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I have pleasure in dedicating this paper to Krystyna Wasylikowa on the occasion of her 70th birthday. Her pioneering work with plant macrofossils and her detailed ecological approach to their interpretation has been a continuing inspiration.

The recent extinction of *Azolla nilotica* in the Nile Delta, Egypt

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ABSTRACT. *Azolla nilotica* does not occur in Egypt today, reaching as far north as central Sudan. Its spores have been recorded in sediment cores from the Nile Delta near Manzala Lake up to ca. 550 AD. As part of the CASSARINA Project on recent changes in ecosystems of North African lakes, short sediment cores, covering up to the last two centuries, were taken from the open water of the large Delta lagoons, Lakes Edku, Burullus, and Manzala. *Azolla nilotica* megaspores were recovered from all three cores. Its most recent record at Manzala Lake was during the 19th century, at Edku Lake around 1920, and at Burullus Lake in the 1960s. *A. nilotica* is associated with fossil assemblages typical of high conductivity fresh-water and brackish conditions, all with a low nutrient content. It may have become locally extinct in Manzala Lake after a rise in sea-level destroyed its habitat of open water within reed-swamp vegetation. At Edku Lake it became extinct due to the decreased influence of sea-water combined with the increased input of fresh-water and nutrients as a result of Nile diversions to improve irrigation. Burullus Lake remains brackish today, and *A. nilotica* survived until the closure of the Aswan High Dam accelerated fresh-water and nutrient supply to the lake. In contrast, *A. filiculoides* was introduced as a bio-fertilizer in the 1970s and has subsequently become an aquatic weed. It has been able to flourish in the fresh, nutrient-rich water of Edku and Manzala Lakes, but so far seems to be absent from brackish Burullus Lake. *A. nilotica* persisted in the Nile Delta as long as nutrient levels were low. It seems to be intolerant of increased eutrophication by nitrate and phosphate supplied by agricultural runoff and sewage. As lake-water nutrient levels have steadily risen due to increasing irrigation by fresh-water and use of chemical fertilizers, and the increasing population, *A. nilotica* declined and became extinct in Egypt as recently as the 1960s.

KEY WORDS: *Azolla nilotica*, Nile Delta, Edku Lake, Burullus Lake, Manzala Lake, recent extinction, water quality, nutrient enrichment

INTRODUCTION

The floating water-fern *Azolla nilotica* Decne. ex Mett. does not occur in Egypt at the present day (Boulos 1999). Its nearest recorded occurrence (see Fig. 1) is in central Sudan (Saunders & Fowler 1992). *A. filiculoides* and, to a lesser extent, *A. carolinianum* have been introduced in recent decades (Boulos 1999, El-Shenawy 1994) to rice paddies in the Nile Delta as a bio-fertilizer, utilising the nitrogen-fixing capacity of their associated cyanobacterial symbiont, *Anabaena azollae* (El-Shenawy 1994). *A. filiculoides* has subsequently escaped and spread vigorously into Delta drains and the Delta lakes.

Azolla nilotica belongs to the section *Rhizosperma* (Mey.) Mett. which is distinguished from section *Azolla* Meyen containing *A. filiculoides* by the presence of 9 rather than 3 floats in the megaspore apparatus (e.g. Saunders & Fowler, 1992, Field 1999; see Plate 1). There are two African species in section *Rhizosperma*. The megaspores of *Azolla nilotica* differ

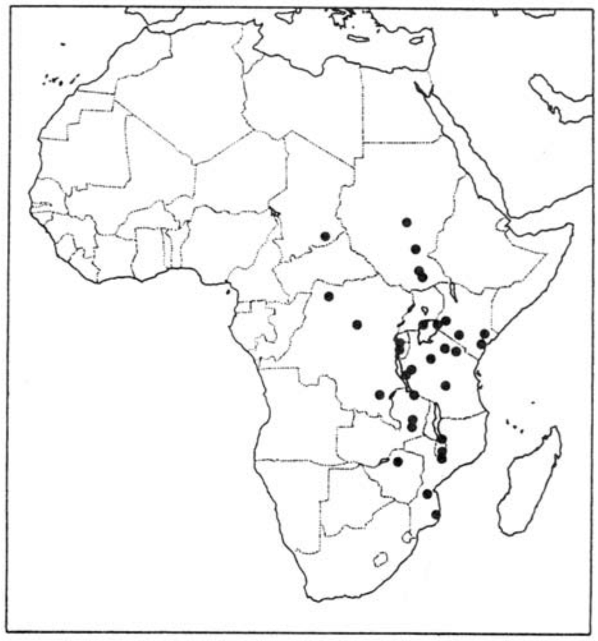

Fig. 1. Modern distribution of *Azolla nilotica*. From Saunders & Fowler (1992)

from those of *A. pinnata* in the presence of pronounced spiny excrescences, often with a blunt or recurved apex, especially on the distal part of the megaspore (Fowler & Stennett-Willson 1978).

Megaspores and microspores of *Azolla nilotica* were recorded by Leroy (1992) in cores of Nile Delta sediments in the vicinity of Lake Manzala, and dated between ca. 5000 – ca. 1400 ^{14}C yr BP (up to ca. 550–600 AD). Leroy (1992) proposed that *A. nilotica* became extinct in the Nile Delta after this time, mainly as a result of habitat alteration by human activity. *A. nilotica* spores were associated at two sites with assemblages of pollen and other microfossils that were interpreted as representing rather open *Cyperus* (papyrus) marshes in shallow water that were isolated from riverine and marine influence. The water was fresh, but may have been slightly saline. At two other sites, *Azolla* spores were associated with riverine sediment with saline influence, indicated by the occurrence of Foraminifera, for example. The present-day water quality preferences of *A. nilotica* are unknown, although it seems likely that the water it inhabits is usually of high conductivity but not eutrophic.

During the recent CASSARINA (Change Stress and Sustainability: Aquatic Ecosystem Resilience in North Africa) Project (Flower 2001), short sediment cores, up to 1 m long, were retrieved from three Nile Delta lakes, Edku, Burullus, and Manzala (Fig. 2). These are large, shallow lakes in the northern Delta (Ramdani et al. 2001a), with average depths between 1 and 3 m. They are all connected to the sea (Fig. 2). Their hydrology is controlled by the balance between sea-level and the inflow of fresh-water which increased during the Nile annual floods before the closure of the Aswan High Dam in 1964. The aim of the

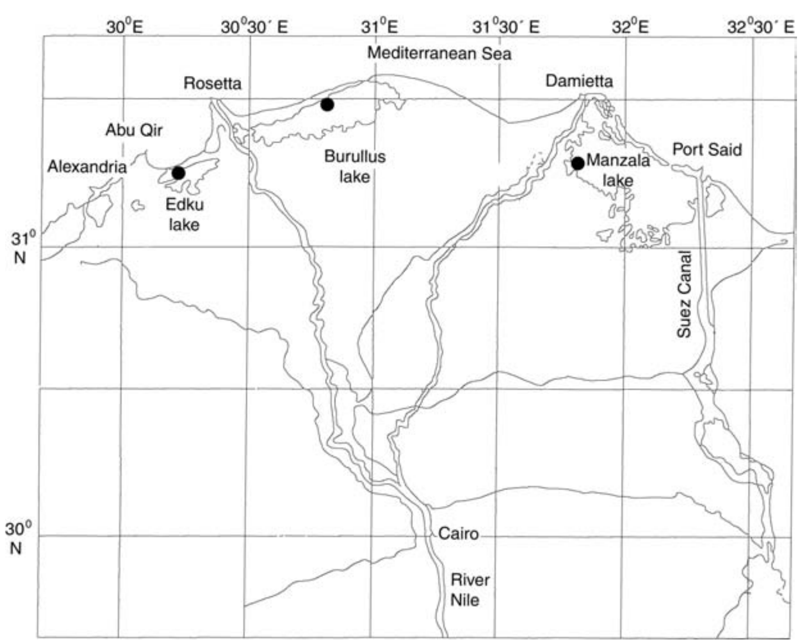

Fig. 2. Map of the Nile Delta showing the Delta lagoon lakes. The positions of the sediment cores are indicated

CASSARINA Project was to undertake multi-proxy palaeolimnological analyses to assess the impact of recent changes in their catchments on the lake ecosystems (Birks et al. 2001, Flower et al. 2001, Peglar et al. 2001, Ramdani et al. 2001b, Birks & Birks 2001). During the macrofossil and palynological analyses, megaspores and microspores of *Azolla* spp. were recorded. Megaspores of *A. nilotica* were found in all three lakes, and megaspores of *A. filiculoides* were found in two of them. *A. nilotica* became extinct in the records at different times in the three lakes, according to the sediment chronologies of Appleby et al. (2001).

EDKU LAKE

The recent ecosystem changes during the last 100 years have been discussed by Birks et al. (2001), Flower et al. (2001), Ramdani et al. (2001b), and Birks & Birks (2001). The plant and animal macrofossil record, presented in full by Birks et al. (2001), is summarized in Fig. 3 together with an interpretation of the water quality made from these and other indicators such as diatoms and zooplankton. *Azolla nilotica* megaspores occurred in all the samples below 40 cm, and reached a particularly high abundance at 50 cm in zone 3. In zone 1 the water was brackish, as indicated by the abundance of Foraminifera and molluscs typical of brackish lagoons, and the presence of the salt-tolerant macrophyte *Ruppia*. Reed-marsh of Gramineae (*Phragmites*) and *Typha domingensis* alternated with halophytic vegetation represented by Chenopodiaceae (e.g. Montasir 1937). During zone 2, conditions became less saline, *Ruppia* and lagoon invertebrates were reduced, and fresh-water animals (e.g. *Plumatella*) flourished. A marked increase in salinity occurred in zone 3, as shown by the expansion of lagoon Mollusca, including the more marine *Pholas dactylis*, and the presence of the foram *Quinqueloculina seminulum*, the salt-tolerant *Ruppia*, and the marine macrophyte *Zostera*.

There was a marked reduction in salinity in zone 4, starting ca. 1920, indicated by the arrival of fresh-water Mollusca and reduction in lagoon types, and the replacement of *Ruppia* and *Zostera* by *Potamogeton pectinatus*. The

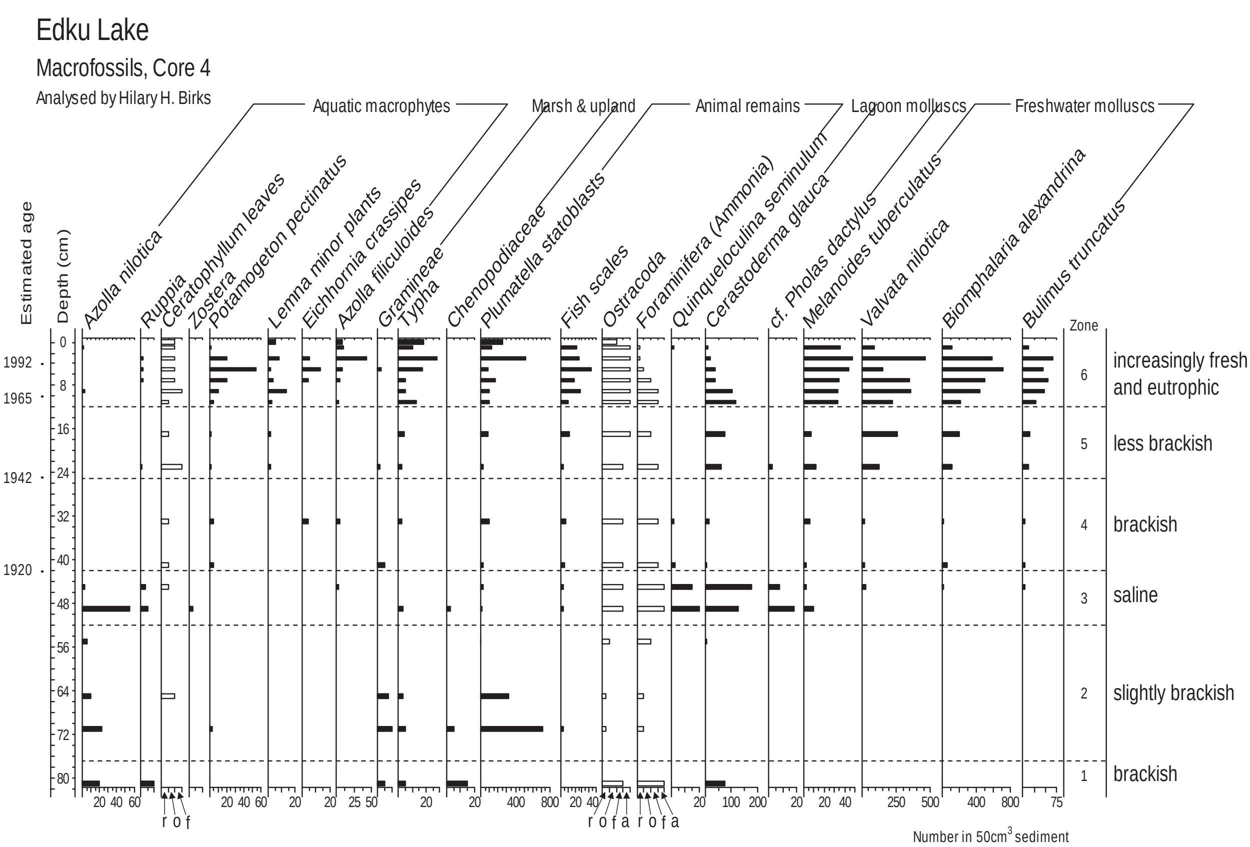

Fig. 3. Stratigraphic diagram of selected plant and animal macrofossil concentrations in core 4 from Edku Lake. Ages (AD) are estimated from the timescale constructed by Appleby et al. (2001). **r** = rare, **o** = occasional**, f** = frequent, **a** = abundant

water may also have been nutrient enriched, as *Ceratophyllum* expanded. The trend continued in zone 5 during the 1940s, with further expansion of fresh-water molluscs and the presence of *Lemna minor*. After 1965, the assemblage indicates that the water was increasingly fresh and nutrient rich. Reed-marshes dominated by *Typha* expanded markedly. The great increase in fresh-water molluscs, fish, and aquatic macrophytes implies an increase in nutrient supply leading to increased productivity and biomass. *Eichhornia crassipes* and *Azolla filiculoides* are recorded in the 1980s. Both are introduced. *Eichhornia* escaped from garden ponds during the 1930s (Zahran & Willis 1992) and has subsequently expanded to pest proportions. It covers a large part of Edku Lake today. *A. filiculoides* escaped from rice fields where it was introduced as a bio-fertilizer in the 1970s (El-Shenawy 1994) and it covered Edku Lake in 1992, fixing an estimated 90,000 tonnes of nitrogen that year. The scattered isolated records of *Eichhornia* and *Azolla filiculoides* down to ca. 45 cm and the two single records of *A. nilotica* in zone 6 are probably a result of sediment disturbance. During fishing, punts are poled across the lake and people walk on the bottom whilst setting nets. But any such disturbance must have been small, as no recent short-lived radionuclides were found at this level (Appleby et al. 2001).

Before major human intereference with the flow of the Nile, marine and fresh-water influences in the Nile Delta lakes alternated naturally with the balance of sea-level and the strength of the Nile floods. The salinity conditions fluctuated through the seasons, as well as on average over longer time periods. These conditions evidently suited the growth of *Azolla nilotica* in Edku Lake. It was associated with brackish and rather fresh water during zones 1 and 2, probably living in sheltered open water within the reed-marsh. It became locally common during the saline phase before 1920, seeming to flourish in the saline water. The continuous record of *A. nilotica* ceased at about 1920. In the early twentieth century, control of the Nile floodwater by barrages and diversions increased, thus increasing the year-round supply of fresh-water which remained because the natural drainage was indadequate to remove it (Waterbury 1979, Stanley & Warne 1993). In addition the use of fertilizers in the Delta gradually increased, increasing the nutrient load to the lakes. The extinction of *A. nilotica* coincided with this overall reduction in salinity and the gradual increase in nutrients. With the closure of the Aswan High Dam in 1964, the Nile floods were eliminated and fresh-water entered the Delta lakes all year. The poor drainage resulted in further decreased marine influence and in the water becoming increasing fresh (Waterbury 1979). This, combined with the increased nutrient input, led to increased productivity and the expansion of aquatic macrophytes (including *Eichhornia* and *Azolla filiculoides*) and fresh-water molluscs, some of which carry bilharzia (Birks et al. 2001).

BURULLUS LAKE

The recent changes in the ecosystem of Burullus Lake were reconstructed during the CASSARINA palaeolimnology study (Birks et al. 2001, Flower et al. 2001, Ramdani et al. 2001b, Peglar et al. 2001, Birks & Birks 2001). The plant and animal macrofossil record is summarized in Fig. 4. The lower part of the sequence (zone 1) is characterized by locally extensive reed-marsh dominated by *Phragmites*, with other grasses and *Cyperus* spp., forming a mosaic with halophytic and xerophytic vegetation typified by *Salicornia europaea* and other Chenopodiaceae. *Azolla nilotica* was nearly the only aquatic macrophyte recorded in the sequence. In zone 2, the local reed-marsh and salt-marsh declined, possibly caused by a rise in water-level, and marine influence increased, as shown by the massive abundance of lagoon Mollusca, Foraminifera, and Ostracoda, and the expansion of *Ruppia*. *Azolla nilotica* continued to thrive in these conditions.

As in Edku Lake, this more strongly saline period ended around 1920, and the increased inflow of fresh-water allowed the immigration and expansion of fresh-water Mollusca. After about 1940 (zone 3a) the influence of the increasing nutrient input was reflected in the greater productivity of macrophytes, fish, and the expansion of reed-marsh dominated by *Typha*, and the concomitant reduction in salt-marsh vegetation typified by Chenopodiaceae. However, the abundance of *Ruppia* and *Najas armata* and the continued presence of lagoon invertebrates show that the water was still

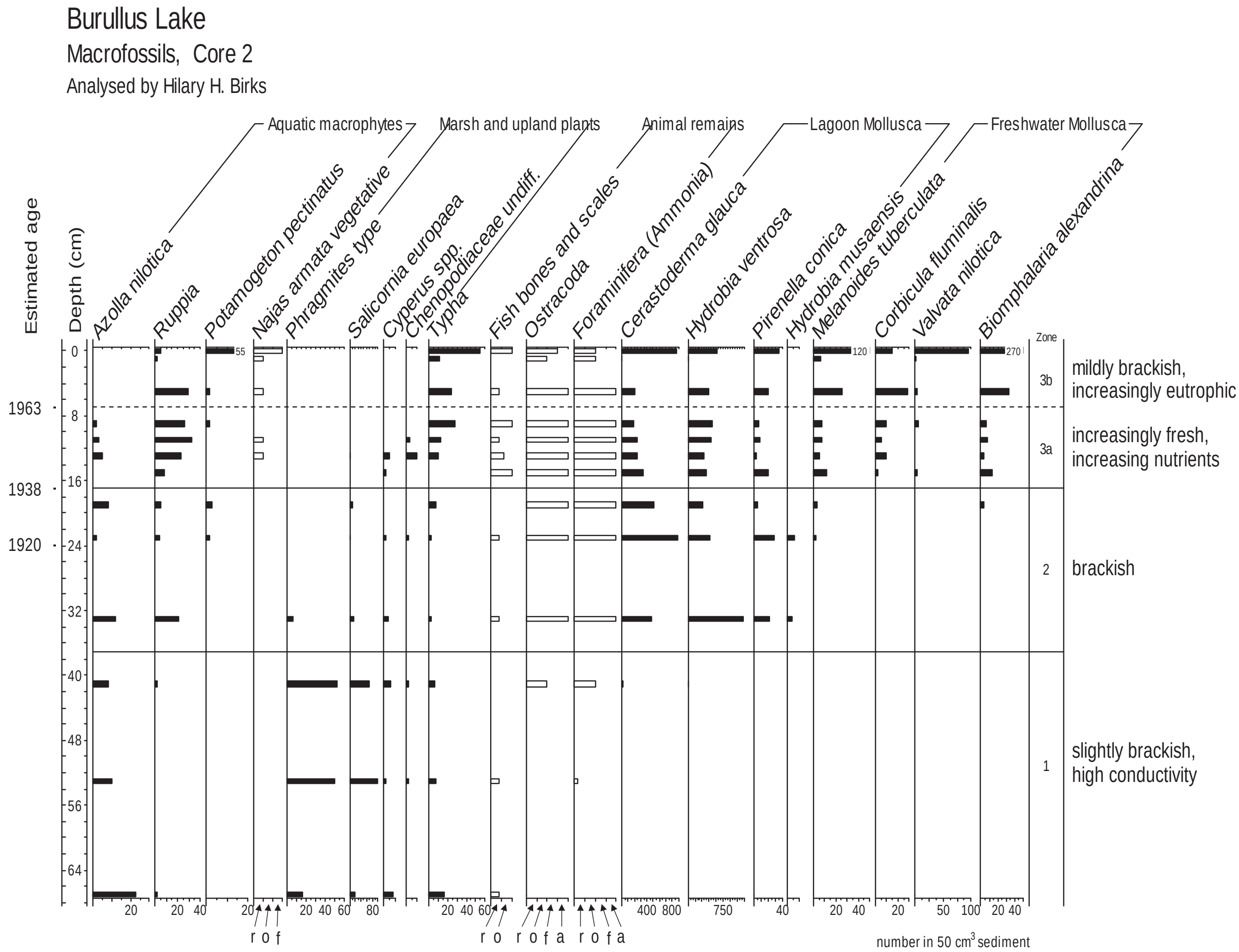

Fig. 4. Stratigraphic diagram of selected plant and animal macrofossil concentrations in core 2 from Burullus Lake. Ages (AD) are estimated from the timescale constructed by Appleby et al. (2001). **r** = rare, **o** = occasional, **f** = frequent, **a** = abundant

markedly brackish. *Azolla nilotica* declined during this zone and was last recorded about 1960. The freshening trend and nutrient increase continued into zone 3b, the increased eutrophication being indicated by the decline of *Ruppia* and the huge increase in *Potamogeton pectinatus* that dominates the open water today, accompanied by *Najas armata* in the shallows and the spread of *Typha* near the shores. The water is still brackish today (Birks & Birks 2001) and fish productivity is high, but the influence of nutrients, pollution, and increasing amounts of fresh-water is ensuring that these changes continue, resulting especially in the recent large increases in fresh-water Mollusca, including the bilharzia-carrying *Biomphalaria alexandrina*.

Azolla nilotica persisted in Burullus Lake until about 1960. It thrived in the naturally fluctuating brackish-saline water conditions, probably floating on sheltered open water within the reed-marsh. The north shore of Burullus Lake, where the core was taken, has been less affected by nutrient addition than other parts of this lake. *A. nilotica* survived here until the closure of the Aswan High Dam allowed year-round irrigation and cultivation, particularly on the south shore, that resulted in increased fresh-water inflow and nutrient loading.

MANZALA LAKE

A summary of the recent changes that occurred in the ecosystem of Manzala Lake is shown in Fig. 5. The full plant and animal macrofossil diagram, including Ostracoda analysis, is presented by Birks et al. (2001). Additional multi-proxy palaeolimnological evidence is discussed by Flower et al. (2001), Ramdani et al. (2001b), and Peglar et al. (2001), and synthesized by Birks and Birks (2001). The overall sedimentation rate is slower in Manzala Lake than in the other two lakes, the last

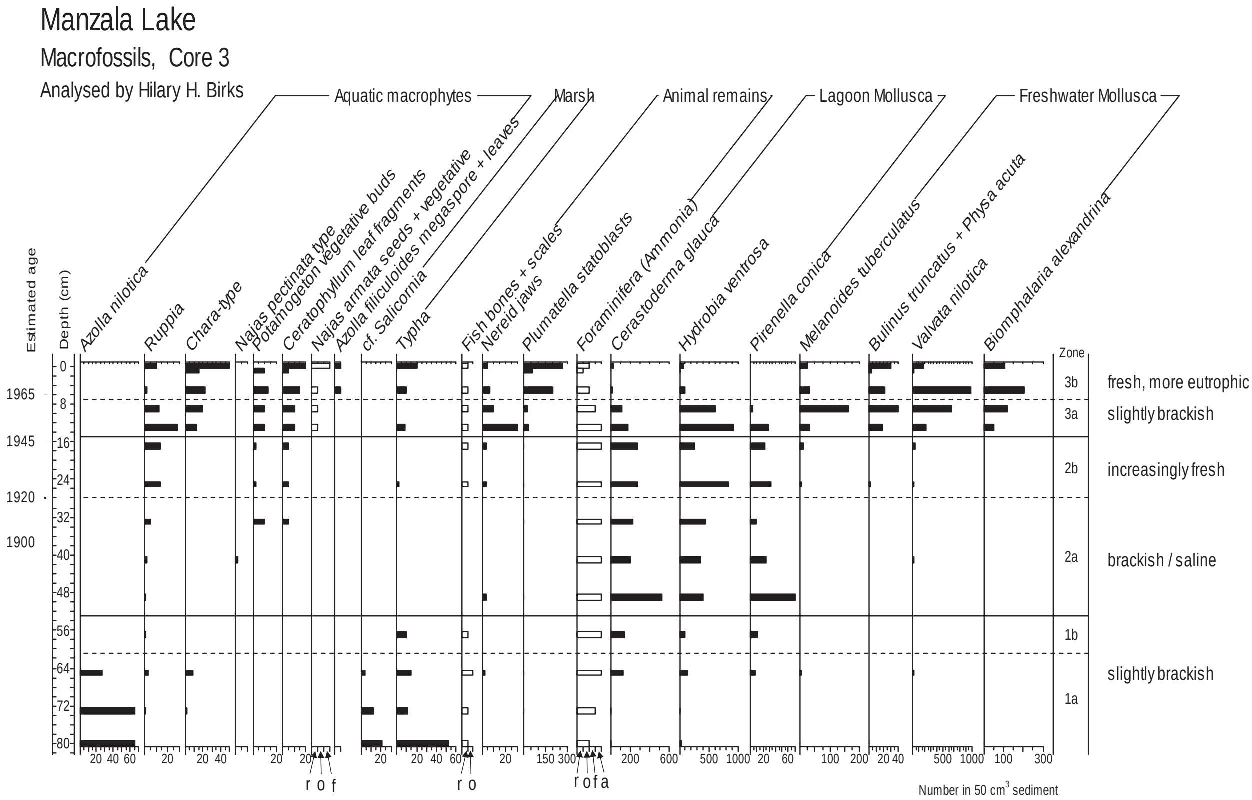

Fig. 5. Stratigraphic diagram of selected plant and animal macrofossil concentrations in core 3 from Manzala Lake. Ages (AD) are estimated from the timescale constructed by Appleby et al. (2001). **r** = rare, **o** = occasional, **f** = frequent, **a** = abundant

100 years being represented by the top ca. 35 cm of the sequence. It is not possible to date the lower sediments, and thus the age of the previous changes is uncertain.

At the base of the sequence in zone 1, Foraminifera and a few lagoon Mollusca indicate that the water was brackish. Reed-marsh dominated by *Typha* occurred near the coring site, and probably formed a mosaic with halophytic communities on shores, represented by cf. *Salicornia* seeds. This type of vegetation was common in Manzala Lake in the 1930s, as described by Montasir (1937) and is still present in more saline parts of the lake and in less disturbed parts elswhere in the Delta (Zahran & Willis 1992) and widely in Burullus Lake (Khedr 1999). *Azolla nilotica* was abundant during zone 1, presumably growing in association with the reed-marsh. However, its record ceases abruptly above 64 cm. There is little change otherwise, although cf. *Salicornia* and *Chara* type also disappeared, followed a little later by *Typha*. There was possibly a rise in water-level, as in the following zone marine influence increased. The sediment is full of shells of lagoon Mollusca and Foraminifera. *Ruppia* persisted and the salt-tolerant *Najas pectinata* is recorded. Although *Typha domingensis* is tolerant of brackish water, a rise in water-level would probably result in its local disappearance.

If the end of the saline phase at Manzala Lake was synchronous with the other lakes, it occurred around 1920, which fits in with the proposed sediment chronology (Appleby et al. 2001). *Potamogeton* and *Ceratophyllum* appeared near the top of zone 2a and *Ruppia* and fish remains increased. These changes may reflect the beginning of nutrient addition as the use of fertilizers gradually increased. In zone 2b indicators of fresher water appeared, including fresh-water Mollusca and other invertebrates. *Typha* reed-marsh began to develop again near the coring site.

The influence of fresh-water and nutrients increased in the mid 1940s during zone 3a. As *Ruppia* declined, *Potamogeton*, *Chara* type, *Ceratophyllum*, and *Najas armata* expanded and *Typha* marsh increased. Lagoon Mollusca decreased and fresh-water Mollusca, mainly gastropods, substantially increased. As parts of this very large and shallow lake were progressively filled in for land reclamation, the circulation of sea-water to the coring area became reduced and fresh irrigation drainage water had a large influence. This was intensified after ca. 1965 as the operation of the Aswan High Dam allowed the provision of year-round fresh-water which further reduced any sea-water influence. Megaspores of *Azolla filiculoides* were found in the upper sediment. Although not recorded in aquatic vegetation surveys in 1989, *A. filiculoides* colonised Manzala Lake via irrigation drains and became abundant in the early 1990s, associated with nutrient-rich (especially phosphate) non-saline water in the southern and western parts (Khedr 1997). Today the water of Manzala Lake near the coring site is fresh, but with relatively high conductivity and nutrient levels (Birks & Birks 2001).

THE EXTINCTION OF *AZOLLA NILOTICA* IN THE NILE DELTA

The occurrence of *Azolla nilotica* megaspores in recent sediments in all three Nile Delta lakes investigated shows that it survived widely in the Delta after 550 AD, the time of its extinction postulated by Leroy (1992). The cores she investigated around Manzala Lake are all from areas that are presently terrestrial, where *Azolla* would not be expected to survive. The reduction in area of the lake was probably partly due to natural processes involving silting of the distributaries, relative sea-level changes, and Nile flood levels combined with increasing human manipulation of the Delta environment. However, *A. nilotica* survived and flourished in the lakes until quite recently.

The lakes are all very large (see Ramdani et al. 2001a) and their ecosystem development was assessed from only one core from each lake. The spatial distribution of aquatic and terrestrial macrofossils is usually rather local around the parent plants (e.g. Birks 1973, Dieffenbacher–Krall & Halteman 2001). Some re-distribution of remains could have occurred in these large and open shallow lakes. Nevertheless, the macrofossils in the cores are likely to be representative of the small area around them. They reflect local aquatic changes, and cores from other parts of the lakes are needed to make lake-wide general reconstructions. However, major changes are recorded in each lake that show a consistent pattern between themselves, even though there are differences between the lakes in water chemistry. During the eighteenth and nineteenth centuries the lakes were all relatively fresh, but then became more saline, possibly as a result of the combination of gradual rise in sea-level, gradual land-subsidence, and removal of Nile water for agricultural irrigation (Stanley & Warne 1993). Around 1920, the marine influence receded. Progressive modification of the Nile flow to improve irrigation for agriculture since the 1920s increased the flow of fresh-water to the lakes. Use of fertilizers and effluent from the increasing human population resulted in increased nutrient levels, particularly of nitrates and phosphates. This effect gradually increased and was substantially reinforced after the closure of the Aswan High Dam. Edku and Manzala Lakes became fresh and rather eutrophic with a strong development of aquatic macrophytes and reed-marsh to the detriment of halophytic shore vegetation and lagoon species dependent on brackish water. Burullus Lake remained brackish, but in the last decades has increasingly shown the effects of increased fresh-water and nutrients.

Azolla nilotica megaspores are associated in all three lakes with the occurrence of reed-marsh, and with water quality ranging from fresh to brackish conditions. *A. nilotica* was a consistent component of the natural aquatic ecosystems. At Manzala Lake, it was no longer recorded at the coring site some considerable time before 1900. The reason postulated is a rise in water-level that locally eliminated its reed-marsh habitat. It may have survived in other parts of the lake for longer, but it is certainly extinct there today. At Edku Lake, *A. nilotica* flourished even in the saline conditions up to about 1920. It died out probably as a result of increased nutrient levels, as inorganic fertilizer use intensified and the inflow of irrigation drainage water increased. The overall increase of macrophyte density may also have had a deleterious effect on its habitat. At Burullus Lake, *A. nilotica* survived until the 1960s. This lake remained brackish and was less influenced by agricultural run-off near the core site. However, the intensification of year-round irrigation and nutrient supply resulting from the operation of the Aswan High Dam probably elevated the nutrient levels beyond *A. nilotica*'s tolerance limit.

In contrast, *A. filiculoides* has become an aquatic weed in the Delta since its introduction and escape in the 1980s. It was able to colonise the relatively fresh-water Manzala and Edku Lakes. It is apparently tolerant of high conductivity and nutrient levels. However, it was not recorded at Burullus Lake where brackish conditions have persisted and even *Eichhornia crassipes* is uncommon, in contrast to the fresh-water conditions in Edku and Manzala.

Therefore, as Leroy (1992) proposed, it appears that human activity is indeed responsible for the demise of *A. nilotica* in the Nile Delta. However, the direct cause seems to be the alteration of the aquatic environment by the continued and ever-increasing addition of nutrients supplied in the irrigation drainage water from intensive agriculture and the increasing human population.

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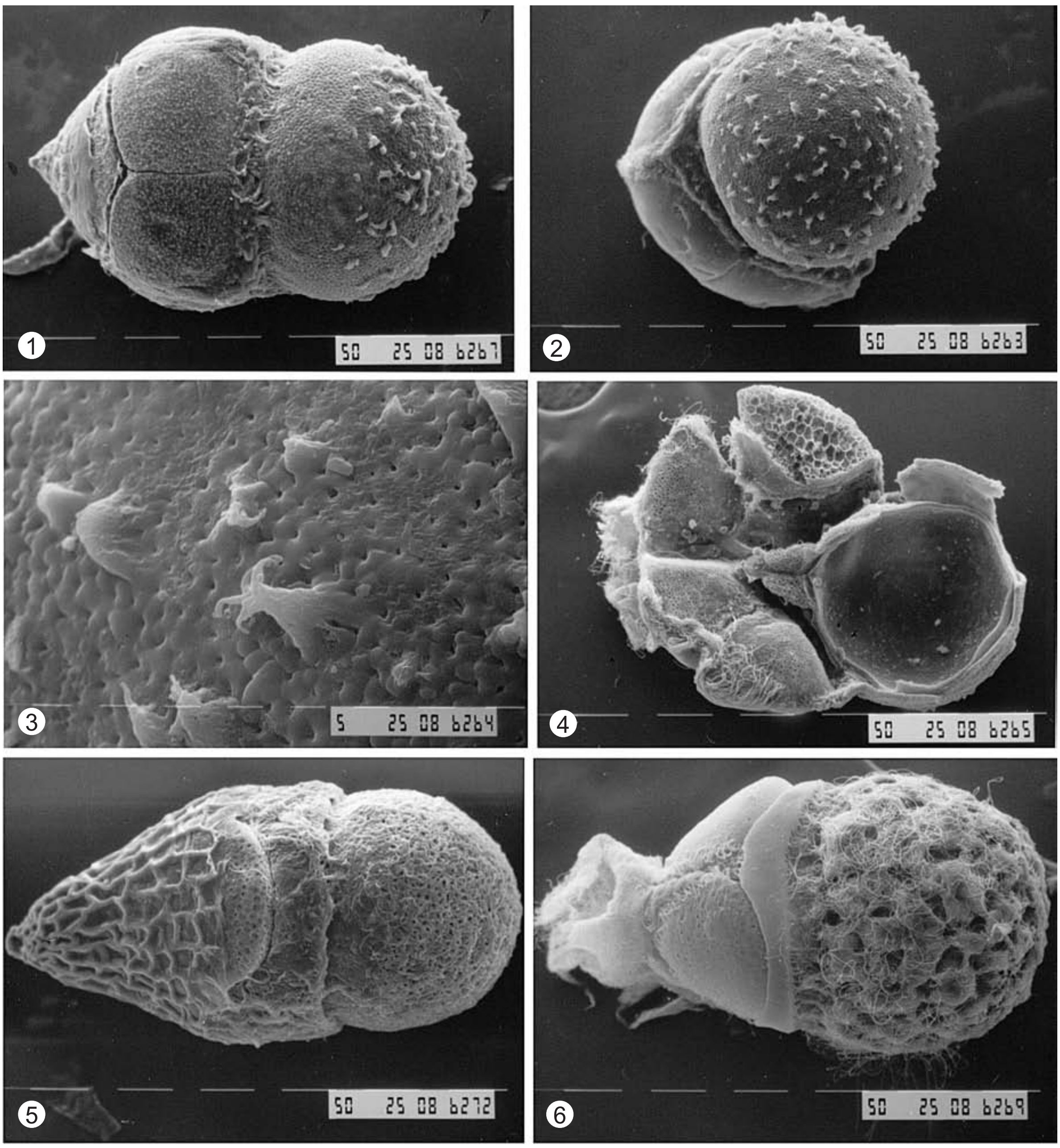
PLATE

Plate 1

Scanning electron microscope photographs of *Azolla nilotica* and *A. filiculoides*

1. *A. nilotica* megaspore, Edku Lake 2–4 cm, ×150.
2. *A. nilotica* megaspore top view, Edku Lake 4–6 cm, ×150.
3. *A. nilotica* megaspore, detail of spore surface, Edku Lake 4–6 cm, ×1000.
4. *A. nilotica* megaspore, cut in half to show double layer of floats and spongy float material, Edku Lake 4–6 cm, ×150.
5. *A. filiculoides* megaspore, Edku Lake 2–4 cm, ×150.
6. *A. filiculoides* megaspore, cap peeled back to show the 3 floats in a single layer, modern, ×150. The horizontal lines on 3 are 5 μm and on 1,2,4,5, and 6 are 50 μm long.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