), as a clear reflection of increasingly interconnected global transport networks. Seebens et al. (2017) identified three major patterns of non-native species introductions globally: 1) for algae, invertebrates and some vertebrates there were weak increases until ~1950, followed by strong increases via the unintended consequences of increasing trade; 2) a decrease in the *deliberate* translocation of mammals and fish after ~1950; and 3) a high rate of introductions of plants in the 19th century associated with European colonization (and inventions such as the 'Wardian Case' – a device for transporting live plants via shipping), and a continued high rate in the latter part of the 20th century associated with trade (e.g., of food, pets, and ornamental plants). In this section we examine signals of patterns 1 and 3, including those causally linked to the post-WWII Great Acceleration in commerce and trade (Steffen et al., 2015) and the increasing interconnectivity of transport networks (Seebens et al., 2017). We include analysis of taxa recorded at sites that were examined as candidates for a Global boundary Stratotype Section and Point (GSSP), Standard Auxiliary Boundary Stratotypes (SABSs) and reference sections for an Anthropocene series/epoch (Waters et al., 2023 and references therein). We note that in a vote held in March 2024, members of the International Subcommission on Quaternary Stratigraphy decided against formalising an Anthropocene epoch with its proposed start point in 1952 CE. Nevertheless, and pending further developments, we demonstrate that sites additional to those studied by the AWG clearly enable biostratigraphical correlation of a *de facto* Anthropocene epoch (*the lower-case 'e' indicating our informal use of the word 'epoch'*) beginning in the mid-20th century (Fig. 2a, b), and we use the Anthropocene in that



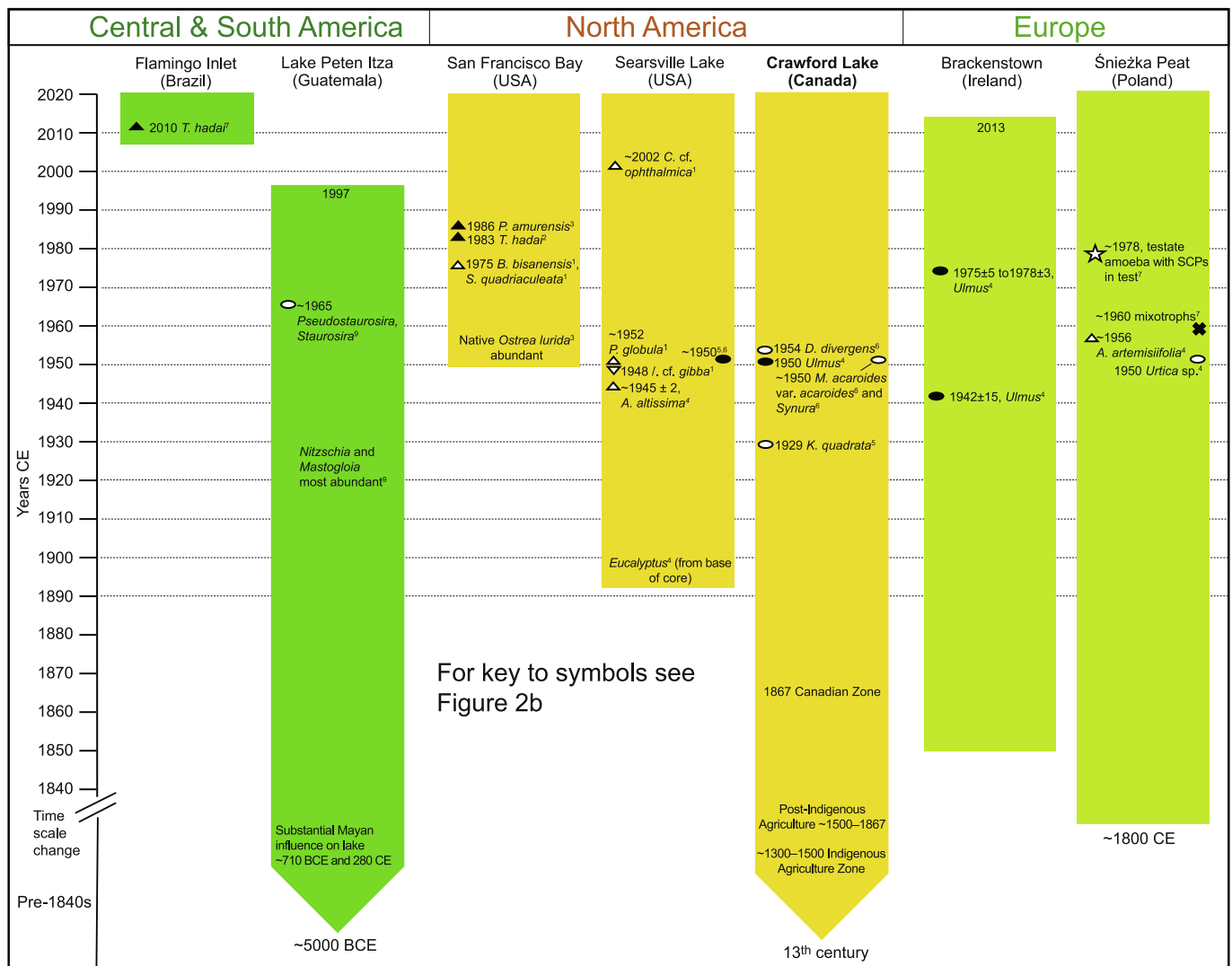
**Fig. 1.** A summary of selected human impacts on the biosphere. Selected key references for items 1–13: 1, decadal-speed translocation of species (Williams et al., 2022a); 2, novel forest products (this article); 3, rapid spread of fruits (this article); 4, rapid change to food processing (Bennett et al., 2018); 5, eutrophication of lakes (this article); 6, increased rate of extinction since 1900 (Ceballos et al., 2015); 7, mass accumulation of animal bones (Plotnick and Koy, 2020); 8, rapid translocation of species (Seebens et al., 2017); 9, increased rate of extinction over the past 500 years (Barnosky et al., 2011); 10, landscape and animal domestication (Price and Bar-Yosef, 2011); 11, human mediated species translocation (Williams et al., 2022a and references therein); 12, megafauna extinction (Sandom et al., 2014); 13, origins of human technology (Harmand et al., 2015). Note that we use ‘human’ to include all species of the genus *Homo*.

chronostratigraphic sense throughout this paper. In our analysis we focus on those recent taxa known to have a fossil record, some of which include an Anthropocene record. We include minute (millimetric or smaller) non-native species, which are often under reported in studies of non-native species (Briski et al., 2024). Our analysis encompasses taxa listed amongst the world’s 100 most invasive species (Lowe et al., 2000), including the fungi that cause Dutch elm disease, common ragweed, the giant African snail, golden apple snails, the cannibal snail (alias, rosy wolf snail), the Amur River clam, the cane toad, common carp, and Nile perch. Our focus is on palaeontological (e.g., skeletal, palynological) markers and not on eDNA, though that provides an important new tool for recognizing the introduction of non-native species and changes to ecologies in the Anthropocene.

A palaeontological signal of the change into the Anthropocene, including plants, animals and micro-organisms with recalcitrant parts (Williams et al., 2022a), is evident in the candidate GSSP site of Crawford Lake (Canada), the candidate SABSS of Beppu Bay (Japan), Sihai-longwan Lake (China) and Śnieżka peatland (Poland) and the additional reference localities of San Francisco Estuary and Searsville Lake (both in California), studied by the AWG to delineate the mid-20th century level for the base of the Anthropocene (Fig. 2a, b; Waters et al., 2023 and references therein). In Table 1 and Fig. 3 we summarise key taxa of likely widespread utility as Anthropocene palaeontological markers, a snapshot of the potentially useful taxa.

### 2.1. Plants

At Crawford Lake the decrease in *Ulmus* (elm) pollen from the beginning of the 1950s (McCarthy et al., 2023; Fig. 2a) marks a regional decline of these trees in North America resulting from the introduction of Dutch elm disease, and therefore is a proxy for that disease and for the transport interconnections that enabled its migration. Two introduced fungal pathogens, *Ophiostoma ulmi* and *O. novo-ulmi*, cause the infection and are spread by both indigenous and non-native beetles. There have been two waves of infection in North America, with *O. ulmi* arriving in the late 1920s, likely in shipments of timber from Europe, and *O. novo-ulmi* in the 1940s. In North America *O. ulmi* was more virulent than in Europe, while in Europe the later species was more damaging. Although Dutch elm disease is not widely documented in the recent pollen records of North America (as few studies focus on the last century), more detailed sampling may elucidate such patterns. When linked to the known chronology of the spread of *O. ulmi* westwards (it had reached the Great Lakes region by the 1950s) it may be predicted as a good Anthropocene indicator. Indeed, stratigraphical correlation might be achieved intercontinentally, because early reductions in elm trees associated with the dispersal of *O. ulmi* are detectable in European lake successions, for example at the Brackenstown millpond north of Dublin, Ireland (Fig. 2a). There, a dip in the percentage of elm pollen evident at the stratigraphical level of 1942 CE ± 15 years indicates the first wave of



**Fig. 2.** Selected biostratigraphical makers of a mid-20th century Anthropocene in sedimentary successions. a (upper), examples from North, Central and South America, and Europe; b (lower), examples from East Asia, Oceania, and Africa. Source references are: Flamingo Inlet (Eichler et al., 2016); Lake Peten Itza (Rosenmeier et al., 2004); San Francisco Estuary (Himson et al., 2023); Searsville Lake (Stegner et al., 2023); Crawford Lake (McCarthy et al., 2023); Brackenstown (Flynn and Mitchell, 2019); Śnieżka peatland (Fialkiewicz-Koziel et al., 2023); Sihailongwan Maar (Han et al., 2023); Chenghai Lake (Wu et al., 2004; Liu et al., 2015; Yan et al., 2023); Beppu Bay (Kuwaie et al., 2023); Leschenault Inlet (Tremblin et al., 2022); Lake Kutubu (Long et al., 2022); Maha ulepu sinkhole (Burney et al., 2001); Lake Victoria (Verschuren et al., 2002; Stager et al., 2009). For Leschenault Inlet, the arrival of *T. hadai* might have occurred as early as 1982 CE, when the first Japanese vessel 'Hoyo Maru' was recorded in the Bunbury harbour (Tremblin et al., 2022). For 2a, SCPs = spheroidal carbonaceous particles (see Rose, 2015). For the key in Fig. 2b, FAD = first appearance datum and LAD = last appearance datum; and in the column for Africa changes for 1940–early 1960s are abundance increases for the planktonic diatoms *Cyclotella*, *Aulacoseira* and *Nitzschia*, followed by their declines in the late 1980s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Dutch elm disease, enabling correlation to North American successions with approximately decadal precision (see Flynn and Mitchell, 2019). The later spread of the more virulent *O. novo-ulmi* in Europe is also registered at Brackenstown by a more severe elm decline at 1977 CE  $\pm$  4 years, marking a second stratigraphical proxy for *Ophiostoma* within the Anthropocene (Fig. 2a).

The common ragweed *Ambrosia artemisiifolia* (Fig. 3j) is an introduced plant in Europe, South America, Asia and Oceania. Native to North America, it is reported to have arrived in many regions of Europe during the 19th century via seed imports (Makra et al., 2015), although it may have had an earlier 17th century introduction (Tokarska-Guzik et al., 2011). Its rapid spread in the 20th century is identified as a biostratigraphical marker in the Linje Mire (Marcisz et al., 2015) and Śnieżka peat cores from southern Poland (Fialkiewicz-Koziel et al., 2023; Fig. 2a). Although common ragweed arrived in Poland much

earlier than the 1950s and had a sporadic distribution as early as the late 19th century (Tokarska-Guzik et al., 2011, Fig. 2), it is only after the 1950s that it became both common and widespread. Common ragweed spreads along railway tracks, roadsides and human-disturbed ground (e.g., Tokarska-Guzik et al., 2011; Essl et al., 2015). It adapts its reproductive strategy where invasive (Kralemann et al., 2018), and both climate change (Janella et al., 2019) and the further spread of transport connections will favour its wider distribution during the 21st century. In Australia, the species has been expanding its range since the 1950s (Boheemen et al., 2017), and in China since the 1930s (Makra et al., 2015). Where its time of introduction is known, pollen of *A. artemisiifolia* type can help constrain Anthropocene deposits; even in its native North America its range is extending by human-driven dispersal (e.g., Lavoie et al., 2007) and habitat disturbance.

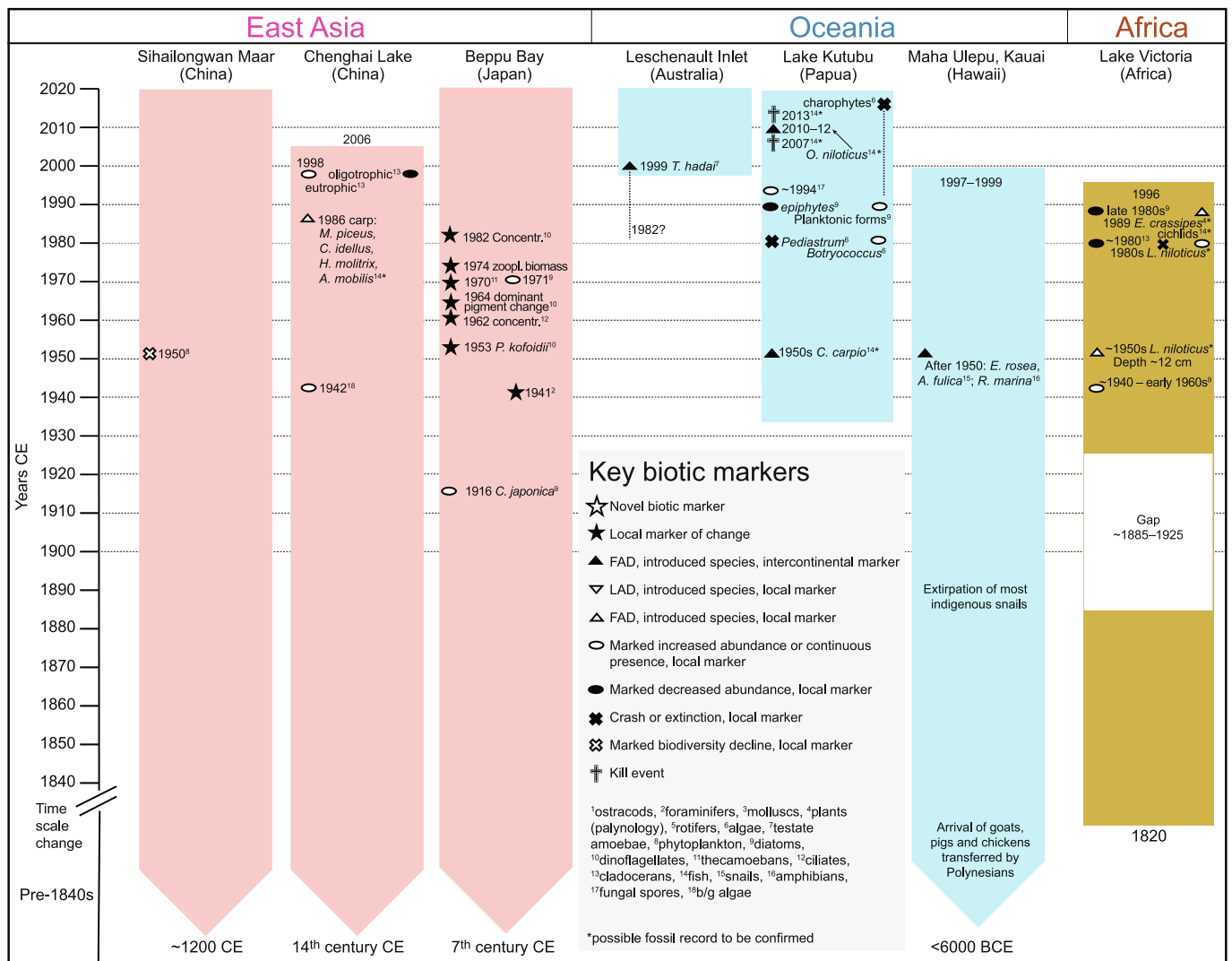


Fig. 2. (continued).

## 2.2. Invertebrates

Many invertebrate taxa have been translocated during the Great Acceleration (e.g., Seebens et al., 2017), including mollusc and arthropod species with durable shells and carapaces (Table 1, Fig. 3). On land, the spread of invasive snails has been documented as a potential marker of Anthropocene deposits (Hausdorf, 2018). This reflects changes in shipping and transport causing accidental introductions (e.g., Clarke et al., 2017), new methods of shopping via garden centres (Bergey et al., 2014), deliberate introductions to control pests (e.g., Cowie, 1998), and the commodification of snail meat that developed in the later 20th century (e.g., Thiengo et al., 2007; Massari and Pastore, 2014; Fig. 4). The giant African snail *Achatina fulica* is the most widespread exemplar: native to East Africa, it spread through the Indian Ocean region in the pre-Anthropocene 19th century, and then had more rapid introductions through southeast Asia and the Pacific in the 20th century, aided by its use as a food source for Japanese soldiers during WWII (Raut and Barker, 2002; Hausdorf, 2018). In many regions, including West Africa and South America, the introduction of the giant African snail in the mid to late 20th century makes it a clear marker of Anthropocene deposits. The snails spread through Brazil from deliberate and illegal introduction as a commercial food product in the 1980s – a replacement for traditional snails used as escargot. The enterprise failed and the snails were discarded, but they subsequently became abundant in urban

and small-scale cultivated landscapes, while also spreading into less human-influenced ecologies (Thiengo et al., 2007). Giant African snails are also unintentionally transported on international shipping, being one of the species most frequently intercepted by port authorities in Australia (Clarke et al., 2017). In Brazil, active programmes to eradicate the snail have resulted in their collection, crushing, deposition in 2 m-deep ditches, and covering with kaolin and soil (Thiengo et al., 2007), as a localised but distinctive Anthropocene deposit. Hausdorf (2018) emphasised that the giant African snail may, with other palaeontological markers, allow definitive recognition of deposits formed in the second half of the 20th century. Its appearance in the fossil record of sediments from a sinkhole on the Hawaiian island of Kauai has been used to determine deposits of the 1950s or later (Fig. 2b; and Burney et al., 2001), in conjunction with shells of the cannibal snail (*Euglandina rosea*; Fig. 3f) introduced in 1957 with disastrous consequences for indigenous snails (Cowie, 1998). *Achatina* species are known at archaeological sites (Wojcieszak et al., 2023) and, given their robust shells, are likely to leave a widespread fossil record.

Aquatic molluscs also mark Anthropocene deposits. The snail genus *Pomacea* possesses a fossil record extending back to the Eocene in its native South America, and the golden apple snail *Pomacea canaliculata* is known from Quaternary deposits there (Martín and De Francesco, 2006). *Pomacea canaliculata*, a native of Argentina and Uruguay, was deliberately introduced to Taiwan in 1980 as a food source (Naylor,

**Table 1**  
Potential palaeontological markers of the Anthropocene.

| Species                                      | Common name         | Organism type and fossilizable component | Ecology             | Native region        | Fossil record prior to the Anthropocene                 | Non-native utility as an Anthropocene marker      | Decade of arrival or proliferation | Anthropocene fossil record in non-native region | Key references  |
|--|---------------------|--|---------------------|----------------------|---|---|------------------------------------|---|---|
| <b>North America</b>                         |                     |  |                     |                      |   |   |                                    |   |   |
| <i>Dreissena polymorpha</i>                  | zebra mussel        | Mollusc (shell)                          | Fresh/brackish      | Black/Caspian/Aral   | Fossil record of dreissenids                            | North America, widespread in the East             | 1980s                              | Not yet reported                                | <a href="#">Bukontaite and Zaiko, 2008</a>  |
| <i>Dreissena rostriformis bugensis</i>       | quagga mussel       | Mollusc (shell)                          | Freshwater          | Dnieper/Southern Bug | Fossil record of dreissenids                            | North America                                     | mid-1980s                          | Not yet reported                                | <a href="#">Wong and Mastitsky, 2014</a>  |
| <i>Potamocorbula amurensis</i>               | Amur River clam     | Mollusc (shell)                          | Marine/brackish     | East Asia            | Holocene  | North America, California                         | 1980s                              | San Francisco Estuary                           | <a href="#">Himson et al., 2023</a>   |
| <i>Ruditapes philippinarum</i>               | Manila clam         | Mollusc (shell)                          | Marine/brackish     | East Asia            | Holocene  | North America, west coast                         | 1920s–30s                          | Not yet reported                                | <a href="#">Shimoyama et al., 2015</a> ; <a href="#">Bonham et al., 2018</a> ; <a href="#">Ojaveer et al., 2018</a> |
| <i>Carcinus maenus</i>                       | European green crab | Crustacean (exoskeleton)                 | Littoral/estuarine  | NE Atlantic & Baltic | Extensive fossil record of arthropods                   | North America, west coast                         | 1980s* <sup>1</sup>                | Not yet reported                                | <a href="#">Carlton and Cohen, 2003</a>   |
| <i>Trochammina hadai</i>                     | None                | Foraminifer (test)                       | Marine/brackish     | East Asia            | Quaternary  | North America, west coast                         | 1970s                              | West coast                                      | <a href="#">McGann et al., 2000, 2002, 2012</a> ; <a href="#">Himson et al., 2023</a>                               |
| <i>Ophiostoma ulmi</i> , <i>O. novo-ulmi</i> | Dutch elm Disease   | Elm pollen decline                       | Terrestrial         | Asia                 | Not reported for <i>Ophiostoma</i> spores* <sup>2</sup> | North America, Great Lakes region westwards       | 1950s                              | Crawford Lake                                   | <a href="#">McCarthy et al., 2023</a>   |
| <b>South America</b>                         |                     |  |                     |                      |   |   |                                    |   |   |
| <i>Achatina fulica</i>                       | giant African snail | Mollusc (shell)                          | Terrestrial         | East Africa          | Fossil record of Achatininae in Africa                  | Brazil (and present elsewhere at different times) | 1980s                              | Not yet reported                                | <a href="#">Thiengo et al., 2007</a> ; <a href="#">Hausdorf, 2018</a> ; <a href="#">Baldreki et al., 2024</a>       |
| <i>Bradybaena similaris</i>                  | Asian tramp snail   | Mollusc (shell)                          | Terrestrial         | SE Asia              | Camaenidae have a fossil record                         | Argentina (19th century introduction to Brazil)   | 1950s                              | Not yet reported                                | <a href="#">Serniotti et al., 2020</a>  |
| <i>Limnoperna fortunei</i>                   | golden mussel       | Mollusc (shell)                          | Freshwater          | China/SE Asia        | Mytilids have an extensive fossil record                | Argentina, then widespread (Brazil, Paraguay...)  | 1990s                              | Not yet reported                                | <a href="#">Darrigan, 2008</a>  |
| <i>Magallana gigas</i>                       | Pacific oyster      | Mollusc (shell)                          | Marine/brackish     | East Asia            | Oysters have an extensive fossil record                 | Chile, Ecuador (and widespread)                   | 1980s                              | Not yet reported                                | <a href="#">Bonham and Gouletquer, 2017</a>   |
| <i>Hippopotamus amphibius</i>                | hippo               | Mammal bones and teeth                   | Terrestrial aquatic | Sub-Saharan Africa   | Miocene for hippos more generally                       | Colombia  | 1970s                              | Not yet reported                                | <a href="#">Castelblanco-Martínez et al., 2021</a>  |

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Table 1 (continued)

| Species                                | Common name              | Organism type and fossilizable component | Ecology                 | Native region               | Fossil record prior to the Anthropocene       | Non-native utility as an Anthropocene marker | Decade of arrival or proliferation | Anthropocene fossil record in non-native region | Key references   |
|--|--------------------------|--|-------------------------|-----------------------------|---|--|------------------------------------|---|--|
| <i>Trochammina hadai</i>               | None                     | Foraminifer (test)                       | Marine/<br>brackish     | East Asia                   | Quaternary                                    | Brazil                                       | 2010s                              | Not yet reported                                | <a href="#">Eichler et al., 2016</a>   |
| <i>Fabaeformiscandona subacuta</i>     | None                     | Ostracod (shell)                         | Freshwater              | probably<br>East Asia       | Neogene                                       | Colombia                                     | 2010s                              | Not yet reported                                | <a href="#">Escrivà et al., 2012</a>   |
| <b>Europe</b>                          |                          |  |                         |                             |   |  |                                    |   |  |
| <i>Corbicula fluminea</i>              | Asian clam               | Mollusc (shell)                          | Freshwater              | East Asia                   | Fossil record of <i>Corbicula</i>             | Europe, widespread                           | 1980s                              | River Thames                                    | <a href="#">Allen, 2019</a> ; <a href="#">Himson et al., 2020</a>  |
| <i>Dreissena rostriformis bugensis</i> | quagga mussel            | Mollusc (shell)                          | Freshwater              | Dnieper/<br>Southern<br>Bug | Fossil record of dreissenids                  | Europe, widespread                           | 1940s                              | Not yet reported                                | <a href="#">Wong and Mastitsky, 2014</a>   |
| <i>Magallana gigas</i>                 | Pacific oyster           | Mollusc (shell)                          | Marine/<br>brackish     | East Asia                   | Oysters have an extensive fossil record       | north Europe (Germany, Denmark, Sweden etc.) | 1960s                              | Not yet reported                                | <a href="#">Nehring, 2011</a>  |
| <i>Potamocorbula amurensis</i>         | Amur River clam          | Mollusc (shell)                          | Marine/<br>brackish     | East Asia                   | Holocene                                      | Europe, Belgium                              | 2010s                              | Not yet reported                                | <a href="#">Thompson, 2022</a>   |
| <i>Ruditapes philippinarum</i>         | Manila clam              | Mollusc (shell)                          | Marine/<br>brackish     | East Asia                   | Holocene                                      | Europe, widespread                           | 1960s                              | Not yet reported                                | <a href="#">Shimoyama et al., 2015</a> ; <a href="#">Bonham et al., 2018</a>   |
| <i>Pacifastacus leniusculus</i>        | American signal crayfish | Crustacean (exoskeleton)                 | Freshwater/<br>brackish | North America               | Genus <i>Pacifastacus</i> has a fossil record | Europe, widespread                           | 1960s                              | Not yet reported                                | <a href="#">Houghton and Allen, 2014</a> ; <a href="#">Rode and Babcock, 2003</a>  |
| <i>Trochammina hadai</i>               | None                     | Foraminifer (test)                       | Marine/<br>brackish     | East Asia                   | Quaternary                                    | France                                       | 2020s                              | Not yet reported                                | <a href="#">Bouchet et al., 2023</a>   |
| <i>Nonionella stella</i>               | None                     | Foraminifer (test)                       | Marine                  | East Pacific                | Quaternary                                    | north Europe (Norway, Sweden)                | 1980s                              | Gullmar Fjord, Oslofjord                        | <a href="#">Polovodova Asterman and Schönfeld, 2016</a> ; <a href="#">Deldicq et al., 2019</a>   |
| <i>Fabaeformiscandona subacuta</i>     | None                     | Ostracod (shell)                         | Freshwater              | probably<br>East Asia       | Neogene                                       | Spain  | 2000s                              | Not yet reported                                | <a href="#">Escrivà et al., 2012</a>   |
| <i>Ambrosia artemisiifolia</i>         | common ragweed           | Plant (pollen)                           | Terrestrial             | North/<br>South<br>America  | Pleistocene for <i>Ambrosia</i>               | Europe, widespread                           | 1950s* <sup>3</sup>                | Śnieżka peatland                                | <a href="#">Bassett and Compton, 1975</a> ; <a href="#">Ricciardi, 2006</a> ; <a href="#">Iamonico, 2016</a> ; <a href="#">Fiałkiewicz-Koziet et al., 2023</a> |
| <b>Africa</b>                          |                          |  |                         |                             |   |  |                                    |   |  |
| <i>Euglandina rosea</i> complex        | cannibal snail           | Mollusc (shell)                          | Terrestrial             | SE USA                      | <i>Euglandina</i> fossil record in Florida    | Madagascar                                   | 1970s                              | Not yet reported                                | <a href="#">Bergendahl, 1956</a> ; <a href="#">CABI, 2019</a> ; <a href="#">Gerlach et al., 2021</a>   |

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Table 1 (continued)

| Species   | Common name          | Organism type and fossilizable component | Ecology             | Native region       | Fossil record prior to the Anthropocene     | Non-native utility as an Anthropocene marker   | Decade of arrival or proliferation | Anthropocene fossil record in non-native region | Key references  |
|---|----------------------|--|---------------------|---------------------|---|--|------------------------------------|---|---|
| <i>Mytilus galloprovincialis</i> * <sup>4</sup> | Mediterranean mussel | Mollusc (shell)                          | Marine              | Europe/Black Sea    | Ancient fossil record of <i>Mytilus</i>     | southern Africa, Atlantic coast                | 1970s                              | Not yet reported                                | <a href="#">Grant and Cherry, 1985</a> ; <a href="#">Branch et al., 2010</a> ; <a href="#">Bonham and Roberts, 2017</a> ; <a href="#">Bonham et al., 2017</a> |
| <i>Chromolaena odorata</i>                      | Siam weed            | Plant (pollen)                           | Terrestrial         | North/South America | Not reported                                | widespread in sub-Saharan Africa               | 1940s                              | Present in soil samples* <sup>5</sup>           | <a href="#">Gautier, 1992</a> ; <a href="#">Goodall and Erasmus, 1996</a> ; <a href="#">Vincens et al., 2000</a> ; <a href="#">Pasiercznik, 2007</a>          |
| <i>Eichhornia crassipes</i>                     | water hyacinth       | Plant (pollen/seed)                      | Terrestrial aquatic | South America       | Not reported                                | widespread in Africa (Nile, Congo, Niger etc.) | 1950s                              | Africa  | <a href="#">Birks et al., 2001</a> ; <a href="#">Peglar et al., 2001</a> ; <a href="#">Rojas-Sandoval and Acevedo-Rodriguez, 2013</a>                         |
| <i>Procambarus clarkii</i>                      | Red swamp crayfish   | Crustacean (exoskeleton)                 | Terrestrial aquatic | North America       | Extensive fossil record of arthropods       | widespread in Africa (north and sub-Saharan)   | 1960s (Uganda)                     | Not yet reported                                | <a href="#">Ballinger, 2022</a>   |
| <i>Cyprinus carpio</i>                          | common carp          | Fish (bones)                             | Terrestrial aquatic | Eurasia             | Pliocene (for <i>C. carpio sensu lato</i> ) | Sub-Saharan Africa* <sup>6</sup> (widespread)  | 1940s                              | Not yet reported                                | <a href="#">Váradi, 2019</a>  |
| <i>Lates niloticus</i>                          | Nile perch           | Fish (bones)                             | Terrestrial aquatic | Africa              | Pleistocene                                 | Africa, Lake Victoria                          | 1950s                              | Not yet reported                                | <a href="#">Pringle, 2005</a> ; <a href="#">Stewart, 2009</a>   |
| ∞   |                      |  |                     |                     |   |  |                                    |   |   |
| <b>Asia</b>                                     |                      |  |                     |                     |   |  |                                    |   |   |
| <i>Bradybaena similaris</i>                     | Asian tramp snail    | Mollusc (shell)                          | Terrestrial         | SE Asia             | Camaenidae have a fossil record             | Bangladesh                                     | 2020s                              | Not yet reported                                | <a href="#">Hirano et al., 2020</a>   |
| <i>Limnoperna fortunei</i>                      | golden mussel        | Mollusc (shell)                          | Terrestrial aquatic | China/SE Asia       | Mytilids have an extensive fossil record    | Japan  | 1990s                              | Not yet reported                                | <a href="#">Darrigan, 2008</a>  |
| <i>Magallana gigas</i>                          | Pacific oyster       | Mollusc (shell)                          | Marine/brackish     | East Asia           | Oysters have an extensive fossil record     | SE Asia (Indonesia, Malaysia...)               | 1980s                              | Not yet reported                                | <a href="#">Bonham and Gouletquer, 2017</a>   |
| <i>Pomacea canaliculata</i>                     | golden apple snail   | Mollusc (shell)                          | Terrestrial aquatic | South America       | Quaternary                                  | East and South East Asia                       | 1980s                              | Not yet reported                                | <a href="#">Cowie, 2013</a>   |
| <i>Daphnia pulex</i>                            | water flea           | Crustacean (exoskeleton)                 | Freshwater          | North America       | Not reported                                | Japan* <sup>7</sup>                            | 1990s                              | Lake Biwa, Japan                                | <a href="#">Tsugeki et al., 2022</a>  |
| <i>Alternanthera philoxeroides</i>              | alligator weed       | Plant (pollen)                           | Terrestrial aquatic | South America       | Not reported                                | China (widespread), many other Earth regions   | 1930s                              | Not yet reported                                | <a href="#">Rojas-Sandoval, 2016</a> ; <a href="#">Chu et al., 2019</a>   |
| <i>Chromolaena odorata</i>                      | Siam weed            | Plant (pollen)                           | Terrestrial         | North/South America | Not reported                                | Indonesia, Java, Kalimantan, Sumatra, Sulawesi | 1930s                              | Not yet reported                                | <a href="#">Gautier, 1992</a> ; <a href="#">Pasiercznik, 2007</a>   |

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Table 1 (continued)

| Species                            | Common name              | Organism type and fossilizable component | Ecology         | Native region       | Fossil record prior to the Anthropocene      | Non-native utility as an Anthropocene marker         | Decade of arrival or proliferation | Anthropocene fossil record in non-native region | Key references   |
|------------------------------------|--------------------------|--|-----------------|---------------------|--|--|------------------------------------|---|--|
| <i>Elaeis guineensis</i>           | African oil palm         | Plant (pollen/seed)                      | Terrestrial     | Africa              | Seed/pollen record, Miocene–Holocene, Africa | Indonesia, Malaysia, widespread in SE Asia           | 1910s <sup>*8</sup>                | Not yet reported                                | <a href="#">Pan et al., 2006</a> ; <a href="#">Baudoin et al., 2017</a> ; <a href="#">Bakewell-Stone, 2023</a>                             |
| <b>Oceania</b>                     |                          |  |                 |                     |  |  |                                    |   |  |
| <i>Euglandina rosea</i> complex    | cannibal snail           | Mollusc (shell)                          | Terrestrial     | SE USA              | <i>Euglandina</i> fossil record in Florida   | Island Oceania, Guam, Hawaiian Islands <sup>*9</sup> | 1950s                              | Kauai   | <a href="#">Bergendahl, 1956</a> ; <a href="#">Burney et al., 2001</a> ; <a href="#">CABI, 2019</a> ; <a href="#">Gerlach et al., 2021</a> |
| <i>Magallana gigas</i>             | Pacific oyster           | Mollusc (shell)                          | Marine/brackish | East Asia           | Oysters have an extensive fossil record      | Australia (including Tasmania)                       | 1940s                              | Not yet reported                                | <a href="#">Bonham and Gouletquer, 2017</a>  |
| <i>Magallana gigas</i>             | Pacific oyster           | Mollusc (shell)                          | Marine/brackish | East Asia           | Oysters have an extensive fossil record      | Fiji   | 1960s                              | Not yet reported                                | <a href="#">Bonham and Gouletquer, 2017</a>  |
| <i>Asterias amurensis</i>          | northern Pacific seastar | Echinoderm (skeleton)                    | Marine/brackish | NE Asia             | Echinoderms have an extensive fossil record  | Australia (including Tasmania)                       | 1980s                              | Not yet reported                                | <a href="#">Stevens, 2010</a>  |
| <i>Trochammina hadai</i>           | None                     | Foraminifer (test)                       | Marine/brackish | East Asia           | Quaternary                                   | Australia  | 2020s                              | Not yet reported                                | <a href="#">Tremblin et al., 2022</a>  |
| <i>Fabaeformiscandona subacuta</i> | None                     | Ostracod (shell)                         | Freshwater      | probably East Asia  | Neogene                                      | Western Australia                                    | 2000s                              | Not yet reported                                | <a href="#">Escrivà et al., 2012</a>   |
| <i>Cyprinus carpio</i>             | common carp              | Fish (bones)                             | Freshwater      | Eurasia             | Pliocene (for <i>C. carpio</i> sensu lato)   | Papua New Guinea                                     | 1950s                              | Not yet reported                                | <a href="#">Balon, 1995</a> ; <a href="#">Long et al., 2022</a>  |
| <i>Rhinella marina</i>             | cane toad                | Amphibian (bones)                        | Terrestrial     | North/South America | Neogene                                      | Australia  | 1930s <sup>*10</sup>               | Not yet reported                                | <a href="#">CABI, 2010</a>   |
| <i>Rhinella marina</i>             | cane toad                | Amphibian (bones)                        | Terrestrial     | North/South America | Neogene                                      | Hawaiian islands                                     | 1930s                              | Kauai, 1950s                                    | <a href="#">Burney et al., 2001</a> ; <a href="#">CABI, 2010</a>   |

<sup>\*1</sup>Present on the east coast since 1817, see [Carlton and Cohen, 2003](#).

<sup>\*2</sup>Elm pollen indicates multiple earlier (pre-Anthropocene) incidents of Dutch elm Disease, for example see [Innes et al., 2006](#).

<sup>\*3</sup>Arrived in the 19th century, proliferated in the 20th century.

<sup>\*4</sup>Sibling species are *M. edulis* and *M. trossulus*, but neither of these are native to southern Africa, see [Bonham and Roberts, 2017](#), [Bonham et al., 2017](#).

<sup>\*5</sup>See [Vincens et al., 2000](#), for Cameroon.

<sup>\*6</sup>Earlier appearance in North Africa.

<sup>\*7</sup>Widely distributed beyond its native range.

<sup>\*8</sup>Rapid development from the 1960s, and especially from the 2000s.

<sup>\*9</sup>Very widespread in island Oceania from the 1950s.

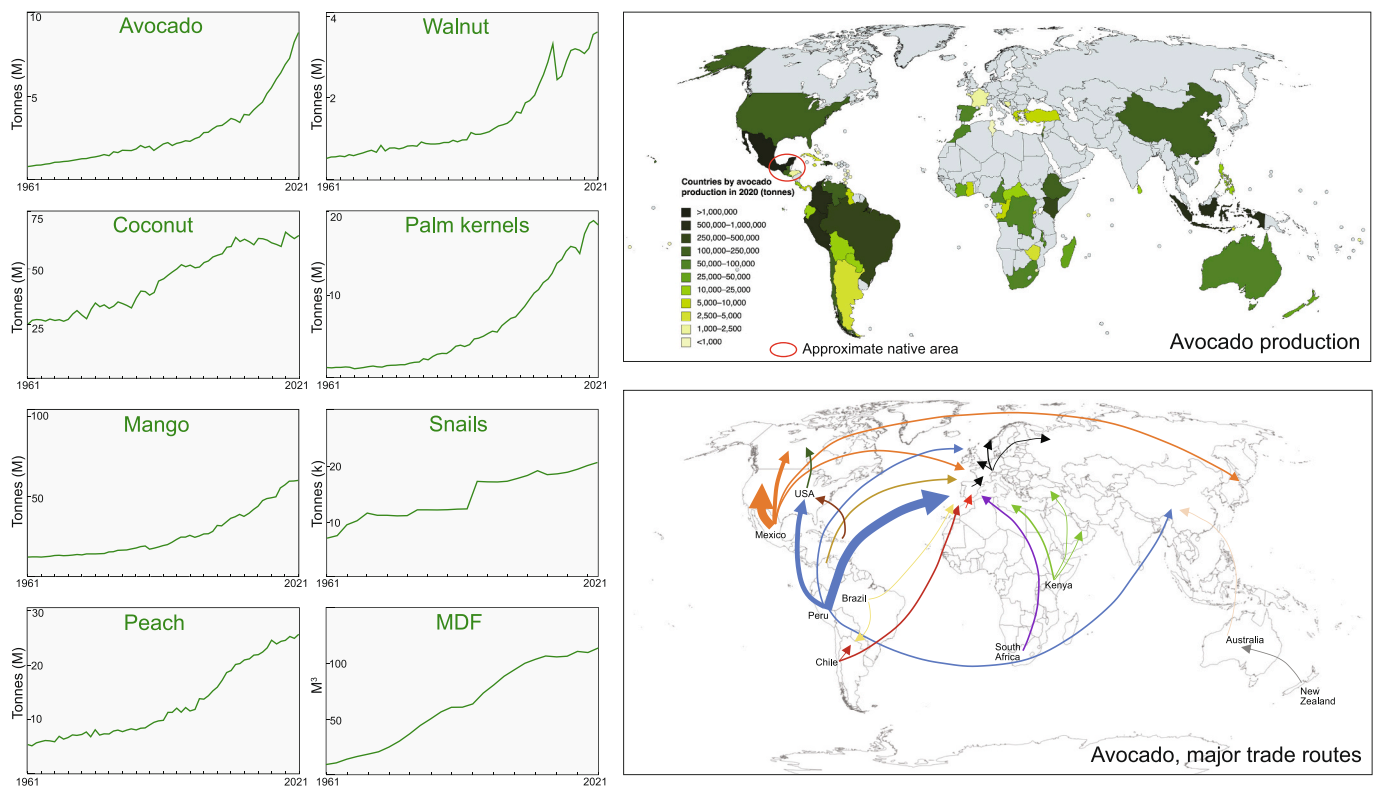
<sup>\*10</sup>Widely distributed in Australia by the 1980s.



**Fig. 3.** Examples of invasive species likely to leave a fossil record: a, Asian clams at Teddington Lock on the River Thames, UK; b, Asian clams in the River Soar, Leicestershire, UK; c, quagga mussels revealed on the rocks lining Grafham Water reservoir, UK, during low water levels.; d, zebra mussels on a native freshwater clam in Manitoba, Canada; e, Himalayan balsam along the banks of the River Soar, Leicestershire, UK; f, cannibal snail on Kauai, Hawaii; g, Pacific oysters at the village of Yerseke, Netherlands; h, Amur River clams recovered in core sediments from San Francisco Estuary, USA; i, red swamp crayfish, *Procambarus clarkii*, collected from irrigation canals in Uganda and widely introduced for food; j, common ragweed growing in a chicken house in Belgium; k, cane toad in the Philippines; l, shells of zebra and quagga mussels lining a small stream in the UK. Shells enter the location from an upstream reservoir. Image credits: a, h, Stephen Himson; b, e, Amy Wrisdale; c, i, l, David Aldridge; d, Province of Manitoba, Department of Sustainable Development. <https://www.fortwhyte.org/zebra-mussels-in-manitoba/>; f, Dylan Parker - Flickr, CC BY-SA 2.0, <https://commons.wikimedia.org/w/index.php?curid=5087491>; g, Takeaway – Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=34908724>; j, Meneerke Bloem, [https://commons.wikimedia.org/wiki/File:Ambrosia\\_artemisiifolia\\_001.jpg](https://commons.wikimedia.org/wiki/File:Ambrosia_artemisiifolia_001.jpg); k, [https://commons.wikimedia.org/wiki/File:Rhinella\\_marina\\_\(Philippines\).jpg](https://commons.wikimedia.org/wiki/File:Rhinella_marina_(Philippines).jpg).

1996). Together with other *Pomacea* species from South America, it subsequently migrated through Southeast Asia along irrigation networks, and more recently invaded such settings in East Africa (Djedjour et al., 2021). Because of their aquatic ecology (Seuffert and Martín, 2013), relatively large size (Cristini and De Francesco, 2019) and known fossil record (Martín and De Francesco, 2006), golden apple snails are likely to leave a widespread palaeontological record in those irrigated areas they have invaded, just as fossil molluscs are closely associated with ancient irrigation structures (Moshier and El-Kalani, 2008; Beach

et al., 2009; Storozum et al., 2018; Cajigas et al., 2020; and below). Other aquatic molluscan Anthropocene markers include zebra mussels (*Dreissena polymorpha*; Fig. 3d) dispersed through North American lakes since the 1980s, Asian clams (*Corbicula fluminea*; Fig. 3a, b) invading the waterways of Europe during the same period (Himson et al., 2020), and quagga mussels (*Dreissena rostriformis bugensis*; Fig. 3c), now supplanting earlier invasions by zebra mussels (Aldridge et al., 2014). When masses of these molluscs are cleared from raw water intake tunnels and screens (i.e., by water companies) they end up in landfills (McLaughlan et al.,



**Fig. 4.** Late 20th and 21st century production of avocados, coconuts, mangos, peach, walnut, palm kernels, snails and MDF, <https://www.fao.org/faostat/en/#data/QCL/visualize> (data downloaded August 2023). Maps show those countries producing avocados (from [https://commons.wikimedia.org/wiki/File:Countries\\_by\\_avocado\\_production\\_in\\_2020.png](https://commons.wikimedia.org/wiki/File:Countries_by_avocado_production_in_2020.png)) and the major export routes (modified from <https://wherethefoodcomesfrom.com/world-avocado-map-2023-global-growth-far-from-over/>). A future fossil pattern of avocado seeds – as with other patterns documented here – preserved in landfill deposits or recycled into other deposits, would be a signature of growing human interconnectivity and patterns of consumption in the Anthropocene. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2014), as another Anthropocene deposit. In coastal marine environments dense accumulations of the Pacific oyster (*Magallana gigas*; Fig. 3g) in northern Europe, southeast Asia and South America characterise Anthropocene deposits (Table 1), whilst the translocation of the Mediterranean mussel (*Mytilus galloprovincialis*) to South Africa, possibly during the 1970s (Grant and Cherry, 1985; Branch et al., 2010), may be another such marker. This species is widely distributed beyond its native range but can be difficult to distinguish from *Mytilus edulis* and *M. trossulus*, with which it hybridizes (Bonham et al., 2017). However, in South Africa *Mytilus* was not previously present (Grant and Cherry, 1985). In San Francisco Estuary, Himson et al. (2023) showed the Amur River clam (*Potamocorbula amurensis*; Fig. 3h) to be a biostratigraphical marker of Anthropocene deposits; it is also recorded in the Scheldt Estuary of Belgium (Thompson, 2022). The Japanese carpet shell (also known as the Manila clam) *Ruditapes philippinarum*, is now widespread in Europe, Oceania, and the Pacific coast of North America and is likely to spread as sea temperatures warm (Bonham et al., 2018), as will other mollusc species (e.g., Gama et al., 2016).

Arthropods have a long and extensive fossil record and have also changed their distribution patterns in the Anthropocene (Seebens et al., 2017). For example, crayfish, ostracod crustaceans and water fleas (*Daphnia*) have been spreading rapidly through non-native aquatic ecologies. These include the red swamp crayfish (*Procambarus clarkii*; Fig. 3i), a native to the USA and northern Mexico, now widely introduced as a food source into Europe, Africa and East Asia (Ballinger, 2022). The North American signal crayfish (*Pacifastacus leniusculus*) is widely invasive in Europe (Houghton and Allen, 2014). Of ostracods, *Bicorncythere bisanensis* and *Spinileberis quadriculeata* were introduced into San Francisco Estuary, probably from East Asia via shipping, in the 1970s (Williams et al., 2022b; Himson et al., 2023; also Fig. 2a). These

taxa are widely known from fossil and recent deposits of Japan and China (e.g., Yasuhara, 2008; Hong et al., 2019). *Fabaeformiscandona subacuta* was probably introduced from East Asia into the inland waterways of Spain in the 1970s, and into South America and Australia in the 2000s (Escrivà et al., 2012; see Table 1). Colonization of human-modified aquatic habitats by successive ostracod species can be used regionally and locally to recognise the Anthropocene, as with the occurrence of *Physicypria globula* and *Cypria* cf. *ophthalmica* in Searsville Lake, California (Stegner et al., 2023; Fig. 2a). Such distinctive ostracod markers of the Anthropocene are likely to be found in many natural and human-made waterbodies (Escrivà et al., 2014). And, the water flea *Daphnia pulex*, a native to North America that has been widely distributed beyond its original range, is found in the recent sediment record of Lake Biwa, Japan from the 1990s onwards (Tsugeki et al., 2022; Table 1), whilst concurrently its populations have declined in parts of its native area, resulting from the introduced cladoceran *Bythotrephes longimanus* (Barbiero and Tuchman, 2004).

### 2.3. Vertebrates

Non-native vertebrates, including fish, amphibians, birds, and mammals also mark the stratigraphical Anthropocene. One of the largest signatures is the reconfiguration of global freshwater fish communities by the widespread release of non-native species to 'improve fisheries', for aquaculture and recreation (e.g., Hampton et al., 2018; Leroy et al., 2023). Two freshwater fish we discuss are amongst the world's most invasive species, the Nile perch and the common carp (Lowe et al., 2000). The Nile perch (*Lates niloticus*) has a fossil record in its indigenous African range (Lernau, 1986; Stewart, 2009; Otero et al., 2017). In the mid- to late 20th century, it was introduced to many regions of Africa

outside its natural range, often linked to recreational fishing. Its most widely documented environmental impact is in Lake Victoria, Africa, where it was released during the early 1950s by the British colonial administration, ostensibly to improve local fisheries. This had drastic (and foreseen) consequences on the lake's ecology (Graham, 1929 *vide* Pringle, 2005), with the demise of most of the indigenous fish (Pringle, 2005). The introduction of Nile perch in Lake Victoria and its proliferation during the 1980s is contemporaneous with significant ecological changes in the lake caused by increasing human population (a five-fold rise between the 1930s and 1990s) and agricultural activity in the hinterland. This has left a profound palaeontological signal in diatom communities from the 1940s onwards (Fig. 2b, Verschuren et al., 2002) associated with the development of persistent anoxia in the deep lake from the 1970s, enhancing the likely fossilization of Nile perch.

The common carp (alias European or Eurasian carp, *Cyprinus carpio*) has been introduced to more than 300 aquatic basins globally (Leroy et al., 2023) and is highly invasive. In sub-Saharan Africa it has become widespread since the 1920s, and in many parts of South, East and southeast Asia (Bangladesh, Bhutan, Cambodia, Korea, Laos, Pakistan) its introduction was post-1950, and so during the Anthropocene epoch (Welcomme, 1988; Varadi, 2019). In many regions of Oceania, the common carp was released in the 19th and early 20th centuries (Welcomme, 1988), but in Papua New Guinea (PNG) its introduction was in the 1950s. Thus, its release into Lake Kutubu (PNG) in the 1950s, and later (~2010–2012) that of the Nile tilapia (*Oreochromis niloticus*), are coincident with the Anthropocene and represent a time of increasing connectivity of Lake Kutubu's hinterland into the global economy (Long et al., 2022). Since both tilapia and carp occur as fossils in archaeological and sedimentological contexts (e.g., Carnevale et al., 2003; Mabuchi et al., 2005; Van Neer et al., 2020), Lake Kutubu will likely preserve the fossil record of these non-native fish, particularly as tilapia formed 50% of the lake's biomass in 2015 (Long et al., 2022 and references therein). The lowest appearance datums of these non-native fish species are likely to be stratigraphically coincident with the highest appearance datums of several indigenous and now extinct Lake Kutubu fish. Palynological and diatom evidence also indicate substantial changes to the lake's ecology since the 1980s (Long et al., 2022; Fig. 2b).

The highly invasive cane toad (*Rhinella marina*; Fig. 3k), has a fossil record extending back to the Neogene in its native range of northern South America to Texas (Barcelos and Verdade, 2020). The toads were deliberately introduced into Oceania, including northern Australia, and into East Asia in the 1930s and thereafter, to control 'pests' on crops, though with limited success. Proliferating rapidly, cane toads have caused extensive ecological damage in their non-indigenous ranges, and their fossil remains have been used as a marker of 1950s and younger deposits in Kauai, Hawaii (Burney et al., 2001; Fig. 2b, Table 1).

Many bird species are becoming markers of the Anthropocene and, given their ability to fly, can disperse both rapidly and widely once introduced. Parrots (Psittaciformes) have been transported and traded, mostly as exotic pets, for the past 2000 years or more, with 71 species now established in at least one country outside their natural range (Calzada Preston and Pruet Jones, 2021). Of these, the ring-necked parakeet (*Psittacula krameri*), native to sub-Saharan Africa and the Indian subcontinent, is now found on every continent except Antarctica (Menchetti et al., 2016). Its breeding range increased more than 440-fold from the late 1960s to mid-2010s (Balmer et al., 2013), and its non-native global distribution is essentially restricted to the Anthropocene. Although the fossil record of Psittaciformes is sparse (e.g., Waterhouse, 2006), the wide environmental range of the ring-necked parakeet, including into human-modified habitats, and its nesting in cavities suggests it may become a potential stratigraphical marker of the Anthropocene.

Coincident with the dispersal of ring-necked parakeets was the development of broiler chickens (*Gallus domesticus*) – a distinctive morphotype engineered by breeding programmes since the 1950s, and now globally distributed. Broilers are consumed in their tens of billions

each year and are likely to form a fossil signal of discarded bones in landfill deposits since the 1950s (Bennett et al., 2018), possibly joined by the fossilised bones of the diverse bird populations that now forage on landfill in large numbers, and which include seabirds remote from their traditional ecologies (Dee, 2021).

Many non-native mammal species have been widely distributed for centuries as domesticates, pets, and game animals. These translocations commonly had significant impacts on local ecologies, including the extinction of indigenous species, and they have left a distinctive fossil record from before the proposed Anthropocene epoch in the sense of the AWG (Plotnick and Koy, 2020). Twentieth-century introductions and spread of non-domesticated mammal taxa are often more geographically localised and their fossil occurrence may therefore be sporadic, but some distinctive species may become Anthropocene markers. Of these, the widespread introduction of the North American mink (*Neovison vison*) to regions such as Europe (from the 1920s, becoming more widespread from the 1950s), and South America and Asia (from the 1930s) may be a widespread marker (Palazón and Roy, 2014), given that mink fossils are known from their native range (Harding and Smith, 2009 and references therein). Other potential mammal species include introductions of non-native deer that have a fossil and archaeological record in their indigenous ranges (e.g., Turvey et al., 2016; Stimpson et al., 2019). For example, in the UK, the muntjac deer *Muntiacus reevesi* (Putman, 2009), a native of China and Taiwan, was introduced to southern England in the late 19th century and became widespread from the mid-20th century through deliberate dispersal (Chapman et al., 1994). Perhaps the most notorious 20th century introduction of a mammal species is that of hippos (*Hippopotamus amphibians*) to Colombia during the 1970s, which now number ~ 80 individuals in the Magdalena River basin (Taylor, 2023), and extend over an area of 2000 km<sup>2</sup>, with the population predicted to expand to ~1500 individuals within a few decades (Castelblanco-Martínez et al., 2021). A palaeontological record would be likely, given the extensive fossil record of hippopotamids (e.g., Harris et al., 2008; Adams et al., 2021). Moreover, hippos dramatically change the ecologies of the rivers they invade, adding phosphorus and nitrogen to the waters that cause cyanobacterial blooms and eutrophication, a change likely to be evident in the sedimentary record (Castelblanco-Martínez et al., 2021). However, a move to sterilise the animals (Taylor, 2023) may mean that this is a short-lived and very localised record.

#### 2.4. Microorganisms

The most widely documented Anthropocene marker for shallow marine and estuarine deposits is the Japanese foraminifer *Trochammina hadai* which has become intercontinental in a few decades, transported via the ballast water of shipping (McGann et al., 2019; Fig. 2a, b). Unintentionally introduced along the Pacific coast of North America since at least the 1970s, it was first recorded in the San Francisco Estuary in 1983 (McGann et al., 2000, 2002, 2012). Subsequently it has been reported in Brazil (Eichler et al., 2016), Australia (Tremblin et al., 2022), and France (Bouchet et al., 2023). In the San Francisco Estuary it proliferated to become the most common benthic foraminifer and is a biostratigraphic marker of Anthropocene deposits there (McGann et al., 2002), especially in conjunction with the invasive Amur River clam (*Potamocorbula amurensis*), which arrived in San Francisco Estuary in 1986 (Himson et al., 2023). The lowest appearance datum of *T. hadai* in sediment cores from San Francisco Estuary is above that of the non-native ostracods *Bicornucythere bisanensis* and *Spinileberis quadriculeata*, that were introduced in the 1970s (Himson et al., 2023). The introduction of *T. hadai* via ballast water is a clear indicator of the rapid development of international shipping in the 20th and 21st centuries and of its associated risk of species invasion (Seebens et al., 2013).

As another example, the benthic foraminifer *Nonionella stella*, a calcareous, shallow infaunal species typically found in the oxygen-minimum zones of its native eastern Pacific, was first recorded in ~1985 CE in sediment samples from Gullmar Fjord, Sweden,

subsequently increasing in abundance during regional episodes of severe hypoxia (Polovodova Asterman and Schönfeld, 2016). In 2012, specimens of living *N. stella* were observed in bottom sediment of the Oslo Fjord, Norway (Deldicq et al., 2019), likely transported from Sweden to Norway via northward coastal currents. By 2013 and 2014 *N. stella* had reached the Skagerrak-Kattegat area and adjacent fjords (Polovodova Asterman and Schönfeld, 2016).

### 3. Fossil patterns of the Great Acceleration will reflect intensification of farming, industrialization and urbanization

Recent syntheses have demonstrated rapid change to lake ecologies globally (Hampton et al., 2018; Jenny et al., 2020) that reflect the Great Acceleration use of phosphorus and nitrogen fertilisers to increase food production, the deliberate introduction of non-native species as food sources, the incursion of non-native species via increasing transport connections, and climate change (Carpenter et al., 1998; Hall and Mills, 2000; Rühland et al., 2008; Hampton et al., 2018). Similar patterns of accelerating ecological degradation caused by nutrient enrichment, eutrophication and hypoxia in the post-WWII period are also evident in marine records of microfossils (Yasuhara et al., 2012).

The release of phosphorus and nitrogen fertiliser into lakes and rivers has increased greatly since the 1940s. Phosphorus loading rose in 50 out of 100 of the world's largest lakes from 1990 to 2010 (Jenny et al., 2020). Carpenter et al. (1998) estimated about 600 million tonnes of phosphorus was used for fertiliser between 1960 and 1995 and noted the rapid increase in nitrogen fertiliser from virtually zero in 1940 to 80 million tons per year in the 1990s. The latter has produced a marked perturbation to the nitrogen cycle recognised as a primary stratigraphical feature of the Anthropocene (Holtgrieve et al., 2011; Dean et al., 2014). Phosphorus and nitrogen penetrate aquatic ecologies via surface run-off and soil infiltration, and from sewage, while nitrogen compounds produced by various industrial processes and emitted from internal combustion engines enters aquatic bodies from the air as soluble and particulate matter, even in remote regions. The resulting eutrophication of lakes has changed the structure of both benthic and planktonic assemblages and commonly dovetails with signals of introduced non-native species (Fig. 2a, b) as evident in lakes worldwide. For example, in Lake Petén Itzá, Guatemala, rapid increases in human population and associated deforestation in the hinterland from the 1940s are associated with changes in sediment flux, increased input of nutrients – both phosphorus and nitrogen compounds especially after 1965 – and changes to the fossil algal and diatom assemblages that indicate eutrophication (Rosenmeier et al., 2004). There is a similar pattern of recent eutrophication in Guatemala's largest lake, Izabal (Obrist-Farner et al., 2019). In Africa, post-1960s changes in planktonic diatom assemblages in Lake Victoria from those dominated by *Aulacoseira* to those dominated by *Nitzschia* are associated with eutrophication, with the steepest rise in *Nitzschia* abundance occurring in the 1970s and 1980s (Verschuren et al., 2002; Stager et al., 2009; Fig. 2b). In Lake Chenghai, Yunnan Province, China, geochemical and sedimentary algal data from a 660-year and another 1000-year sediment core indicate increasingly eutrophic waters from the 1940s marked by an increase in cyanobacterial productivity and the occurrence of bloom-forming taxa (e.g., *Aphanizomenon*) that are related to both the growth of intensive farming and industry in the hinterland, and to sewage input (Wu et al., 2004; Yan et al., 2023). A similar pattern emerges from investigation of Lake Taihu in Jiangsu Province (Wu et al., 2007). In Lake Kutubu, Papua New Guinea, changes to algal communities in the 1980s reflect eutrophication, likely from increased livestock in the lake's hinterland, though also resulting from geochemical changes associated with nearby mining. There, changes to diatom assemblages also likely reflect the loss of some of the lake's aquatic plant communities (Long et al., 2022; Fig. 2b).

Lake Erie is the most susceptible of the North American Great Lakes to anthropogenic eutrophication, being shallow with an intensively farmed and industrialized catchment, and therefore responds quickly to

a changing climate. Diatom assemblages from sediment cores covering the past 200 years show several significant water-quality changes from 1935 CE onwards, with the effects of increasing temperature and dissolved silica becoming apparent in the 1980s (Sgro and Reavie, 2018). The chironomid record also reflects the hydrographic development of Lake Erie, with a major assemblage transition occurring in the central basin at ~1954 CE indicating a decline in bottom-water dissolved oxygen levels since the mid-20th century (Perlov et al., 2023). By such tracking of ecological degradation (Wilkinson et al., 2014), a post-1950 interval can be widely recognised in lake sediments (see also Wolfe et al., 2013).

Changes to lake ecologies also reflect the rise in atmospheric CO<sub>2</sub>. Even slight increases can impact photosynthesis, especially in algal groups with weak carbon concentration capacity and Rubisco specificity, notably in green algae (Low-Décarie et al., 2015). A subtle increase in green algal palynomorphs was noted in varved sediments deposited in Crawford Lake since the mid-20th century (McCarthy et al., 2023) and more widespread patterns have been noted in North American and European lakes (Pilkington et al., 2021). However, the major micropalaeontological difference in Crawford Lake is in the chrysophyte record (Gushulak et al., 2022; Marshall et al., 2023). Abundant palynomorphs identified as loricae and cysts of the chrysophyte *Dinobryon divergens* (= 'Cyst 3' of Rybak et al., 1987) characterise the Anthropocene epoch (McCarthy et al., 2023). *Dinobryon* loricae are rare in sediments from the earlier part of the two-century-long Euro-Canadian record of Crawford Lake and unrecorded from the late 13th through 15th century Indigenous agricultural settlement. Chrysophytes are one of the few groups of chromalveolate algae that lack a carbon-concentrating mechanism based on active transport across membranes, and so rely on passive diffusion of CO<sub>2</sub> to fix carbon (Giordano et al., 2005). Although freshwater pCO<sub>2</sub> varies across systems and is controlled by a diverse array of factors (Hasler et al., 2016), the concentration of loricae of the chrysophyte *D. divergens* in palynological preparations of varved sediments deposited since 1952 CE tracks CO<sub>2</sub> emissions. At two other sites considered by the AWG, mid-20th century changes in lake communities are also evident: at Searsville Lake in California, the 1948–1952 CE stratigraphic interval shows rapid decline of rotifers, algae and protozoa, and markedly increased abundance of the cladoceran *Ceriodaphnia* (Stegner et al., 2023); and at Sihailongwan Maar in China, significant phytoplankton community changes occur from 1950 CE (Han et al., 2023), possibly linked with climate change.

Stratigraphical signatures of Anthropocene ecological change in lakes can be correlated to those in marine basins resulting from the recent input of nitrogen and phosphorus fertiliser and consequent spread of 'dead zones'. In the Baltic Sea this left a clear sedimentological change from grey silty muds prior to the 1950s to unbioturbated, organic-rich hemipelagic sediments prevailing thereafter, a transition also associated with biomarker and geochemical changes (Kaiser et al., 2023; though see Moros et al., 2023 for an alternative interpretation). In the Gulf of Mexico, naturally occurring hypoxic events have been amplified by the input of fertilisers since the 1950s, giving rise to opportunistic, hypoxia-tolerant assemblages of benthic foraminifera that are adapted to high-nutrient and low oxygen conditions (Osterman et al., 2005) and amongst ostracods a reduction in diversity and increased abundance of hypoxia-tolerant species (Ruiz et al., 2005). Similar patterns of eutrophication of waters in the Seto Inland Sea of Japan result from the input of urban, industrial, and agricultural pollution changing patterns of benthic ostracod and planktonic diatom assemblages from the 1950s onwards, with taxonomic and abundance changes that signal eutrophication (Irizuki et al., 2018), and which are also evident in Osaka Bay (Yasuhara et al., 2007). Changes to diatom assemblages at Beppu Bay provide a correlatable signal of the Anthropocene in Japan (Kuwaie et al., 2023). Further changes to the Seto Inland Sea assemblages from the 1980s reflect a reduction in pollution and the return of more oxygenated sea bottom environments (Irizuki et al., 2018), a pattern of ecological recovery when there has been decisive human intervention

that is also evident in a few other marine sites (Yasuhara et al., 2012). Wilkinson et al. (2014) record coastal examples where certain dinoflagellate cyst species abundances and/or heterotrophic/ autotrophic ratios increase in line with cultural eutrophication in several Norwegian and Swedish fjords, the Adriatic Sea (Italy), Massachusetts (USA), St. Lawrence Estuary (Canada) and Tokyo Bay (Japan). Although many of these areas show changes initiating in the mid-19th century, marked changes are observed in the early to mid-20th century.

#### 4. Fossil patterns of the Great Acceleration will reflect global consumption

Here we address the likely fossil signature of landfills, which contain large quantities of organic waste, whose degradation contributes to global methane production, while preserving recalcitrant organic tissues such as lignin over long timeframes (Bogner and Spokas, 1993). We focus on plant products, including the seeds of internationally traded fruit now widely present in landfills as proxies for the rapid globalization of food production during the Great Acceleration. Additionally, forest products, which are often the most significant components of landfills, show how reconfigured organic materials of the Great Acceleration, such as medium density fibreboard (MDF), will leave a distinctive Anthropocene signal. We review too, the likely fossil signature from terrestrial and marine animals.

##### 4.1. Seed cases (endocarps)

Seed cases are amongst the most recalcitrant of organic tissues, contain high percentages of woody tissue (lignin), and are commonly preserved in the fossil record (e.g., Cevallos-Ferriz and Stockey, 1991). We focus on four large and robust seeds – avocados, coconuts, mangos and peaches – known to have fossil or archaeological records. We note that many other fruits with recalcitrant tissues (e.g., sunflower seeds, palm kernels, walnuts, coffee husks, etc.), whose production rapidly accelerated in the mid- to late 20th century, will also produce a fossil record. Seeds are a major waste product of a global fruit industry that has altered the distribution pattern of seed-bearing plants. They symbolize the profligacy of the Great Acceleration, particularly as they represent materials that could be recycled for many uses, including fuels and construction (e.g., Wechsler et al., 2019). We explore their distinctive fossil record, extending far beyond the natural range of their parent plants.

The avocado *Persea americana*, originally native to Central and South America, is now produced across the world in tropical and subtropical regions. Production increased from less than a million tonnes in 1960, to more than 8 million tonnes in 2021, a time interval coinciding with the commercial export of this fruit to such countries as the UK, USA and Canada; the most rapid increase has been in the last decade (FAOSTAT, 2023, Fig. 4). Avocado cultivation covered over 800,000 ha in 2021 (FAOSTAT, 2023; see also Sommaruga and May Eldridge, 2021). Whilst much of the avocado fruit is perishable, its high fossilization potential lies in the recalcitrant endocarp of the ‘seed’ that sits at the core of the fruit and represents between 25 and 35% of the fruit’s mass (Domínguez et al., 2014; Tesfaye et al., 2018). Avocado endocarps are preserved in archaeological contexts, providing evidence of its domestication – and of the preservability of the seed over millennia (Smith, 1966; Fuller, 2018). Nowadays, avocado seeds are mainly disposed of in landfill, both in the regions where the fruits are grown, and where the fruit is imported. The distribution of *P. americana* is already highly distinctive with respect to its native environmental range of Mexico and Central America, first spreading to tropical and subtropical regions throughout the world, and then subsequently its fruit being transported into the temperate regions (Fig. 4), with avocado seeds entering landfills in southern and northern Europe, northern Asia, the USA and Canada, and New Zealand.

Coconuts (*Cocos nucifera*) probably originated in South and Southeast Asia (Baudouin and Lebrun, 2009). Fossil seeds referred to the

genus *Cocos* are known from the Eocene of India (Singh et al., 2016) and from the Miocene of New Zealand (Ballance et al., 1981). Coconuts dispersed widely in the tropical Indian and Pacific oceans in prehistoric times through their buoyant seeds (Harries, 1990). They are cultivated widely in the tropics, and world production shows an upwards trend with just under 24 million tonnes harvested in 1961 and over 63 million tonnes in 2021 (FAOSTAT, 2023, Fig. 4). Coconut endocarps are highly durable on the land surface where they take a decade to decay (Nunes et al., 2020; Rosli and Jumali, 2022). Commonly the husks are also burned (e.g., Obeng et al., 2020), leading to further potential for entering the fossil record in a recalcitrant carbonized form. In landfill, the lignified tissues of coconuts have high preservability over long time frames.

Mango likely originated in South and Southeast Asia, but is now grown in tropical and subtropical regions from Central and South America to the Philippines. Its seeds are preserved in archaeological contexts that mimic those of landfill (Cherian, 2012). Although mangos have been cultivated around the world since the 19th century, it was through the development of more durable cultivars of *Mangifera indica* in the mid-20th century, such as the ‘Kent’ and ‘Tommy Atkins’ in Florida in the 1940s and 1950s (Brooks and Olmo, 1952; Campbell and Campbell, 2006), that this fruit became widely exported. Its increased production follows that of avocados (Fig. 4), more than tripling between 1990 and 2020, with more than 55 million tonnes produced in 2019 (Manhongo et al., 2021). At present, mango seeds – which represent up to 45% of the fruit’s weight (Yousef et al., 2021) – are largely disposed of in landfill. The endocarps of these seeds, like those of avocados and coconuts, have been transported far beyond the areas where they grow.

Peaches (*Prunus persica*) are native to China, and there is a fossil record of *Prunus* seeds from the Late Pliocene (Su et al., 2015). The plant has been cultivated in Asia for thousands of years and reached Europe in the first millennium BCE (McNeill, 2011). Its global production has also accelerated in the second part of the 20th century, from a little over 5 million tonnes in 1961 (including nectarines), to nearly 25 million tonnes in 2021, production particularly increasing in the first two decades of the 21st century (FAOSTAT, 2023, Fig. 4). The peach endocarp represents about 5 to 12.5% of the fruit’s weight and very many find their way into landfill each year (e.g., Lopičić et al., 2017; Wechsler et al., 2019; Rudke et al., 2023) well beyond the natural geographical range and environmental tolerance of the parent species.

##### 4.2. Forest products

Fossilised seeds preserved in landfills will be accompanied by novel reconfigured tree materials that signal the Great Acceleration. Forest products commonly represent the bulk of landfill, and comprise paper, newspaper, paperboard, and engineered wood products that include those from demolished buildings (Micales and Skog, 1997; Ximenes et al., 2018). Estimates in the 1990s suggested as much as 30–40% of landfills in the USA were taken up by paper alone. Such waste more than doubled in the USA from the 1960s to the 1990s (Micales and Skog, 1997) and in UK landfills paper and card showed an eight-fold increase between 1892 and 1999 (Ford et al., 2014). An Anthropocene exemplar of forest products is medium- and high-density fibreboard (MDF/HDF) which is now widely used for flooring and furniture. MDF was invented in the 1960s, making its presence in sedimentary deposits a clear marker of the Anthropocene (Fig. 1). Its production increased from ~8 million m<sup>3</sup> in 1995 to over 111 million m<sup>3</sup> in 2021 (FAOSTAT, 2023; Fig. 4). Most MDF waste has gone into landfill (e.g., Farjana et al., 2023; Zimmer and Bachmann, 2023). As the wood fibres are resin-bound and include preservatives to increase decay resistance, their preservation potential is enhanced (Wang et al., 2013). The distinctively engineered MDF will be joined in landfill by many other technofossils – artefacts of human manufactures – that demarcate the Anthropocene (Zalasiewicz et al., 2014, 2019).

#### 4.3. Animals

Agricultural intensification has accelerated meat production from ~75.6 million tonnes in 1961 to 352.1 million tonnes in 2021, of which over two-thirds are pigs and poultry (graphs updated to 2021 in Ritchie et al., 2017), with a standing crop of a billion or more of each of cattle, sheep, goats, and pigs (Gilbert et al., 2018), and over 21 billion chickens (Bennett et al., 2018). Such patterns – especially the concentration of biomass in a few large terrestrial mammal species (Bar-On et al., 2018; Greenspoon et al., 2023) – have no known precedent in terrestrial vertebrate evolution. Domesticated animals and cultivated plants now utilize half of the habitable surface of the land (Ritchie, 2017 and references therein). Therefore, a geologically long-term marker of humanity will be an ‘acme biozone’ (a stratigraphical interval where certain taxa become much more frequent) of human skeletons and those of the animals we have domesticated (Plotnick and Koy, 2020), co-occurring with the pollen record of domesticated plants. In part, this record will be enhanced by the many novel taphonomic settings constructed by humanity, including graveyards, gardens, animal burials, dams, and landfills (Plotnick and Koy, 2020; Vaverková and Koda, 2023). These settings became more common since 1800 CE, and especially so in the 20th century, in what Plotnick and Koy (2020) refer to as the Anthropocene *sensu lato*, resulting from the rapid population growth of humans and of the animals we consume. The palaeontologically distinctive post-1950 broiler chicken is now consumed in tens of billions each year (Bennett et al., 2018). Its rapidly accumulating bones in landfill, with patterns of dismemberment reflecting regional culinary habits, exemplifies these patterns, which mirror those of the Great Acceleration in production and consumption (Steffen et al., 2015).

Yet more recent developments in fisheries and aquaculture have reconfigured coastal ecologies in many regions of the world, including the introduction of non-native mollusc taxa such as the Pacific oyster (Fig. 3g) and the Mediterranean mussel (Table 1). Aquaculture and fisheries accounted for 178 million tons in 2019 (FAOSTAT, 2021). Much of the annual waste material, comprising ~8 million tons of crustacean carapaces and over 10 million tons of mollusc shells, ends up in landfill or is dumped at sea (Topić Popović et al., 2023). Furthermore, the import of non-native molluscs often impacts on indigenous ecosystems, through disease introduction, and via competitive replacement where non-native taxa escape and naturalize (Gallardi, 2014).

#### 5. Extinction as a symptom of the Great Acceleration

In concert with accelerating changes to the biosphere, species extinctions have accelerated to levels much higher than background (Pimm et al., 2014), especially since 1900 CE (Ceballos et al., 2015). Population losses have been even greater: while many species are not yet extinct, contractions of their populations and ecological ranges threaten global biodiversity, potentially leading to a sixth mass extinction within a few centuries (Barnosky et al., 2011; Ceballos et al., 2017; WWF, 2022) and to a state shift in the biosphere (Barnosky et al., 2012). Some groups, including molluscs, are already registering a major, rapid (centennial-scale) and global phase of extinction (e.g., Cowie et al., 2022) and evidence of this extinction is manifested in the fossil record, notably of island faunas (Goodfriend et al., 1994; Burney et al., 2001). Lake ecosystems with an influx of non-native species (Ricciardi et al., 1998), and river deposits where impoundment has altered both upstream and downstream ecologies (Vaughn and Taylor, 1999) are also likely to be major recorders of mollusc extirpation/extinction, as is the fragmentation of wetland ecologies (Pasterski et al., 2020). In these sedimentary contexts, the lowest occurrence datums of non-native species such as zebra mussels may be closely stratigraphically associated with the highest occurrence datums of indigenous species such as unionid mussels (e.g., Ricciardi et al., 1998).

Whilst there is an extensive observational record of current extinctions, its transition into the sedimentary record is more subtle. Plotnick

et al. (2016) have noted how only a small percentage of recent vertebrate extinctions have a fossil record. Nevertheless, predicted ecological patterns in the novel ecosystems of the Anthropocene suggest there will be elevated rates of extinction (Pandolfi et al., 2020), so that species translocations – as identified above – will be closely associated with species extinctions in the fossil record.

A near-future major extinction is likely to preserve an extensive fossil record if it affects major structures that are both biological and geological, such as coral reefs (Pandolfi and Kiessling, 2014). Previous major extinctions of reef builders are associated with rapid climate change, notably global warming, often linked to large igneous provinces (LIPs) such as the Siberian Traps during the late Permian at ~252 Ma, the Central Atlantic Magmatic Province (CAMP) of the Late Triassic at ~201 Ma, and the Paleocene-Eocene Thermal Maximum (PETM) at ~56 Ma. Following such events, reef extent was restricted, and the end Permian extinction resulted in a reef gap of ~8 million years (Pandolfi and Kiessling, 2014; for LIP-dating see Kasbohm et al., 2021). The Frasnian/Famennian extinction of the Late Devonian (~372 Ma) produced a shallow-water coral reef gap of ~140 million years, until the first scleractinian corals appeared in the mid-Triassic to form large reefs from the late Triassic onwards (with the CAMP-setback mentioned above (Veron, 1995, 2008; Stanley, 2001; Leinfelder, 2019)). For other events, such as the PETM, the extent of reef loss and diversity was much lower, but nevertheless in many regions such as in the Paleotethys Ocean, coral reef systems were replaced by those made of benthic foraminifera (e.g., *Alveolina*, *Nummulites* and *Orbitolites*) leaving a distinctive fossil record (Afzal et al., 2011). The major difference between former reef crises and that of the present is the rate of change. Thus, widespread coral bleaching events, recorded from the 1980s (Baker et al., 2008), now occur frequently (e.g., in the South Pacific in at least six years within a 20-year period) (Hughes et al., 2019; Virgen-Urcelay and Donner, 2023). Bleaching and coral death is mostly attributed to rising sea temperatures, projected to increase given current greenhouse gas emission trends (Jones, 2023) and are increasingly decoupling from El Niño-events (McGowan and Theobald, 2023), to suggest this pattern of coral bleaching and death will accelerate (Hoegh-Guldberg et al., 2023; Nogrady, 2024). Scleractinian corals, adapted to oligotrophic waters, are also susceptible to pollution as well as the impacts of rising atmospheric CO<sub>2</sub> (Hughes et al., 2017; Gove et al., 2023).

Given sufficient time for adaptation, modern coral reef systems might respond to climate change by migration to higher latitudes (Yamano et al., 2011), adaptation through hybridization or thermal responses (Marzoni et al., 2023; Morais et al., 2023), modifications of coral community composition and function (Zinke et al., 2018) and extinction. Often overlooked, atavistic coral taxa, such as relic species from the Neogene (e.g., Brazilian Abrolhos reefs; Leão and Kikuchi, 2001), several *Porites* and *Agaricia* species in the Caribbean (e.g., Almirante Bay, Leinfelder et al., 2012; Seemann et al., 2012), the Mediterranean *Cladocora caespitosa* (Kersting and Linares, 2019; Kersting et al., 2023), and several Pacific species from Palau and American Samoa adapted to lower pH (Shamberger et al., 2014), or higher temperatures (Thomas et al., 2018), might serve as a stock for such potential adaptation. Predicted responses of reefs to 21st century climate change range from severe loss of reef area, to limited loss, but at the regional level are likely to show patterns that will leave a distinctive fossil record, for example the potential loss of *Acropora* in Indo-Pacific reefs (Pandolfi et al., 2011). Even with new management and protection strategies, reefs may go through a long lasting ‘atavistic’ phase (sensu Leinfelder, 2019, see also Hoegh-Guldberg et al., 2009). The current trajectory is leading to a “post reef-Anthropocene” with few to no shallow-water coral reefs and possibly widespread microbial-sponge reef mounds and some similarities to the fossil record of the Late Carboniferous–Permian transition (Leinfelder, 2019 and references therein).

Other biodiverse ecologies face considerable threats in the 21st century, including those of deltas being inundated by rapid global sea-

level rise compounded by sediment starvation resulting from upstream engineering (Giosan et al., 2014), islands susceptible to sea-level rise (Ortiz et al., 2023), forest ecosystems exposed to fire (Armenteras et al., 2021; Parisien et al., 2023) and semi-enclosed marine basins subject to rapid warming (Albano et al., 2021). Plans to mine the ocean floors for rare earth metals will degrade biodiversity hotspots there (Niner et al., 2018). Changes to polar ecologies resulting from rapid global warming risk significant impacts on ecosystems (Pantiukhin et al., 2024) and increased extinctions of many species reliant on seasonal sea ice cover, including those that live on the ice, in the water column below it, and on the seabed, where the reduction of ice and increased light penetration can have dramatic impacts on benthic communities (Robinson, 2022). Projected threats include those to iconic species including the polar bear (*Ursus maritimus*) in the Arctic (Hunter et al., 2010) and the emperor penguin (*Aptenodytes forsteri*) in the Antarctic (Trathan et al., 2020). And, in terrestrial polar habitats, increasing surface temperatures will favour the spread of vascular plants that can outcompete the local cryptogamic vegetation (Robinson, 2022 and references therein). All the above effects have the potential to leave a substantial palaeontological record of change.

Beyond 2100 the threats to the biosphere are projected to intensify as global mean surface temperature rises to encompass a range from Pliocene-like to Eocene-like climate conditions, depending on the sensitivity to current emissions and the pattern of future emissions

(Burke et al., 2018; IPCC, 2021; Lyon et al., 2021; Hansen et al., 2023). This may result in significant geographical shifts in agriculture, and as with previous changes, this will be recorded in the palynological record. In the worst scenarios whole ecosystems, like that of the Amazon rainforest, may collapse (Lyon et al., 2021), triggering significant regional extinctions. Rapid changes to marine ecosystems will occur as tropical species-diversity drops regionally as thermal tolerances are exceeded, as warm-water species migrate to higher latitudes, and as higher latitude species become extinct as their physiological tolerances are undermined (Payne et al., 2023). Changes in geographical distribution, including local extinctions of marine zooplankton communities in the North Atlantic may cause cascade effects through the structure of food webs (Harris et al., 2015; Villarino et al., 2015), that have already disrupted patterns of cod abundance (Richardson, 2008; Beaugrand et al., 2009). In the southern hemisphere, reduced sea ice cover will affect krill abundance with potentially widespread impacts on whales, birds, seals and fish (Richardson, 2008). Many larger animals, already over-exploited by humans, are at particular extinction risk and there will be considerable losses to functional diversity within ecologies. This will leave a profound Anthropocene signal (Payne et al., 2016), including a marine megafauna extinction that will prolong the continuing megafauna extinctions on land, with the potential loss of iconic animals such as the great white shark (*Carcharodon carcharias*) and whale shark (*Rhincodon typus*), and associated cascade effects that will negatively

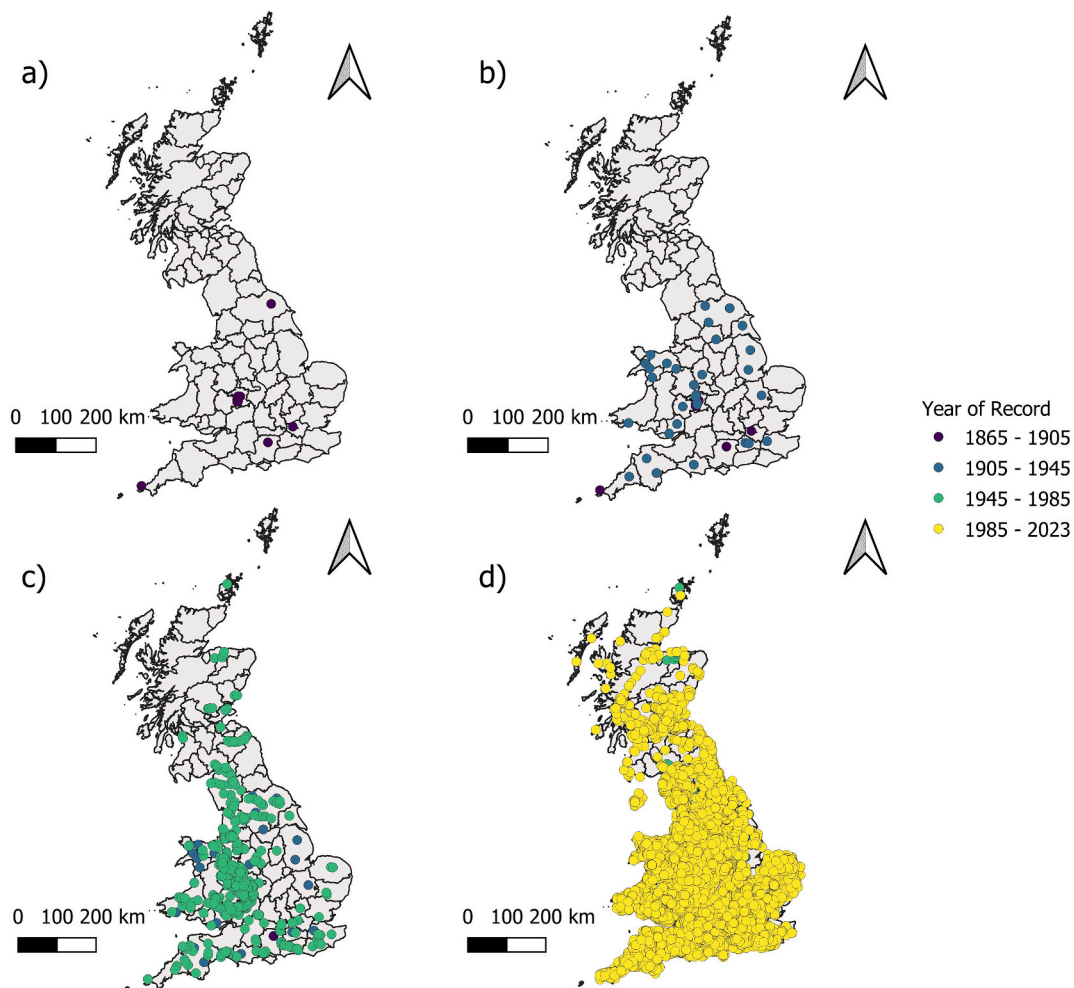


Fig. 5. Maps of Great Britain displaying occurrence data of Himalayan balsam (*Impatiens glandulifera*) from: a): 1865–1905, b): 1905–1945, c): 1945–1985, d): 1985–2023. Occurrence data downloaded from the National Biodiversity Network (NBN) Atlas at <https://nbnatlas.org> accessed on December 1st, 2023. For full details of data providers, please see the supplementary file. Map contains Ordnance Survey data © Crown copyright and database right 2023. All the data used in the figure have either CCO, CC-BY or OGL licence. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



impact ecologies (Pimiento et al., 2020).

## 6. Long-term survivability of the Anthropocene fossil record

The fossil record of the Anthropocene is accumulating in both natural and human sedimentary archives. Uniquely human sedimentary settings include landfills, graveyards (examined in detail by Plotnick and Koy, 2020), modified stretches of rivers, canals and lakes, reservoir construction, and dredged and modified coasts and bays.

### 6.1. Landfills

The amount of solid waste produced by households, commerce, industry and construction is growing, and now ~7–9 billion tonnes annually (Wilson and Velis, 2015; Chen et al., 2020), with urban municipal waste growing particularly steeply (Hoorweg and Bhada-Tata, 2012; Hoorweg et al., 2014; Chen et al., 2020). This amount approaches the annual mass of all sediment moved by rivers prior to human impacts (Syvitski et al., 2005), suggesting that landfills are a substantial and long-lived global geological deposit. Much of the solid waste goes into landfills and dumps, some extensive, with an estimated ‘several million’ such sites globally (Vaverková and Koda, 2023). Even in the small country of England (~130 k km<sup>2</sup>) there are more than 20,000 such sites that map onto the major population centres (Brand et al., 2018, Fig. 1), ~1200 of these within the coastal zone (Nicholls et al., 2021). The map of the USA shows correspondingly abundant landfill sites, especially in the east (Cannon, 2021). Within land-locked sites, some of the biodegradable waste in landfills may be decomposed by bacteria to produce methane, but recalcitrant materials including lignin may survive long into the future (Micales and Skog, 1997; Ximenes et al., 2008, 2018; Head et al., 2021), especially in the kinds of sealed landfills developed from the 1950s onwards. There, degradation of lignin-rich materials may be very slow, with reports of readable newspapers in landfill from 1949 (Meegoda et al., 2016). Many landfill sites within continents will survive as structures over geological timescales, producing a direct stratigraphical feature of the Anthropocene as a series of stratified units with unconformities at their base (Vaverková and Koda, 2023, Fig. 2). Within individual landfills though, a stratigraphy might be developed by the appearance of different materials such as avocado seeds and forest products that could be used to correlate Anthropocene deposits widely. As landfills have also been used to dump invasive molluscs removed from inland waterways, in masses sometimes amounting to many hundreds of tonnes per year (McLaughlan et al., 2014), they will also preserve a ‘displaced’ environmental signal. For the thousands of landfills situated along coastlines or adjacent to rivers, recalcitrant material within them may subsequently be reworked into lacustrine and shallow marine deposits (e.g., Beaven et al., 2020; Nicholls et al., 2021). The longest record of such deposits will likely be preserved in marine basins.

### 6.2. Modified aquatic systems

Present aquatic ecosystems are likely to represent a major geological reservoir for biotic remains, just as the fossil record is dominated by aquatic fossils (Benson et al., 2021). This is because most such ecosystems are present within net sinks for sediment accumulation and are not in upland areas that are mostly subject to erosion. Particularly widespread are human-constructed lakes, with ~16.7 million artificial reservoirs worldwide (Lehner et al., 2011), most of which were emplaced behind dams from the mid-20th century (Syvitski and Kettner, 2011; Syvitski et al., 2020), and which will provide a basal marker evidenced by an unconformity and followed by a highly resolved colonization history, for example as is evident at Searsville Lake in California (Stegner et al., 2023).

Transportation and irrigation canals, modified parts of rivers and lakes, and reservoirs created behind dams preserve their own distinctive

sedimentary patterns (e.g., Russell et al., 2021) and palaeontology, just as rivers and lakes have preserved an extensive geological record in deep time (e.g., Anadón et al., 1991; Davies and Gibling, 2010). Many canals, even those from antiquity, are incised into the underlying geology, and when engineered through lowland landscapes, or within large continents, they readily accumulate sediment. Many ancient canals are preserved in the archaeological record by silting (e.g., Sneh et al., 1975; Wang et al., 2006), and modern canals are subject to the same processes (e.g., Athar and Ayaz, 2022; Saparov et al., 2023). Fossil fauna and flora occur within, or are closely associated with, ancient canals. For example, preserved molluscs including snails indicate the development of irrigation systems and their adjacent wetlands in archaeological contexts as diverse as Mesoamerica (Beach et al., 2009; Cajigas et al., 2020), North Africa (Moshier and El-Kalani, 2008) and China (Storozum et al., 2018). Plant materials including pollen also preserve in such settings (e.g., Li et al., 2012; Bernigaud et al., 2014). Therefore, plants and shell-bearing invertebrates introduced to modern canal-, lake- and river systems are likely to preserve a comparable record to those of earlier deposits.

Modern engineered and interconnected waterbodies often accumulate invasive species such as molluscs at very high densities (Cohen and Carlton, 1995; Corenblit et al., 2013; Himson et al., 2020; Karatayev and Burlakova, 2022) with canals being one of the clearest conduits for their spread (e.g., Pimentel, 2005; Balzani et al., 2022), both through the water within them, and along canal banks (Fig. 3a, b, c, l). While the spread of non-native species via canals is evident since the 18th century, rapidly growing maritime trade and its penetration into continental areas via major canal works in the latter part of the 20th century has facilitated this spread intercontinentally (e.g., Mills et al., 1994; Leuven et al., 2009; Himson et al., 2020). In some river basins, such as the Rhine, there is a clear Anthropocene signal from the accelerated rate of connectivity in the post-WWII interval (Leuven et al., 2009). Major engineering projects such as the St Lawrence Seaway in North America and the Rhine Main Danube Canal in Europe are, for example, implicated in the rapid spread of the highly invasive zebra mussel (Mills et al., 1994; Müller et al., 2002). Since the late 1980s these have accumulated abundantly in many of the large lakes of North America (Benson et al., 2023) where they are likely to provide an important fossil record of the Anthropocene (Fig. 3d), that will also be associated with the extinction of indigenous molluscs (Ricciardi et al., 1998). For example, in the Soulages Canal, a disused waterway in Quebec, invasive zebra and quagga mussels have dominated the mollusc biota since the 1990s, with the latter dominating shell accumulations in the canal’s bottom sediments (Ricciardi and Whoriskey, 2004). The rapid spread of quagga mussels (Fig. 3c, l) through the rivers, lakes and canals of Europe since the 1940s may provide a similarly useful Anthropocene marker there (Matthews et al., 2014), as does the later spread of Asian clams through European waterways since the 1980s (e.g., Elliott and zu Ermgassen, 2008; Minchin, 2014). Asian clams can be recovered in huge numbers from river sediments (Fig. 3a, b) leaving a distinctive biostratigraphical signature of the Anthropocene in European canal and river settings (Himson et al., 2020).

Rivers and canals are places where invasive plants accumulate. The South Asian Himalayan balsam (*Impatiens glandifera*, Fig. 3e) is now widely distributed through the northern hemisphere and is also present in New Zealand (Coakley and Petti, 2021). It was spread around the world in the 19th century as an ornamental plant. In Britain it was introduced in 1839, and had naturalized by the middle of that century, encouraged by its description as “one of the many desirable hardy plants of the North of India which have of late been introduced” (Anon cited in Beerling and Perrins, 1993). An account of the deliberate spread of this plant for ornamental purposes by human interlocutors is given by Rotherham (2000), including taking the seeds on holiday from the UK to France and Spain. Himalayan balsam favours disturbed ground, and wetland areas, and has migrated along the banks of rivers and canals, using water to spread its seeds (Beerling and Perrins, 1993). It is also known to spread in damp ground adjacent to roads (Follak et al., 2018).

Dead plant materials have been noted as contributors to river sediment, including robust stems that are likely to decay more slowly (Coakley and Petti, 2021). Pollen from Himalayan balsam occurs in the concentrated feces of bats in caves (Leroy and Simms, 2006), suggesting its wider presence in sedimentary deposits. In Britain, the species had a limited geographical distribution in the 19th century, but in the latter part of the 20th century became very widespread (Beerling and Perrins, 1993; Fig. 5).

Humans have also been modifying the coastal zone since antiquity, and ancient harbours and ports and the sediments therein preserve a palaeontological record of such influence, for example the use of the gastropod *Murex* for purple dye in the Roman Empire (Schörle, 2010) or the introduction of non-native bivalves (*Mya arenaria*) into the modified harbour of the Hanseatic port of Stralsund, Germany during the early modern era (Daniel et al., 2019). While archaeological and historical contexts record regional changes, sedimentary deposits accumulating in the shallow coastal zone at present will record a global effect. This is evident, for example, in the spread of the invasive foraminifer *Trochammina hadai* along the California coast, and its subsequent recognition in the coastal zone of Brazil, Australia and France over the past four decades (Table 1, Fig. 2a, b), at each locality providing a possible fossil record of the Anthropocene (e.g., Himson et al., 2023). Many other taxa have spread into shallow marine settings during the mid- to late 20th century.

Major inter-ocean canal systems including the Suez and Panama have facilitated the spread of non-native marine species between the Indian Ocean and Mediterranean, and the Atlantic and Pacific oceans respectively. The Lessepsian invasion of the Mediterranean, by means of the Suez Canal opened in 1869, enabled a migration route for organisms by self-dispersal, as stowaways on international shipping (Katsanevakis et al., 2020), and via ichthyochory (ingestion and defecation of viable individuals; Guy-Haim et al., 2017). The Mediterranean marine record shows a widespread signature of such invasions, for example through the spread of benthic foraminifera (Weinmann et al., 2013). At present, the Red Sea foraminiferal species *Amphistegina lobifera* is reported to have invaded the Mediterranean Sea through the Suez Canal (though see Meriç et al., 2016 for an alternative interpretation) and this species is moving progressively westwards (now to Sicily and Malta). *Amphistegina lobifera* reduces native diversity and species richness, transforms the composition, grain size and chemistry of sediments from predominantly siliceous to carbonate deposits, and triggers changes in ecosystem functioning (Stulpinaite et al., 2020). An unusual earlier Mediterranean invasion of *A. lobifera* occurred before 1908 CE. The re-invasion of *A. lobifera* took place in the mid-1940s, followed by a prolonged period of low density, until it became abundant and was first detected alive in the Maltese archipelago in 2006 CE (Mancin et al., 2023). Sea-temperature constraints on a second Red Sea species, *Amphistegina lessoni*, have so far prevented its successful incursion into the Mediterranean, but it is predicted to spread as the eastern Mediterranean warms (Titelboim et al., 2019). Such effects will coincide with global changes to planktonic foraminiferal assemblages that result from climate change, and which are already leaving a distinctive signal in seabed sediments (Jonkers et al., 2019), and with wider changes to phytoplankton and zooplankton assemblages (Benedetti et al., 2021). Stratigraphically these changes are coupled with current degradation (Goreau and Hayes, 2024) and likely near-future loss of many coral reef ecosystems as a widespread marker of Anthropocene environmental change, echoing the deep-time reef record (Pandolfi and Kiessling, 2014), and will also be coincident with the ingress of many non-native species into coastal ecologies resulting from international shipping (Seebens et al., 2013).

## 7. What will a future biostratigraphical record of the Anthropocene look like?

Patterns of biotic change associated with the post-WWII Great Acceleration are already leaving a widespread and global palaeontological

pattern. This includes: (1) biotic homogenization, substantially more extreme now than in the transition from the Pleistocene to Holocene floras and faunas; (2) current rates of extinction higher than the end-Pleistocene, with a second phase of megafauna extinction underway, and survivors confined to small areas; (3) overwhelming replacement of wild animals by humans and domestic animals, most of which occurred in the last 70 years; (4) rapid intercontinental translocation of non-native species coincident with local extirpation of indigenous taxa; (5) rapid changes to lake and marine ecosystems globally; and (6) a record of biota preserved beyond their ecological range associated with the international trade in foodstuffs and forest products (Figs. 1, 4). Some of these patterns have precedents in the fossil record, for example the widespread translocation of non-native species associated with extinction (Stigall, 2012). But as a whole, the post-WWII Great Acceleration signature is unique to the mid-20th century Anthropocene and sharply distinct from previous records of biotic change. Near-future changes may produce yet more significant markers of the Anthropocene, through palaeontological change associated with the loss of metazoan reefs in the oceans, coastal and island ecospace, and of tropical forests.

At present, biogeographical patterns can be used to identify discrete regions of the world with unique associations of organisms that have developed over millions of years through geographical isolation. In a similar way, palaeobiogeographical evidence has been used extensively in the recognition of past continental distributions, helping to reconstruct plate tectonic histories (Torsvik and Cocks, 2016). However, superimposed on the modern biogeographical pattern is the increasing translocation of non-native organisms, at a scale and speed without precedent in Earth's history. Whilst humans are implicated in species translocation from the Late Pleistocene onwards (see summary in Williams et al., 2022a), the process of translocation has accelerated through the past 200 years (Seebens et al., 2017) to begin to homogenise the global flora and fauna (Samways, 1999). Homogenization can be recognised at the regional (e.g., Rahel, 2000; Holmes et al., 2023; Wani et al., 2023) and global scale (Capinha et al., 2015; Seebens et al., 2017, 2018, 2021; Daru et al., 2021), leading some authors to refer to a 'New Pangaea' (Mergey et al., 2006; Baiser et al., 2012; Leroy et al., 2023). Supercontinent Pangaea existed ~300–200 million years ago when most of Earth's large landmasses were united, thereby facilitating the inter-regional migration of species. Its break-up resulted in the present global configuration of continents.

The global patterns of translocated species in the 'New Pangaea' look wholly different from those of the past. For example, existing geographical patterns still bear the imprint of distinct biogeographical provinces, even in regions where there have been significant species introductions. Thus, there is a European flora and fauna discrete from that of South America, but now joined by thousands of non-native species. In some cases, introduced species preserve a fossil record of the wholesale reconfiguration of ecosystems, as in San Francisco Estuary (Cohen and Carlton, 1998; Himson et al., 2023). Given the dispersal limitations of some of the translocated organisms – *Trochammina* uses pseudopodial locomotion of a few mm/h and migration of only a few cm in a lifetime (Gross, 2000; Thibault de Chanvalon et al., 2015; Jauffrais et al., 2016) – this signal requires a unique intermediary (i.e., human) form of transport. Also unique are the parts of fossil organisms that give false ranges of their environmental tolerances, such as concentrated masses of seeds without associated evidence of the parent plant (roots, bark, leaves, stems), again representing the action of a unique intermediary, rather than the geographical range of such species. Such signatures, both of long-distance translocation of thousands of species, and the presence of selected plant fragments beyond the environmental range of the parent plants, are unique.

In conclusion, we predict that a future fossil record of human impacts on the biosphere will comprise three distinct phases: 1) a diachronous and regional signature of human-mediated biotic change extending over tens of millennia and becoming more apparent from the Late Pleistocene onwards (see Williams et al., 2022a; Fig. 1, human impactors 6–13); 2) a

rapid and near-synchronous change associated with the Great Acceleration and Anthropocene, as documented herein (Fig. 1, human impactors 1–5); and 3) an interval of global ecosystem recovery (albeit into a pattern different from before), or alternatively of mass extinction (Fig. 1). Which of these last alternatives occurs will depend on how resilient Earth's geosphere and hydrosphere are and how humans relate to the wider biosphere in the present and near future. In either case, the resulting 'homogenized' (see Samways, 1999) and taxonomically depleted palaeontological pattern will differ markedly from those of Holocene and all previous geological records.

### Author contributions

The concept of the study was designed by M.Wi in association with J. Za, A.D.B., R.L. and C.N.W. M.Wi and J.Za devised Table 1. M.Wi and M. J.H. drafted Figs. 1–4. A.W. drafted Fig. 5. All authors developed and contributed to the drafts of the manuscript.

### Declaration of competing interest

The authors declare no competing interests.

### Data availability

Data sources for Figure 5 are supplied as a supplementary file

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earscirev.2024.104844>.

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