

Recent ecosystem dynamics in nine North African lakes in the CASSARINA Project



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Abstract

An integrated multi-disciplinary study of nine North African lakes (CASSARINA) aims to establish ecological baselines and to explore responses to 20th century human impacts on their ecosystems. Water chemistry measurements (1997–1998) demonstrate a wide range from dilute oligotrophic to calcareous freshwaters and from mildly brackish to hypersaline lagoons. The biota are consequently highly diverse. Aquatic ecosystem responses to environmental stress over the last 100–200 years in all nine lakes are summarised by detrended correspondence analysis (DCA) of plant and animal macrofossil, zooplankton, diatom, and pollen data from short sediment cores. DCA proved to be a powerful tool for summarising multi-proxy sediment records and ecosystem dynamics. compositional changes measured by the DCAs have been very large and rapid, often over a few decades; as great as climate-controlled late-glacial changes over 2000 years and larger than most Holocene (11 000 years) changes. These results emphasise the strength of human impact on the lakes and the surprisingly great resilience and dynamism of their ecosystems. The DCA summaries for the most recent decades indicate ecosystem disequilibrium in all the lakes, implying that their future stability is uncertain and that large or damaging changes may soon occur if the stresses are maintained. Thresholds have recently been passed in 3 lakes. During the project, Merja Bokka (Morocco) was drained and cultivated. The unique acid Megene Chitane (Tunisia) is in danger of drying up permanently due to water extraction. Freshwater diversion from Garaet El Ichkeul (Tunisia) has dramatically altered its wildlife habitat, as reed-marshes were replaced by salt-marsh and bare mud within 20 years. In contrast, the ecosystems of the Delta lakes (Egypt) have responded dramatically to the year-round inflow of fresh irrigation water controlled by Nile dams and the rise in the freshwater table due to

inadequate drainage in the flat delta. The Project has demonstrated remarkably rapid responses by the lakes to environmental stresses. In particular, it highlights the threats to wetland-lake ecosystems in North Africa if uncontrolled exploitation continues.

Introduction

Nine wetland lakes in the Mediterranean fringe of North Africa were investigated during the CASSARINA Project, with the major aims of assessing the impact on the lake ecosystems of the increasingly technologically-based and intensive land-use in their catchments during the 20th century; of establishing ecological baselines for the late 20th century; and through palaeolimnology of the sediment record, of assessing recent diversity and habitat changes in response to human-induced ecosystem stress (see Flower, 2001). The multi-proxy sedimentary historical record provides data on the composition of the aquatic ecosystem and how it has changed through time. Long-term environmental forcing factors are usually climatic, but over the last century in N. Africa, human impacts have been much more important. A major threat to all the Moroccan and Tunisian lakes is water withdrawal, mostly for agricultural irrigation, but also for industry and direct human use. The relatively low rainfall in NW Africa over the last 25 years and the increased water demand has put increasing stress on the lake ecosystems. Other factors such as pollution and eutrophication are important but relatively small. In contrast, the Egyptian Delta lakes have received increased freshwater during the 20th century due to increasing control of the Nile flow to provide year-round irrigation combined with poor drainage.

After comparing the water chemistry of the lakes as measured in 1997–1998, before Merja Bokka was drained, (Fathi et al., 2001) this paper attempts to summarise and synthesise the ecosystem responses to environmental stresses as reflected in the sedimentary records covering approximately the last 100–200 years for zooplankton (Ramdani et al., 2001b), pollen (Peglar et al., 2001), plant and animal macrofossils (Birks et al., 2001), and diatoms (Flower et al., 2001). These records have been discussed individually in these papers in this volume. We attempt to detect major ecosystem changes affecting all the organism types, through environmental stress and habitat change, and to make an assessment of the ability of the ecosystem to sustain itself against the effect of external environmental forcing factors (sustainability).

Sites

The nine CASSARINA lakes, three in each of Morocco, Tunisia, and Egypt, are diverse and cover a wide range of ecological conditions (see Flower, 2001; Ramdani et al., 2001a). All have a depth of about 2 m or less, but have widely different surface areas, catchments, and water chemistry. Six are connected to the sea and show a range of salinity, two are high-conductivity freshwater lakes, and the last is a dilute, acid-water lake. As a consequence, they each have a different value for human exploitation, which includes food (fish) and materials (e.g., reeds), but most importantly they and their inflow streams and rivers are valuable water sources for irrigation. All the lake ecosystems are threatened in various ways and to varying degrees (Flower, 2001).

Water chemistry of the lakes as they were in 1997–1998

The chemical data from the 9 lakes 1997–1998 were summarised numerically. Minimum-variance (= incremental sum-of-squares) hierarchical cluster analysis (Gordon, 1999) was implemented by the program CLUSTER version 2.7 (H.J.B. Birks & J.M. Line, unpublished program). The ordination procedure used was principal components analysis (PCA, Jolliffe, 1986) implemented by the program CANOCO version 3.12 (ter Braak & Šmilauer, 1998) with strict convergence criteria. The data were standardised to zero mean and unit variance prior to cluster analysis and PCA because the chemical determinands are in different measurement units.

The means of the water chemistry variables measured for the lakes are shown in Figure 1. Monitoring at 3-monthly intervals revealed large seasonal variations. Further information is in Fathi et al. (2001) and Fathi and Abdelzaher (2000). The water quality varies from dilute and mildly acidic (pH < 7.0; Chitane), fresh calcareous (Bokka, Sidi Bou Rhaba), fresh to mildly saline (Edku, Burullus, Manzala), saline (Zerga, Ichkeul), and hypersaline (Korba) (Figure 1; Fathi et al., 2001). Cluster analysis (Figure 1) groups the Delta lakes and suggests that Rhaba and Bokka are similar. Chitane is more distinct. On the saline side of the dendrogram, Zerga and Ichkeul are similar, but Korba is completely different from all the rest. Principal Components Analysis (PCA) of the water chemistry data (Figure 2) separates the lakes along a gradient of conductivity and correlated ions associated with salinity along PCA axis 1, emphasising the high salinity in Ichkeul and Zerga, and the hypersalinity of Korba. The other lakes are fresher and are separated along a pH-alkalinity gradient associated also with a nutrient gradient (NO₃) along PCA axis 2. The uniqueness of Chitane is highlighted with dilute water of lowest pH. Water chemistry is often a major factor determining the organisms that live in a lake. The wide range of water chemistry in the CASSARINA lakes is reflected in the widely diverse assemblages of zooplankton (Ramdani et al., 2001b) and diatoms (Flower et al., 2001).

Terrestrial and wetland pollen assemblages reflect the vegetation of the catchments and the lake margins.

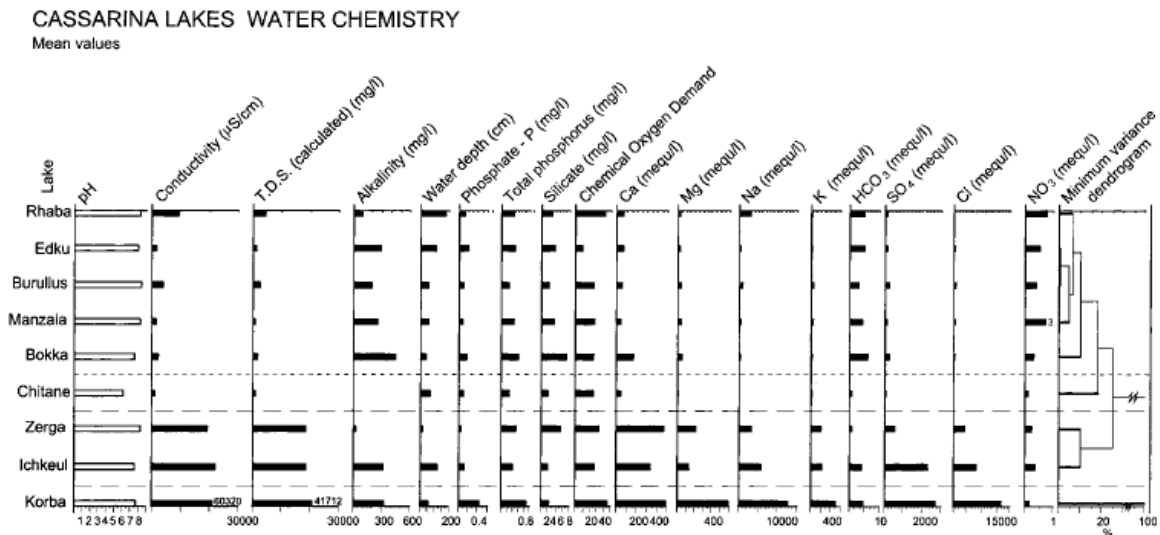


Figure 1. Mean values of water chemistry variables for each CASSARINA lake and minimum variance dendrogram. For further details, see Fathi & Abdelzaher (2000) and Fathi et al. (2001). T.D.S. = Total Dissolved Solids.

The catchment sizes vary from a few ha at Chitane to enormous for the Nile Delta. The other lakes are intermediate, the catchments of Ichkeul and Zerga being quite large and those of Sidi Bou Rhaba and Korba moderately small (Ramdani et al., 2001a; Peglar et al., 2001). PCA and cluster analysis of modern pollen assemblages (not shown) indicate the similarity of the Delta lakes, with high values of *Typha domingensis*-type (reflecting the extent of reed-marsh) and *Casuarina* (a widely planted exotic tree genus) and the occurrence of minor pollen types such as *Phoenix dactylifera*-type, *Cyperus*-type, and *Podocarpus*, characteristic of the cultural landscape of the Nile Delta. The catchments of Zerga, Ichkeul, and Chitane all provide high values of pollen types related to Mediterranean woodland and scrub, such as *Quercus*, *Pistacia*, *Erica arborea*, and *Phillyrea*. Chitane is the most distinct lake, as its small catchment contains substantial amounts of woodland and maquis scrub, but at Ichkeul, the Djebel Ichkeul is covered with this vegetation, and Zerga is supplied by rivers draining wooded hills (Ramdani et al., 2001a; Peglar et al., 2001). Korba, Ichkeul, and the Delta lakes have high percentages of Chenopodiaceae pollen derived from their surrounding salt marshes. Although land-use round the lakes varies (Ramdani et al., 2001a),

pollen of cultivated plants is unimportant in the assemblages because these plants as a whole produce small amounts of pollen that is poorly wind dispersed and tends not to reach the lakes by water transport in any quantity either (Peglar et al., 2001).

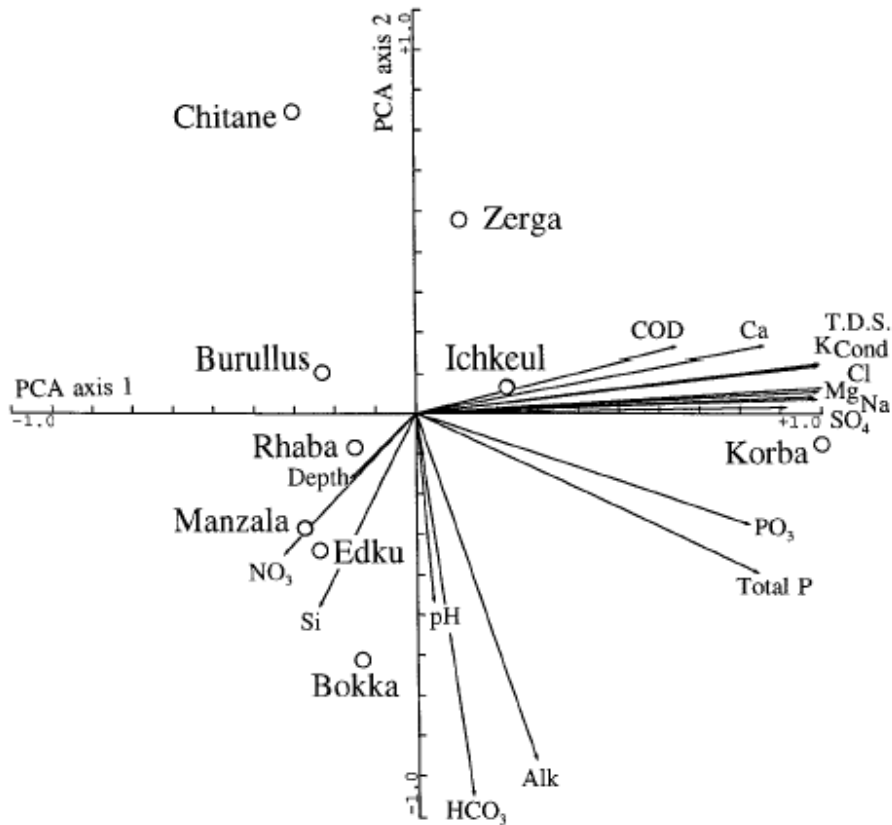


Figure 2. Principal Components Analysis (PCA) correlation biplot of CASSARINA lake water-chemistry data plotted on PCA axes 1 and 2. Abbreviations: COD = Chemical Oxygen Demand; T.D.S. = Total Dissolved Solids; Cond = Conductivity; Alk = Alkalinity.

The last 100–200 years at each lake

Methods

Diatoms, zooplankton, plant and animal macrofossils, (including Ostracoda at 3 sites), and pollen have been analysed from short sediment cores from the nine lakes (Flower, 2001; Ramdani et al., 2001a). Chronology has been provided by radiometric dating combined with biostratigraphy (Appleby et al., 2001). Here we consider all the records from each lake to compare the major palaeolimnological and catchment events interpreted from each fossil group. Detrended correspondence analysis (DCA) (Hill & Gauch, 1980) has been used to summarise the stratigraphical trends in the data-sets. Such summaries extract the major axes of gradients of variation within each data-set and distinguish ‘signal’ from ‘noise’. The general aim of ordination in quantitative gradient analysis (ter Braak & Prentice, 1988) is to construct the single hypothetical environmental or external explanatory or predictor variable that gives the best fit, in a mathematical sense, to the observed biostratigraphical data. This hypothetical variable (‘latent variable’) is simply the first one or two statistically significant ordination axes constructed in such a way as to optimise the fit of the stratigraphical data to an underlying model of how taxon abundances respond along environmental gradients in space or time. DCA provides an effective solution to the general ordination problem under the assumption that taxa have a unimodal response to the latent variable(s) (ter Braak & Prentice, 1988). DCA has the added advantage that the sample scores are expressed in standard

deviation (SD) units and samples that differ by 4 SD can be expected to have no taxa in common. Differences in sample scores provide a measure of the amount of compositional change between samples. DCA thus summarises not only the patterns within a data-set but also quantifies the amount of compositional change within the data and between pairs of samples.

DCA has good mathematical properties as shown by studies using simulated data of known properties (e.g. ter Braak, 1985). The critical question is how well does DCA work in practice with real-life data. In an elegant modern ecological study in Denmark, Ejrnæs (2000) has shown that DCA is remarkably effective at extracting latent variables from plant compositional data, even when not all the taxa show symmetric unimodal responses to the underlying environmental gradients. DCA appears to be a very robust tool for summarising patterns in complex multivariate data and for detecting the major hidden latent variables behind the data. Therefore, we consider that the patterns portrayed in Figures 3–11, especially for the statistically significant DCA axes, are a good reflection of the underlying gradients and latent variables that have influenced the various organism groups over the last ca. 100–200 years at each lake. Interpretation of these gradients is, of course, dependent on a knowledge of the ecology of the taxa concerned. The major gradients detected appear to reflect a variety of factors at the different lakes, such as changes in salinity, eutrophication, and water-level.

Prior to DCA, all concentration data (plant macrofossils, animal macrofossils, zooplankton) were transformed to $\log_e(y + 1)$, whereas all percentage data (pollen, diatoms) were transformed to their square roots in an attempt to stabilise the variance in each data-set. In the DCA detrending was by segments, non-linear rescaling was implemented, and rare taxa were down-weighted (ter Braak & Šmilauer, 1998). All computations were done with CANOCO version 3.12a with strict convergence criteria. The approximate statistical significance of the first four DCA axes was assessed by comparison with the simple broken-stick model (Jolliffe, 1986). The different stratigraphic lengths of the axes depend on the depth levels that were analysed for the fossil type. For diatoms at Zerga, Bokka, Ichkeul, Edku, and Manzala, deeper analyses were prevented by non-preservation of diatoms, and there were no diatoms preserved at Korba below the sediment surface. Plant and animal macrofossil records (Birks et al., 2001) were analysed separately to examine different parts of the ecosystem, except at Sidi Bou Rhaba where macrofossils were combined because of the small numbers of plant fossils apart from *Chara* oospores. Animal macrofossils comprised molluscs, Bryozoa statoblasts, total chironomids, Cladocera ehippia, nereids, ostracods, foraminifera, etc., the types depending on the lake (Birks et al., 2001). The DCA axes for the organism groups are plotted together for each lake (Figures 3–11). The scales are standard deviation (SD) or turnover units that estimate the amount of compositional change (turnover) between samples. Turnover can be compared between stratigraphical records at a site and also between sites. The scales (SD units \times 100) are the same for comparability. The changes in the axes are interpreted following the discussions of the full diagrams presented elsewhere in this volume: plant and animal macrofossils (Birks et al., 2001), pollen (Peglar et al., 2001), diatoms (Flower et al., 2001), and zooplankton (Ramdani et al., 2001b). Since each taxon in DCA is given a weight relative to its relative abundance, some changes in the axes are caused by changes in taxon values that are not considered ecologically significant, so not all the changes in the DCA curves, especially axes 2 and 3 and non-significant axes, can be interpreted in terms of ecosystem changes.

Sidi Bou Rhaba, Morocco. 34°12' N, 6°42' E (Figure 3)

This is an inland lake behind sand dunes but with no connection to the sea (Ramdani et al., 2001a). The area is a Ramsar Site and a nature reserve (Ramdani et al., 2001a). The ²¹⁰Pb chronology (Appleby et al., 2001) indicates a date of ca. 1860 AD for sediment at 100 cm depth. The small 19th century decline in the total macrofossil DCA axis 1 reflects the decrease in *Chara* and the increase in exposed mud habitats that resulted in a shift from a clearwater lake with abundant *Chara* and freshwater animals to turbid water with planktonic algae and Cyanobacteria and reduced *Chara*, oribatid mites, and *Plumatella*. The decline in diatom DCA axis 2 tracks the decline of oligohalobous taxa, especially *Campylodiscus clypeus*, and the concomitant increase in epipellic and mesohalobous taxa. A profound change is indicated in diatom axis 1

around 100 cm, with a turnover of 1 SD within ca. 50 years. At this time, oligohalobous diatoms were replaced by a mesohalobous assemblage, particularly *Achnanthes submarina*, probably reacting to the macrophyte decline and an increase in turbidity and salinity. The zooplankton axes are difficult to interpret as the turnover is not large, reflecting the relatively small changes in the zooplankton record. Most of the common taxa have wide ecological tolerances (Ramdani et al., 2001b). The gradual decline in axis 1 during the 19th century probably reflects the increase of the planktonic chydorid *Chydorus sphaericus*. This ubiquitous species, largely independent of pH and also tolerant of mild salinity, occurs in dense aquatic macrophyte vegetation and also in algal mats (Cyanobacteria), thus increasing with eutrophication and disturbance (Fryer, 1993). At the same time, the freshwater ostracods *Sarscypridopsis* and *Potamocyparis* declined as *Cyprideis torosa littoralis* and other taxa increased that are tolerant of brackish conditions.

Sidi Bou Rhaba (Morocco) DCA scores

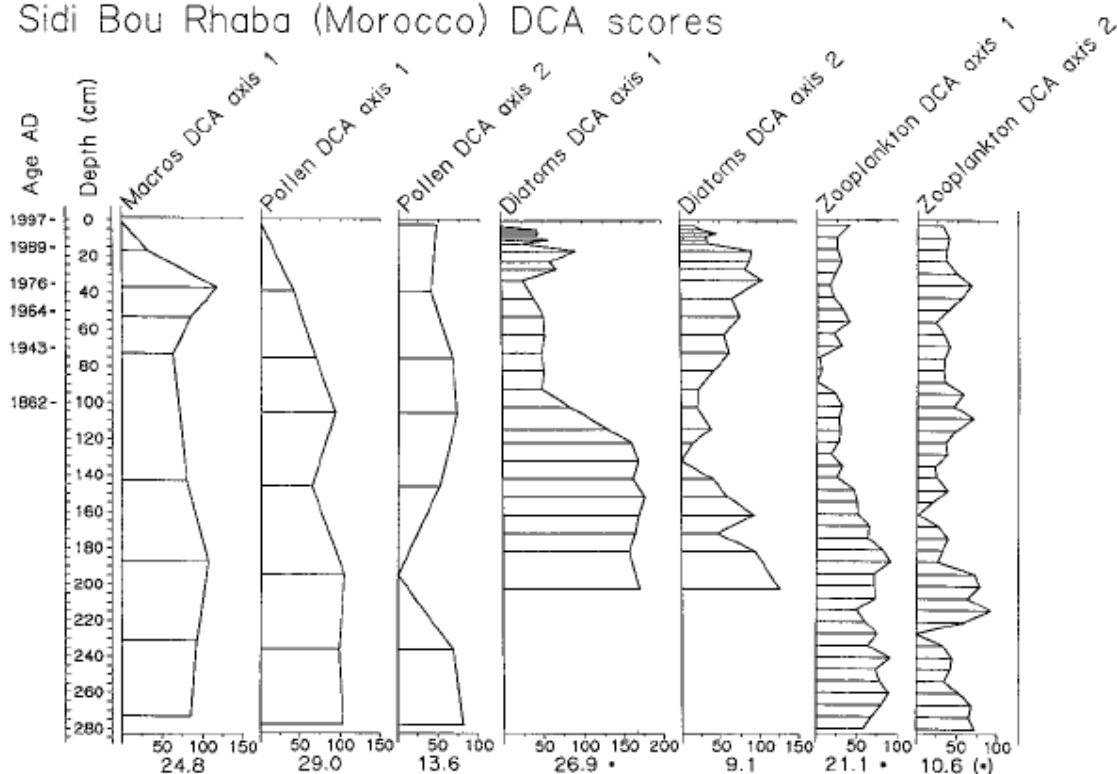


Figure 3. Sidi Bou Rhaba (Morocco). Stratigraphical plots of sample scores on the DCA axes accounting for >5% of the variance for organism groups. Plant and animal macrofossils are combined (Macros). The % variability accounted for by each axis is shown. * indicates that the axis is significant; (*) is on the border of significance; as assessed by comparison with a broken stick model. The horizontal scales are in SD units $\times 100$ (see text) drawn to the same scale. The chronology is from Appleby et al. (2001).

The rise in macrofossil axis 1 above 60 cm (1950s) reflects increases in *Juncus* and *Typha*, and the decrease in pollen axis 1 also reflects *Typha* and *Scirpus* increases, as *Phragmites* was replaced by *Typha*, *Juncus*, and *Scirpus* marsh. The pollen axis is also influenced by the rise in Cupressaceae and decrease in Gramineae pollen, as scrub developed following decreased grazing pressure in the catchment. The rise in macrofossil axis 1 and the subsequent major decline of ca. 1 SD unit in the last 20 years is caused by increases in *Juncus* and the salt-marsh species *Salicornia europaea*, a further decline of Characeae, increases in *Najas marina* (= *armata*) and *Ruppia*, and associated changes in animal macrofossils. These changes were probably caused by shallowing of the lake and increased salinity, both exacerbated by a run of drier than normal years since the 1980s (Ramdani & Elkhiaiti, 2000). The diatom axes also show sharp

changes in the last 20 years. In the 1980s a peak of *Campylodiscus clypeus* indicates fresher water but it was replaced by an abundance of epipellic, mesohalobous *Cymbella pusilla*, reflecting changing water quality. It was rapidly replaced in turn by *Achnanthes submarina* which, with other mesohalobous taxa, became dominant in the 1990s in response to the increased salinity. In contrast, the zooplankton axes show little directional response, although the assemblage indicates more brackish conditions in recent years. The increase in zooplankton axis 2 above 55 cm reflects the further increase in *Chydorus sphaericus*, indicating increased eutrophication and disturbance since 1960.

From a relatively stable, clear-water calcareous lake in the early 19th century, Sidi Bou Rhaba has shown considerable ecosystem changes. In the second half of the 19th century the ecosystem became increasingly disturbed (Ramdani et al., 2001a) and switched to a turbid condition with loss of macrophyte cover (see Scheffer et al., 1993), triggered by decreasing depth, increasing salinity, and possibly the introduction of black bass. The diatoms reacted strongly to this change. The ecosystem was resilient enough to maintain a new state of relative stability until about 25 years ago. Since then, the lake has become increasingly shallower and more saline, which has culminated in another major change in the diatom flora and the expansion of higher plants typical of summer-exposed mud and saline water (*Ruppia*, *Najas marina*). These recent changes have been much faster than previous changes, suggesting that the lake is presently in an unstable state, with further changes likely to occur as the present trends continue to stress the ecosystem. At the present rate of sediment accumulation, the lake is likely to disappear in about 50 years (Flower, 2001). To maintain its conservation and biodiversity value, particularly for birds, some measures need to be taken in the near future to restore its depth and water quality.

Merja Zerga, Morocco. 34°17'N, 6°13' E (Figure 4)

This site is a large tidal lagoon utilised for fishing and collection of molluscs for food. It is a nature reserve and a Ramsar site, mainly for its rich bird-life (Ramdani et al., 2001a). The macrofossil, pollen, and zooplankton assemblages in the stiff shelly sediment below 34 cm (core ZERG-1) or 27 cm (ZERG-2) are typical of lagoon conditions. The pronounced change to the overlying softer mud occurred after 1953 when the drainage Canal du Nador was constructed, entering the lagoon near the coring site (Ramdani et al., 2001a). Animal macrofossil axis 1 summarises the resulting pronounced decline of lagoon molluscs. The zooplankton show a small reaction to this change, caused by the reduction of salt-water ostracods and foraminifera and the appearance of small numbers of fresh and brackish water species, such as *Potamocypris arcuata*, *Mercuria similis*, and *Physa acuta* probably brought in by the canal water. From 1957 to 1965 (24–20 cm) the increase of ca. 1 SD unit in the plant macrofossil axis 1 reflects the development of macrophyte and salt-marsh vegetation in response to the freshwater and fine silt input from the Canal. Small changes in the macrofossil animal axes reflect the increase of freshwater types, perhaps brought in by the canal. Small changes in the pollen axes are due to small changes in the proportion of tree and shrub pollen and the expansion of *Eucalyptus* that was widely planted at this time (Ramdani et al., 2001a). After 1965, the decline in plant macrofossil axis 2 reflects salt-marsh development and the influx of terrestrial weed remains to the core site. The first diatoms were recorded from ca. 1980, with a largely epiphytic flora dependent on the macrophytes.

From 1985 to 1990 there were large ecosystem changes. Perhaps aggravated by increased inflow of nutrients and pesticides (Peters et al., 2001) and probably by a change in the courses of the inflow channels, conditions for the growth of macrophytes and nearby salt-marsh deteriorated rapidly. At the same time, the macroscopic fauna declined, even lagoon animals such as the fish, molluscs, ostracods, and foraminifera. The freshwater zooplankton taxa declined and saltwater taxa increased. The diatoms showed a dramatic response, with replacement of epiphytic taxa by increasing epipellic taxa as macrophyte vegetation was replaced by open mud. The diatoms also reflected an increase in salinity. During this period, pollen changes result from increases in crops and weed pollen, following the intensification of agriculture. The ecosystem trends continued from 1985 to the present day (1997), the most marked being the continued increase in diversity and percentages of epipellic diatoms. Zooplankton axis 1 explains nearly 50% of the variation in the zooplankton record, but the changes in the assemblage are gradual with

no major response to the construction of the Canal, only a gradual decline of ca. 0.5 SD units up to 1990 (ca. 35 years). Since 1990, zooplankton axis 2, previously constant, declined, probably caused by the reduction in fossil concentration and the loss of several species in all the groups.

Merja Zerga (Morocco) DCA scores

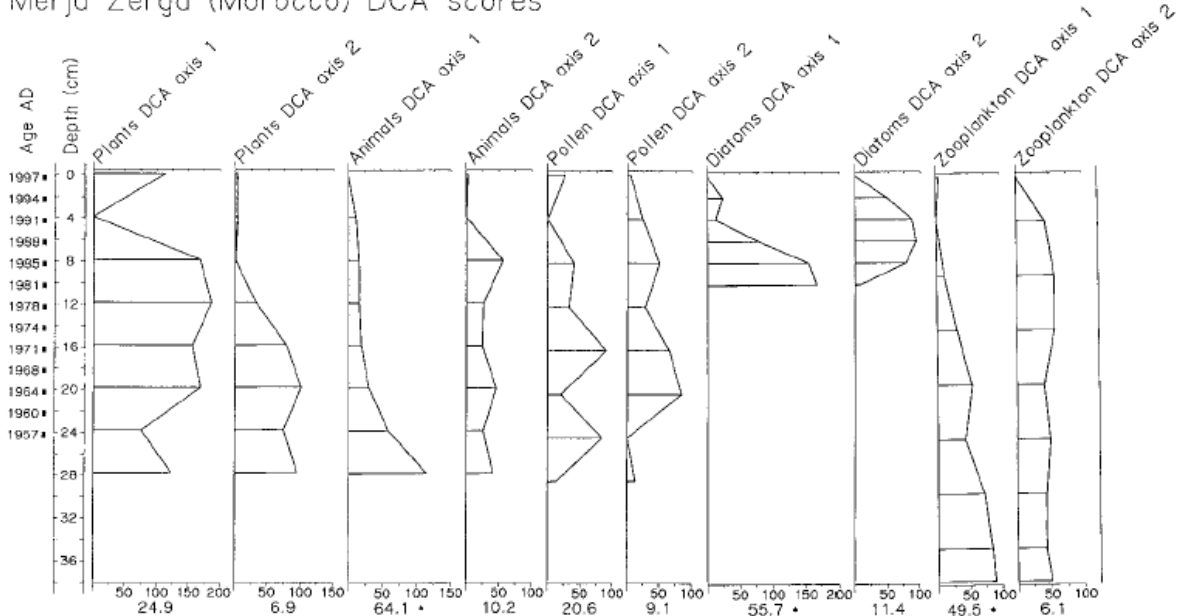


Figure 4. Merja Zerga (Morocco). Stratigraphical plots of sample scores on the DCA axes accounting for >5% of the variance for organism groups. The % variability accounted for by each axis is shown. * indicates that the axis is significant as assessed by comparison with a broken stick model. The horizontal scales are in SD units \times 100 (see text) drawn to the same scale. The chronology is from Appleby et al. (2001).

There are two times of major change at Merja Zerga. After the construction of the Canal du Nador in 1953, the sediment type and water quality changed substantially, allowing macrophyte vegetation with associated animals to develop on the soft silty bottom. Then, around 1985, the ecosystem suffered a major change with the elimination of macrophytes over about 5 years and an increase in salinity. The cause is uncertain. During the severe drought period in the 1980s, winter freshwater supply to the Merja was reduced as much of it was taken for irrigation and the freshwater table dropped (Ramdani et al., 2001a). Changes resulting from altered sedimentary deposition patterns in combination with less freshwater and increased fertilizer and pesticide inputs, may have crossed the resilience threshold. The changes were so recent that it is hard to know if the system has reached a new equilibrium. The changes revealed in the CASSARINA cores may be local around the coring site, due to its proximity to the Canal. Without further investigation, it is not possible to extend these conclusions to the whole large lagoon. However, in spite of its conservation status, changes in the catchment are continuing, with expansion of agriculture, increasing freshwater withdrawal, and increasing local population (Ramdani et al., 2001a).

Merja Bokka, Morocco. 34°25'N, 6°12'E (Figure 5)

Merja Bokka was an inland freshwater lake fed by a stream in the wide marshy Sebou river valley (Ramdani et al., 2001a). The changes at the base of the animal macrofossil axes result mainly from a steep decrease in molluscs. The more gradual overall decline in zooplankton axis 1 reflects changes in the balance of ostracod species and the start of curves of chironomid taxa. Fairly stable conditions were maintained up to ca. 65 cm. The changes in the plant macrofossil axes between 65 and 50 cm represent a pronounced development of macrophytes typical of high conductivity calcareous water. The large change in animal macrofossil axis 1 of ca. 1 SD unit is due to the major re-expansion of freshwater molluscs. The diatom record starts with an assemblage characteristic of calcareous water with some degree of salinity,

shown by a high proportion of mesohalobous taxa. Zooplankton axis 1 starts a steady decline of ca. 1.35 SD units at 65 cm to 0 at 15 cm, resulting from changes in the balance of ostracod and cladocera species, responding to increasing eutrophication and salinity. The macrophyte and animal (mollusc and ostracod) macrofossil assemblages stayed more or less constant, but at ca. 40 cm the diatom axis 1 drops by about 1 SD unit as *Anomooneis sphaerophora* declined and a more freshwater assemblage dominated by epiphytic taxa developed.

The continued decline in zooplankton axis 1 and the small rise in axis 2 reflect the rise in the cladocera *Chydorus sphaericus* and *Alona* spp. at ca. 40 cm, which together with the increase of the macrophyte *Ceratophyllum demersum*, suggest nutrient enrichment. The effects of freshwater irrigation are shown by the decline in pollen axis 2 above 60 cm and the steep decline in pollen axis 1 between 34 and 17 cm, with the decrease of *Chenopodiaceae*, *Gramineae*, and *Scirpus*, and the rise of *Typha* and *Carex* suggesting the expansion of *Typha* marshes along the lake shore as the lake-level fell.

Large changes occur between 15 and 10 cm, from about 1960 to 1980. The abrupt fall of ca. 1.5 SD units in plant macrofossil axis 1 is caused by a steep decline in *Chara* and *Ruppia* and their rapid replacement by *Zannichellia* and *Ranunculus* sect. *Batrachium*, characteristic of shallow disturbed ponds, the development of *Typha* marsh and *Panicum* in shallow water, and the appearance of weed macrofossils. The equally steep fall in animal macrofossil axis 1 is caused by the disappearance of freshwater molluscs and the expansion of small invertebrates characteristic of disturbed habitats that tolerate seasonal desiccation. A similar change is seen in the zooplankton assemblage, to a predominance of types typical of temporary water bodies that survive drought as dormant eggs. From 1980 to 1997, the diatom axes fluctuate and show a steep decline, reflecting the replacement of most of the taxa by *Nitzschia* and *Navicula* spp. and *Achnanthes delicatula* as disturbance increased.

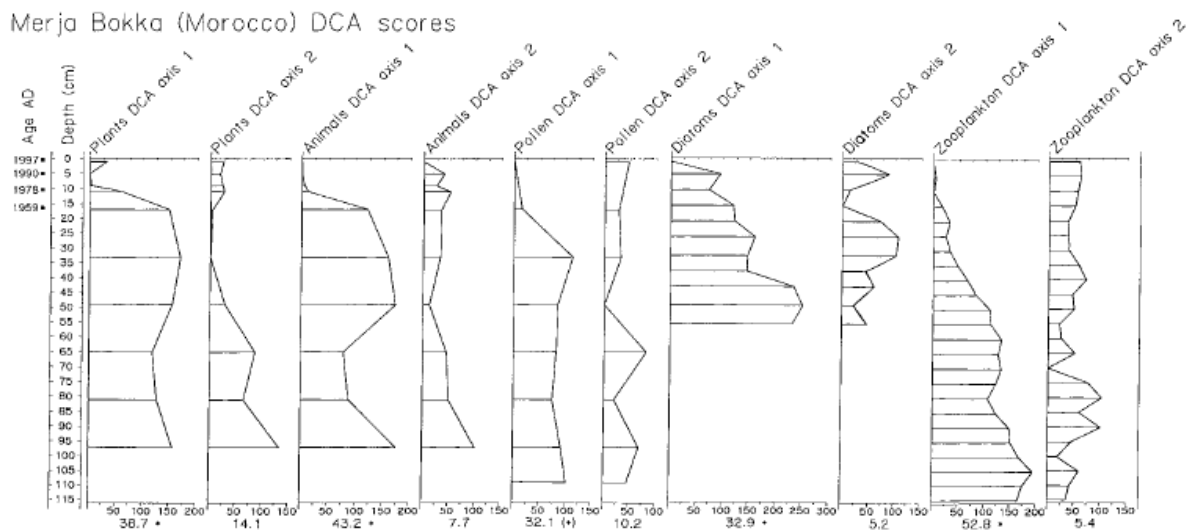


Figure 5. Merja Bokka (Morocco). Stratigraphical plots of sample scores on the DCA axes accounting for >5% of the variance for organism groups. The % variability accounted for by each axis is shown. * indicates that the axis is significant; (*) is on the border of significance; as assessed by comparison with a broken stick model. The horizontal scales are in SD units \times 100 (see text) drawn to the same scale. The chronology is from Appleby et al. (2001).

The DCA axes summarise the changes at Merja Bokka very powerfully. Above ca. 65 cm, the ecosystem responded to environmental changes in a resilient and sustainable way, with the development of an aquatic ecosystem based on a rich macrophyte vegetation in clear water and associated fauna with abundant molluscs, ostracods, and cladocera, and a rich, largely epiphytic diatom flora. However, hydrological alterations intensified during the 1950s as more efficient land-drainage and irrigation schemes were implemented (Ramdani et al., 2001a). As inflow was reduced and water level fluctuated, marginal soil was washed in, exacerbated by cultivation within the reedswamp around the lake. The water

became turbid and shallow and the macrophyte vegetation changed dramatically, together with its associated fauna and diatom flora. The lake temporarily dried up during the 1980s drought period (Ramdani et al., 2001a). During the CASSARINA monitoring period in 1998, the lake became permanently dry and the lake-bed was cultivated (Flower, 2001). During the 1970s, the environmental stress on the ecosystem exceeded its resilience and caused it to switch dramatically from a permanent clear-water lake to a disturbed shallow lake with fluctuating water levels. No lake ecosystem can survive the loss of its water, and the formerly rich and diverse Merja Bokka is now lost.

Megene Chitane, Tunisia. 37°11'N, 9°10'E (Figure 6)

This small lake is the only CASSARINA lake with mildly acid, dilute water (Figure 1) and its fauna and flora are distinct. Most of the DCA axes show rapid changes in the mid-late 1960s. The plant macrofossil axes react to the addition of abundant *Isoetes velata* and *Juncus* spp. to the *Nymphaea* and *Callitriche* assemblage, and the animal axes reflect the expansion of *Plumatella* and oribatid mites. The strong decline of ca. 1.5 SD units in diatom axis 1 and the rise in diatom axis 2 express the dramatic change from a flora typical of clear-water, shallow, oligotrophic lakes with aquatic macrophytes to a mildly saline assemblage indicative of nutrient enrichment. This rapidly became dominated by the epiphyte *Achnanthes exigua* and taxa of damp soil, probably derived from a seasonally exposed littoral zone. The latter declined towards the top of the profile, as the upper littoral zone was colonised by herbaceous plants (Ramdani et al., 2001a). The change in the epiphytic diatom flora coincides with the change in the submerged and emergent plants to species that tolerate shallow fluctuating water levels and summer desiccation and the deposition of hard minerogenic sediment. Zooplankton changes in the 1960s also reflect disturbance and eutrophication. Subsequent minor changes in the DCA curves show trends in all groups towards increasingly shallow water, summer desiccation of the littoral zone, and nutrient enrichment by fertiliser applications upstream as local cultivation expanded in the 1980s, as evidenced in the pollen record.

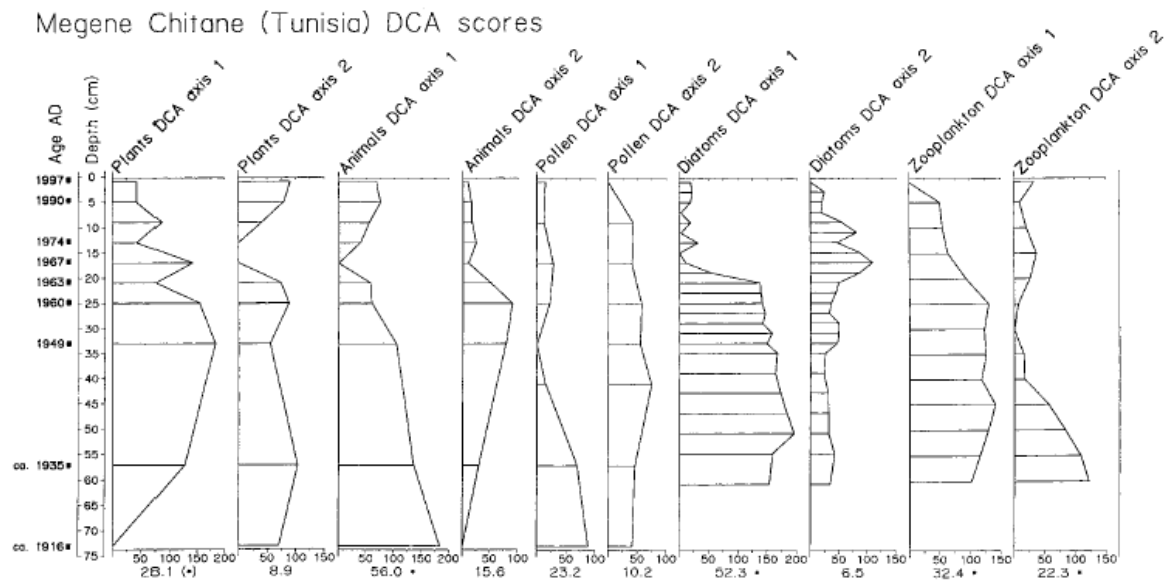


Figure 6. Megene Chitane (Tunisia). Stratigraphical plots of sample scores on the DCA axes accounting for >5% of the variance for organism groups. The % variability accounted for by each axis is shown. * indicates that the axis is significant as assessed by comparison with a broken stick model. The horizontal scales are in SD units \times 100 (see text) drawn to the same scale. The chronology is from Appleby et al. (2001).

The DCA curves suggest a relatively stable oligotrophic lake ecosystem persisted from the early 20th century to the late 1960s, with only minor readjustments in the plant assemblage at the base of the core. However, the pollen axes reflect changes in the catchment, as cultivated fields were abandoned and

replaced by *Quercus*-dominated woodland and scrub during this time. M. Chitane showed a resilient response to the unknown causes of accelerated organic coarse sediment deposition during the 1940s and 1950s (Appleby et al., 2001) with no significant faunal or flora changes apart from a response in Cladocera. However, a strong reaction was shown by all aquatic groups during the late 1960s, with a rapid response to shallowing water and nutrient enrichment that crossed the tolerance threshold and catastrophically altered the whole ecosystem when water was diverted for irrigation. The lake maintained this character for several decades, but warmer and drier summers in the last 20 years have also reduced the flow of the aquifer springs that feed the lake (Ramdani et al., 2001a) and recently the lake has dried up in summer and emergent plants are advancing to its centre. Eutrophication and continued summer water withdrawal has transformed the ecosystem into an unstable state, similar to that of Merja Bokka in its final phase. If the environmental stresses continue unabated, Megene Chitane will also become permanently dry in a few years. Its unique oligotrophic ecosystem supports several organisms not or rarely found elsewhere in N. Africa, notably several cool-water cladocerans and the charophyte *Nitella opaca*. In spite of being a nature reserve since 1993, this little island of biodiversity with its rare biota is under severe threat and needs immediate action to protect and restore it.

Garaet El Ichkeul, Tunisia. 37°02'N, 9°48'E (Figure 7)

This large lake is connected to the sea, and formerly had a seasonal salinity regime with freshwater supply increasing with the winter rainfall and decreasing during summer. This supported extensive *Phragmites* and *Scirpus* marshes and weed-beds dominated by *Potamogeton pectinatus*, a diverse ecosystem especially favourable to bird life. The area is a Biosphere reserve, a Ramsar site, and a World Heritage Site, and became a National Park in 1980 (Kraïem & Ben Hamza, 2000; Ramdani et al., 2001a).

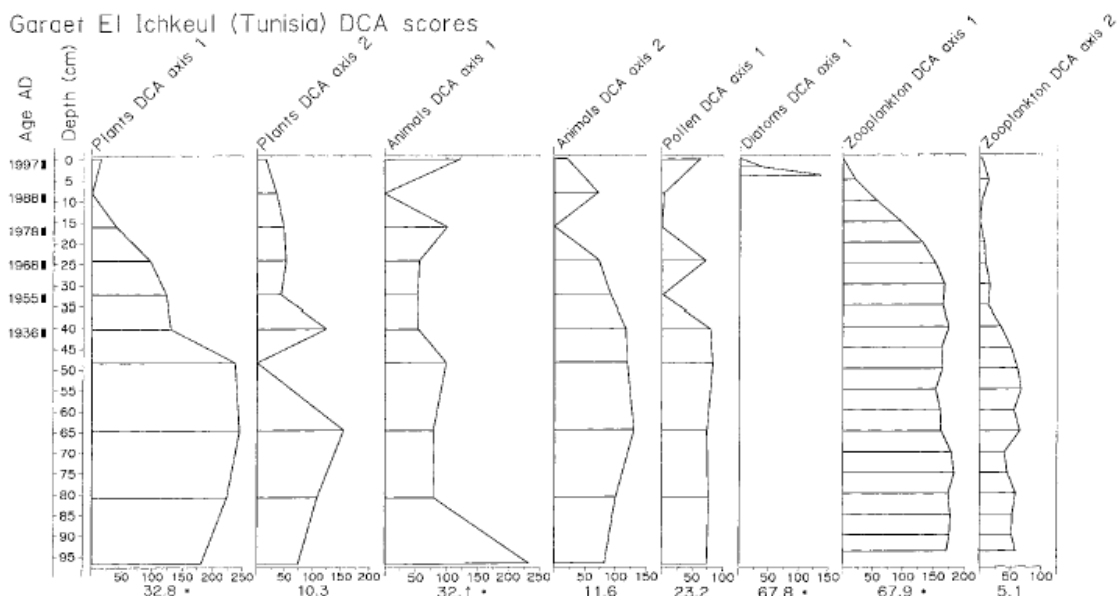


Figure 7. Garaet El Ichkeul (Tunisia). Stratigraphical plots of sample scores on the DCA axes accounting for >5% of the variance for organism groups. The % variability accounted for by each axis is shown. * indicates that the axis is significant as assessed by comparison with a broken stick model. The horizontal scales are in SD units \times 100 (see text) drawn to the same scale. The chronology is from Appleby et al. (2001).

The recent history of the lake is summarised by the DCA curves (Figure 7). The large drop in animal macrofossil axis 1 at the base is an artefact caused by the lack of ostracod and foraminifer analyses in the lowest sample. The lake ecosystem was stable until the early 20th century. The plant macrofossil axes then respond around 40–50 cm to the development of the *Potamogeton* and *Ruppia* weed-beds and

the reed-marshes. Animal macrofossil axis 1 reflects the establishment of lagoon molluscs at this time, but there was little overall change in the diverse zooplankton assemblages. This ecosystem was sustained with only minor changes in the balance of species until the 1980s, when the freshwater supply was increasingly withdrawn (Ramdani et al., 2001a). The decline of plant macrofossil axis 1 results from the decrease of macrophytes and terrestrial taxa (the latter is the effect of reduced inflows) and the expansion of saltmarsh at the expense of reed-marsh. Lagoon molluscs declined and marine and estuarine foraminifera and the brackish-water ostracod *Loxoconcha elliptica* expanded. Zooplankton axis 1 declined steadily above ca. 1970, steepening after ca. 1980 when foraminifera and ostracods declined and brackish-water cladocera and chironomids appeared. This apparent salinity reduction is contrary to the implications of the changes in the macrofossil assemblages, and diatoms also indicate saline conditions in the 1990s. Increased sediment disturbance and turbidity are strongly reflected in the pollen assemblages by a large increase in indeterminable destroyed pollen.

The seasonal salinity in Ichkeul strengthened after the Bizerte Ship Canal, constructed in 1895, made a more effective sea connection. The DCA curves indicate a resilient, flexible ecosystem. After ca. 1980, all the curves move in different ways, following catastrophic ecosystem changes and loss of stability as freshwater inflows were successively dammed and diverted. A new ecosystem state has developed over about 20 years. The macrophyte beds and extensive reed-marsh habitats have been dramatically destroyed, and the rich biodiversity and conservation value of the site have been severely reduced.

Lac de Korba, Tunisia. 36°46' N, 11°00' E (Figure 8)

Large changes in the plant macrofossil axes in the lower part of the profile probably reflect changes in salt-marsh vegetation around the long and narrow Lac de Korba lagoon over the last 2–300 years probably as the connections to the sea through the sand-dune barrier altered. Small changes in the animal macrofossil axes suggest that the lagoon itself was fairly stable. During the last century local changes occurred, as lagoon molluscs decreased gradually at the coring site, but the macrophyte and salt-marsh vegetation persisted relatively unaltered. Zooplankton axis 1 declines steadily, caused by a progressive change in the balance of the foraminiferan and ostracod taxa and the gradual increase of salt-water chironomids and a cladoceran *Moina salina*.

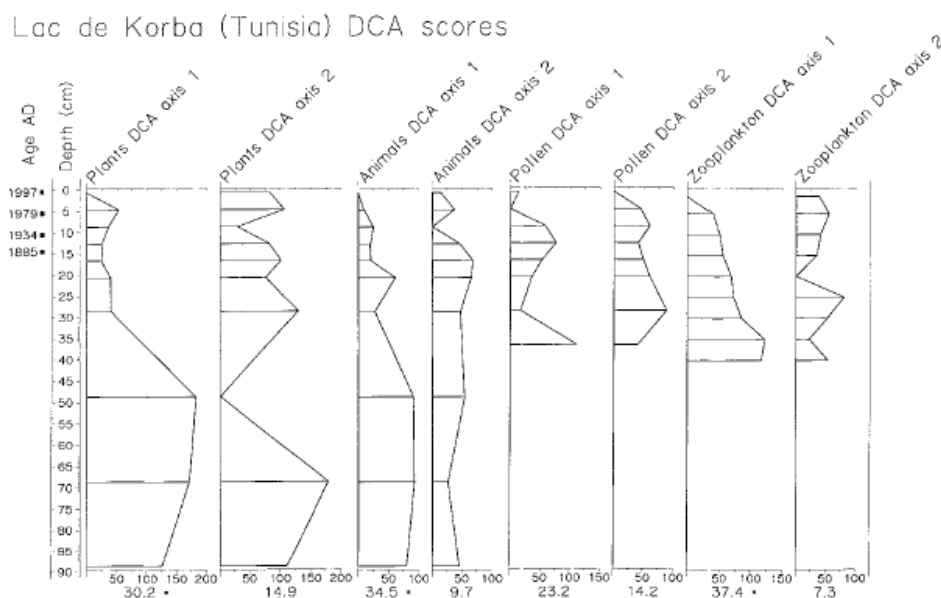


Figure 8. Lac de Korba (Tunisia). Stratigraphical plots of sample scores on the DCA axes accounting for >5% of the variance for organism groups. The % variability accounted for by each axis is shown. * indicates that the axis is significant as assessed by comparison with a broken stick model. The horizontal scales are in SD units \times 100 (see text) drawn to the same scale. The chronology is from Appleby et al. (2001).

All the DCA curves decrease in the top 5 cm, suggesting a simultaneous response to environmental changes over the last 20 years. During this time, Korba town and its industry have developed with the consequent increase in pollution by heavy metals (Birks et al., 2000a), sewage, rubbish, and industrial wastewater. Agriculture has also intensified with consequent release of nutrients and pesticides to the lake and withdrawal of irrigation freshwater from the inflows and from the water-table by wells (Kraïem & Ben Hamza, 2000; Ramdani et al., 2001a). Pollen axis 1 reflects a replacement of Gramineae by Chenopodiaceae pollen percentages, perhaps indicating an advance of saltmarsh as the lagoon became shallower. The water is currently hypersaline (Figure 1) and the former macrophytes have been largely replaced by *Enteromorpha* and *Ulva*. The northern sector is now permanently dry, and other parts dry up in summer. These changes are deleterious to the important bird populations, which have been decreasing in recent years, even though the lagoon is a nature reserve.

The recent changes are the response to increasing human pressure resulting from agriculture and housing development. The formerly stable and resilient ecosystem of Lac de Korba is being destabilized. It is to be hoped that the conservation and restoration measures to maintain its biodiversity and amenity value (Kraïem & Ben Hamza, 2000) will take good effect.

Edku Lake, Egypt. 31°15'N, 30°15'E (Figure 9)

Edku is a large lake in the Nile Delta linked to the Mediterranean Sea. Its area is being rapidly reduced by land reclamation (Ramdani et al., 2001a). At the core base (Figure 9), the turnover of animal macrofossils reflects the disappearance of saline molluscs, foraminifera, and ostracods, and the expansion of freshwater taxa such as *Plumatella*. The plant macrofossil and pollen records also suggest a change to mixed saline/freshwater conditions, with halophytic vegetation on the shores. Above 65 cm, overall salinity increased, causing a sharp decline in *Plumatella* reflected in animal macrofossil axis 2. Large changes occurred around 50 cm. The dramatic decline in plant macrofossil axis 1, of about 2 SD units between 50 and 33 cm (ca. 30–40 yr), is caused by a huge expansion and then extinction of *Azolla nilotica*, a corresponding rise and fall of brackish-water macrophytes and saltmarsh/sandy soil taxa, and the subsequent expansion of taxa more typical of high conductivity freshwater with some nutrient enrichment. A corresponding peak in animal macrofossil axis 1 is caused by the short-lived dominance of lagoon molluscs and foraminifera. The subsequent steep decline of ca. 1.25 SD units reflects the dramatic decrease in the marine and lagoon types and the appearance and subsequent gradual increase in freshwater taxa after ca. 1920 (42 cm). Pollen axis 1 shows a major change at the same time, caused by a peak and decline in *Phragmites*-type pollen, a decline in Chenopodiaceae (salt-marsh), rises of Gramineae and *Typha domingensis*-type (indicating fresher water), and the appearance of many pollen types of trees, shrubs, weeds, and crops, including introduced *Casuarina* and *Eucalyptus* trees. The peak in pollen axis 2 at ca. 1940 reflects increases of *Typha* and *Casuarina*. Intensive year-round cultivation near the lake was initiated following Nile flood control measures and irrigation. Zooplankton axis 1 starts a steady decline from ca. 1930–1960, as foraminifera decrease and freshwater Cladocera, ostracods, chironomids, and mollusca appear and expand, reflecting increasingly fresher water conditions. The other DCA curves show steady values or trends between ca. 1920 and 1960. All organisms point to reduced marine influence and an increase in nutrients. Diatoms are preserved in the sediment younger than ca. 1950. The oligohalobous assemblage with a few mesohalobous types that gradually increase, is dominated by *Cocconeis placentula*, flourishing on the abundant macrophytes.

Marked changes in the DCA curves are apparent in the 1960s, when the Aswan High Dam was built. The plant macrofossil axes respond to increases in *Potamogeton pectinatus*, nutrient-demanding taxa such as *Lemna* and *Ceratophyllum*, and the introduced *Azolla filiculoides* and *Eichhornia*, together with the expansion of *Typha* reed-marsh. Changes in the animal macrofossil axes reflect the increase of freshwater animals, fish, and particularly gastropods, but also the transient abundance of lagoon molluscs and foraminifera which peak and then decline during the 1970s and 1980s. The steep decline in diatom axis 1 and the rise in diatom axis 2 result from the reduction of *Gomphonema gracilis* and *Nitzschia*

amphibia, and the appearance of *Navicula* spp. and *Bacillaria paradoxa*. Zooplankton axis 1 falls more steeply, as the foraminifera record ceases, saline ostracods decline, and freshwater gastropods, ostracods, and chironomids increase, together with the cladoceran *Chydorus sphaericus* that thrives on nutrient enrichment and disturbance. At the top of the sequence the changes in the plant and animal macrofossil curves are caused by the scarcity of macrofossils in the loose surface sediment. The trends continue in the diatom and zooplankton assemblages. The ecosystem appears to be unstable at present, as the movements of the DCA curves continue to the top samples in the cores, continually responding to the maintained environmental stress.

Edku Lake (Egypt) DCA scores

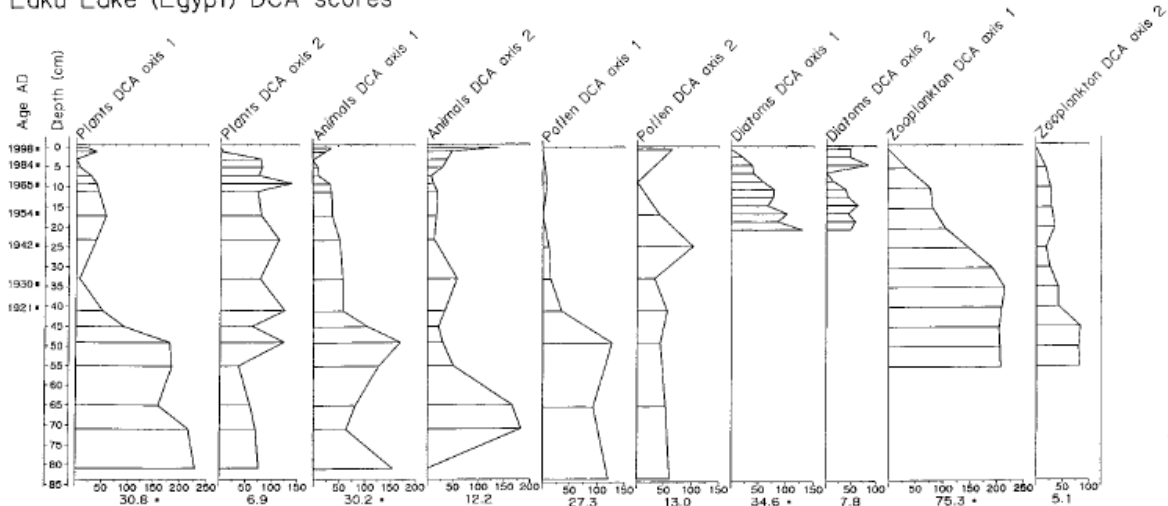


Figure 9. Edku Lake (Egypt). Stratigraphical plots of sample scores on the DCA axes accounting for >5% of the variance for organism groups. The % variability accounted for by each axis is shown. * indicates that the axis is significant as assessed by comparison with a broken stick model. The horizontal scales are in SD units \times 100 (see text) drawn to the same scale. The chronology is from Appleby et al. (2001).

Burullus Lake, Egypt. 31°21'–35'N, 30°31'–31°10'E (Figure 10)

Burullus Lake in the Nile Delta has a more effective connection to the sea than Edku or Manzala Lakes. Its water is more saline (Figure 1) supporting the macrophytes *Potamogeton pectinatus*, *Ruppia maritima*, and *Najas armata*, and halophytic vegetation occupies many shores and islands (Khedr, 1999), although freshwater influence is allowing reed-marsh and freshwater macrophytes to spread around drain inflows. It is a Ramsar reserve.

Of the two Burullus cores, BURL-1 with the zooplankton record is from open water distant from the shore and only the top 9 cm is considered to be recent sediment post-dating 1950 (Appleby et al., 2001). The other records are from core BURL-2 taken at the north shore near reed-marsh vegetation where sedimentation is likely to have been continuous. Therefore the depths of the zooplankton and other records on the DCA axes in Figure 10 are not time-comparable. Diatoms were preserved only at the base and the top of core BURL-2.

The lake underwent seasonal salinity cycles related to the annual Nile flood. In the lowest sediments of the marginal core, the macrofossil and pollen assemblages suggest both freshwater and brackish vegetation, with reed-swamp of *Phragmites* and other grasses, *Scirpus maritimus*, and *Typha*, and *Chenopodiaceae* dominated communities on sand and mud. Macrophytes were few, but *Azolla nilotica* occurred. The diatom assemblage also contained a mixture of polyhalobous and freshwater species. Animal macrofossil axis 1 falls above 54 cm as freshwater *Plumatella* and *Daphnia* were replaced by brackish ostracod and foraminifera taxa. Marked changes in the plant macrofossil axes and animal macrofossil axis 2 around 34 cm and the continued fall of animal macrofossil axis 1 reflect a substantial increase in salinity and perhaps a water-level rise. Reed-swamps retreated, saline-tolerant *Ruppia* expanded, and lagoon molluscs appeared and expanded. Halophytic shore-line vegetation predominated.

The decrease in pollen axis 2 is probably due to increased representation of terrestrial pollen types, including *Artemisia*.

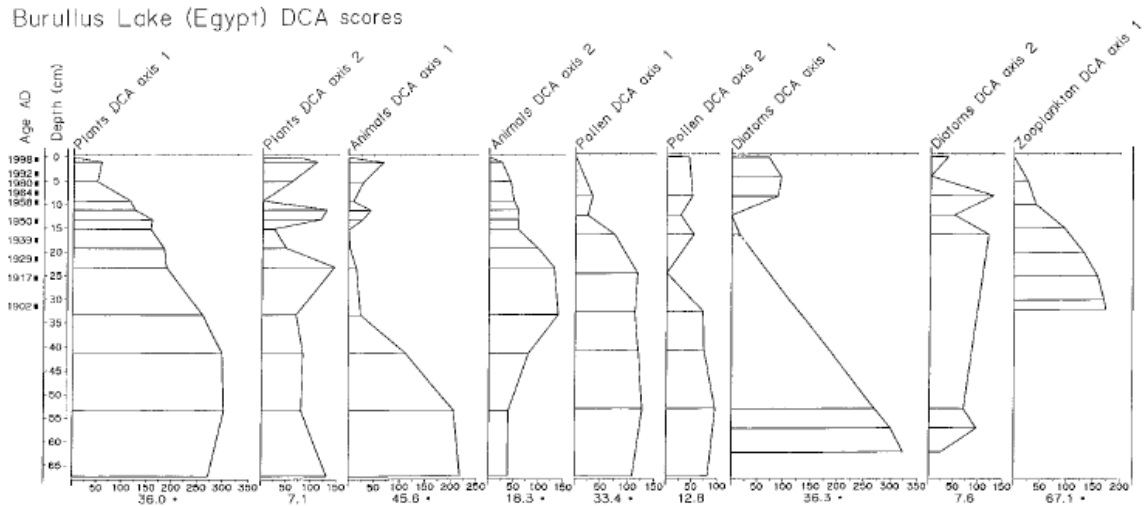


Figure 10. Burullus Lake (Egypt). Stratigraphical plots of sample scores on the DCA axes accounting for >5% of the variance for organism groups. The zooplankton record is from core BURL-1 taken from the open water. The other records are from core BURL-2 taken near the shore. The % variability accounted for by each axis is shown. * indicates that the axis is significant as assessed by comparison with a broken stick model. The horizontal scales are in SD units \times 100 (see text) drawn to the same scale. The chronology is from Appleby et al. (2001).

Between ca. 1920 and ca. 1950 (25–15 cm) salinity declined once more. The peak in plant macrofossil axis 2 records the arrival of macrophytes tolerant of high conductivity and moderate salinity that joined *Ruppia* and *Azolla nilotica*. The fall in animal macrofossil axis 2 is probably related to the arrival of freshwater gastropods such as *Melanoides tuberculata* and *Biomphalaria alexandrina*. The decline in pollen axis 1 follows the gradual decline of Gramineae pollen and the start of an increase in *Typha*. The zooplankton record is composed of brackish taxa of cladocera, ostracods, and chironomids mixed with some freshwater forms. The gradual decline in zooplankton axis 1 reflects the gradual reduction of all cladocera and the rise of other groups, mainly the brackish-water ostracods *Limnocythere inopinata* and *Loxoconcha elliptica*. After ca. 1950, the steeper decline in plant macrofossil axis 1 reflects large rises of *Ruppia* and *Typha*. The irregularity of plant macrofossil axis 2 is caused by intermittent representation of salt-marsh and upland plants. The irregular rise in animal macrofossil axis 1 is due to increases in freshwater *Daphnia*, *Plumatella*, and gastropods. Although freshwater influence increased, the balance between freshwater and saline influence was maintained, and lagoon molluscs and foraminifera were not reduced in either the macrofossil or the zooplankton records.

After the mid-1960s sharp changes in the plant macrofossil axes summarise the decline of *Ruppia*, the expansion of *Potamogeton pectinatus*, and the appearance of *Ceratophyllum*. *Azolla nilotica* became extinct. The changes in the animal macrofossil axes reflect the increased abundance of freshwater gastropods and the entry of new species. The change in pollen axis 1 represents a large increase in *Typha* pollen, in accord with the increase in *Typha* fruits, and in *Potamogeton pectinatus*-type pollen. The diatom axes reflect the replacement of *Thalassiosira* cf. *decipiens* and *Mastogloia* spp. by *Cymbella pusilla* and *Brachysira aponina* near the top of the core.

During the time covered by sediment core BURL- 2, Burullus Lake has received substantial saline influence, even at the core location ca. 20 km from the sea connection (Ramdani et al., 2001a). The balance of reed-marsh and halophytic vegetation has fluctuated over the last ca. 200 years. Since the 1960s, salinity has decreased and productivity has increased. *Potamogeton pectinatus* has become the dominant macrophyte across much of the lake and the record of fish remains has increased. The continuing changes in the DCA curves suggest, however, that the ecosystem balance is dynamic, and therefore uncertain. The lake is presently affected by pollution from Delta drains to the south, but the most

serious threats are probably accelerating land reclamation and the rapid expansion of urban communities (Ramdani et al., 2001a). Environmental impacts are poorly managed and are damaging the biodiversity and habitats, and also causing human health problems with socio-economic implications (Khedr & Lovett-Doust, 2000).

Manzala Lake, Egypt. 31°00'–31°30'N, 31°45'–32°1'5E (Figure 11)

This is the largest Delta lake. It is badly affected by pollution in the eastern part (Zalat, 2000) and accelerating land reclamation is rapidly reducing its area. Brackish parts support halophytic vegetation (Zahran & Willis, 1992) but species diversity increases in the south and west under the influence of fresh, nutrient rich drainage water (Khedr, 1997; Shaheen & Yousef, 1980). The cores were taken from this part of the lake (see Ramdani et al., 2001a), a relatively unpolluted area with extensive reed-marshes and cover of *Eichhornia crassipes*. At the base (19th century) (Figure 11) the animal and plant macrofossils imply brackish water conditions, probably fluctuating seasonally. The drop in animal macrofossil axis 2 above 72 cm reflects the increase of lagoon molluscs. Above 57 cm (late 19th century), plant macrofossil axis 1 falls dramatically by 2 SD units over 10 cm and axis 2 increases strongly at the same time. This is caused by the sudden extinction of *Azolla nilotica* that was previously abundant, and declines of *Typha* and salt-marsh Chenopodiaceae. This large floral change is interpreted as a water-level rise and increase in salinity, perhaps due to a sea incursion. The pollen axes detect a small response in the terrestrial ecosystem as a decrease in Gramineae, probably associated with the reduction of reed-marsh, and an increase in Chenopodiaceae and terrestrial pollen types. The animal axes remain steady and molluscs, ostracods, and foraminifera typical of saline lagoons were abundant. The zooplankton at the base of core MANZ-1 also indicate saline conditions with no freshwater taxa.

The DCA curves start to change around 30 cm, dated to ca. 1920 (Appleby et al., 2001). In particular, zooplankton axis 1 falls steeply and axis 2 rises, as a result of the entry and expansion of freshwater Cladocera and ostracods and the reduction of the saline taxa. The plant macrofossil axes reflect the expansion of macrophytes tolerant of high conductivity and moderate salinity, including *Ceratophyllum*. The animal macrofossil axes show small changes associated with the arrival of a few freshwater gastropods and an increase in fish remains. There were small changes in the pollen record, which is dominated by Chenopodiaceae. The vegetation of Manzala Lake was recorded in 1935 by Montasir (1937) as dominated by halophytic communities of salt-marsh and shoreline sands and shelly deposits. Reed-marshes were restricted around the mouths of irrigation drains at that time.

This brackish ecosystem persisted until around 1945 (ca. 17 cm). The subsequent changes in plant macrofossil axis 1 are caused by the marked increase in *Typha* and macrophytes including *Ruppia*, Characeae, *Ceratophyllum*, and *Najas armata*. Freshwater animals increased and more freshwater gastropod species arrived and expanded, whereas lagoon molluscs and foraminifera started to decline. The zooplankton record shows similar changes as freshwater Cladocera, including *Chydorus sphaericus*, and ostracods increased and brackish taxa continued to decline. The fall in pollen axis 1 results from the decrease in Chenopodiaceae and the rise of *Typha*, as reed-marsh expanded at the expense of salt-marsh. Diatoms were preserved in sediments post-dating ca. 1940, with a mixed brackish-water epipelagic/freshwater epiphytic assemblage, probably reflecting the seasonal salinity cycle. Diatom axis 1 falls steeply after the mid 1940s, due to a strong increase in oligohalobous species at the expense of meso- and polyhalobous species, resulting in a change of ca. 1 SD unit in axis 1 over ca. 20 years. Above 8 cm, in the mid-1960s, the directions of the DCA axes change. Irregular peaks in the plant and animal macrofossil axes reflect different taxa peaking and declining in abundance at different times, such as the arrival of *Azolla filiculoides*, the expansion of *Typha*, maxima of oribatid mites and *Plumatella*, and the abundance of freshwater gastropods. Meanwhile lagoon molluscs and foraminifera almost disappeared. The falls in the pollen axes reflect the further rise of *Typha* and decline of Chenopodiaceae and the expansion of planted *Casuarina* and *Eucalyptus* trees. The recent aquatic vegetation changes have been documented by Khedr (1997). Diatom axis 1 shows a steep decline and axis 2 a small rise. The oligohalobous assemblage dominated by *Fragilaria brevistriata* was replaced by mesohalobous taxa such as *Brachysira aponina*,

Nitzschia elegantula, and *Cymbella pusilla*, a different suite of taxa from the mesohalobous assemblage of the 1940s.

The rapidly fluctuating DCA curves imply that further changes in this part of Manzala Lake can be expected as environmental stress continues. Although still relatively unpolluted, the nutrient load from agriculture and sewage has increased and the circulation of sea water has been reduced by land reclamation and reed-swamp development between the sampling site and the sea (Ramdani et al., 2001a). *Eichhornia crassipes* now blankets the lake, accompanied by *Azolla filiculoides* (Khedr, 1997). The resulting winter anoxia and eutrophication has reduced fish productivity. This part of the lake seems to be resilient at present, but the DCA curves indicate that the ecosystem is in flux, and the extent of its adaptability is uncertain, especially as the vital sea/freshwater circulation is being reduced.

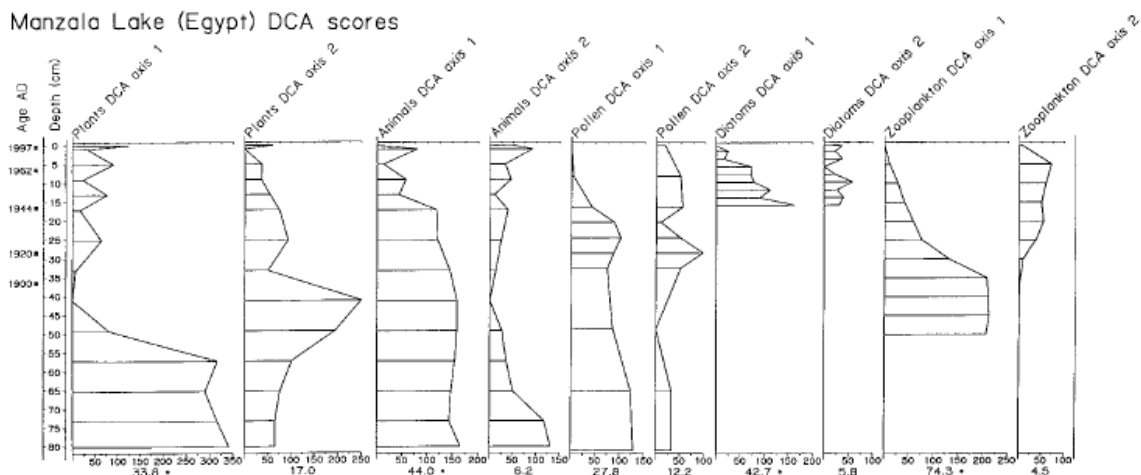


Figure 11. Manzala Lake (Egypt). Stratigraphical plots of sample scores on the DCA axes accounting for >5% of the variance for organism groups (4.5% for Zooplankton DCA axis 2). The % variability accounted for by each axis is shown. * indicates that the axis is significant as assessed by comparison with a broken stick model. The horizontal scales are in SD units \times 100 (see text) drawn to the same scale. The chronology is from Appleby et al. (2001).

Natural changes in the Delta Lake ecosystems have been considerable over the last ca. 150 years. Before ca. 1920, large salinity changes were caused by variations in the balance between the influx of sea water and the seasonal freshwater inflow from the Nile floods. Marked and rapid responses occurred in the aquatic ecosystems, but they were resilient and remained in balance with the environmental forcing. The fauna and flora were able to survive adverse periods and expand when conditions became suitable for them. The terrestrial vegetation was typical Chenopodiaceae-dominated salt-marsh and sandy soils that was universal around all the Delta Lakes (Montasir, 1937; Zahran & Willis, 1992).

A fundamental hydrological change became apparent around the 1920s, as year-round freshwater irrigation was increased by successive Nile barrage schemes, which culminated in the closure of the Aswan High Dam in 1964 (Waterbury, 1979). The effects of the transformation of the seasonal Nile flow to perennial irrigation combined with inefficient drainage were registered by the colonisation and subsequent increase of, in particular, freshwater gastropods, some species of which carry bilharzia, and the expansion of reed-marsh at the expense of halophytic vegetation. Burullus Lake remains brackish today (Figure 1) and so far, its ecosystem has absorbed the freshwater increase. However, Edku and Manzala Lakes developed freshwater ecosystems that were new in the lakes' recent history. Reeds expanded and macrophytes be Natural changes in the Delta Lake ecosystems have been considerable over the last ca. 150 years. Before ca. 1920, large salinity changes were caused by variations in the balance between the influx of sea water and the seasonal freshwater inflow from the Nile floods. Marked and rapid responses occurred in the aquatic ecosystems, but they were resilient and remained in balance with the environmental forcing. The fauna and flora were able to survive adverse periods and expand when

conditions became suitable for them. The terrestrial vegetation was typical Chenopodiaceae-dominated salt-marsh and sandy soils that was universal around all the Delta Lakes (Montasir, 1937; Zahran & Willis, 1992). A fundamental hydrological change became apparent around the 1920s, as year-round freshwater irrigation was increased by successive Nile barrage schemes, which culminated in the closure of the Aswan High Dam in 1964 (Waterbury, 1979). The effects of the transformation of the seasonal Nile flow to perennial irrigation combined with inefficient drainage were registered by the colonisation and subsequent increase of, in particular, freshwater gastropods, some species of which carry bilharzia, and the expansion of reed-marsh at the expense of halophytic vegetation. Burullus Lake remains brackish today (Figure 1) and so far, its ecosystem has absorbed the freshwater increase. However, Edku and Manzala Lakes developed freshwater ecosystems that were new in the lakes' recent history. Reeds expanded and macrophytes became abundant, supporting freshwater diatoms and animals. The overwhelming expansion of introduced *Eichhornia crassipes* (water hyacinth) induces anoxic conditions during winter by the decay of its large biomass, and nutrient levels in all the lakes are increasing, especially after the spread of the introduced nitrogen-fixing *Azolla filiculoides*, threatening water quality.

The Delta lake ecosystems are not in balance as shown by the movements of the DCA curves through to the top samples in the cores, but they are resilient enough to sustain the impacts of the continuing environmental stresses at present. Major threats are urbanisation and land reclamation. The lakes should be carefully monitored to detect any signs of catastrophic changes indicating that the sustainability limit is reached and a new regime is taking over that will undoubtedly be deleterious to the organisms, and especially the fish upon which the local and regional human population depends.

Conclusion

A striking feature of many of the DCA axes is the large amounts of turnover or compositional change that have occurred in very short time periods of 100 years or even decades. In a study of several fossil groups over a period of about 3500 years during deglaciation at Kråkenes Lake, western Norway, the amount of compositional change ranged from 2.4 to 5.3 SD (Birks et al., 2000b). During the 11 000 years of the Holocene, the amount of compositional change shown by pollen, diatoms, chironomids, and plant macrofossils is usually about 1.8–2.5 SD (unpublished data). In the last 100–200 years the CASSARINA lakes all have DCA axes ranging across at least 2 SD, and 3 of them surpass 3 SD. The rapid changes of up to 3.5 SD (Figures 3–11) highlight the remarkable amount of change that has occurred and the range of ecosystem flexibility shown by the CASSARINA aquatic ecosystems in response to human-induced lake ecosystem stress. The DCA summaries also indicate accelerating change and recent ecosystem perturbation at all the lakes. Three have passed resilience thresholds and changed to new states. The equilibrium of others is fluctuating and thresholds will be undoubtedly passed in the near future if the external stresses are maintained.

Acknowledgements

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References

- Appleby PG, Birks HH, Flower RJ, Rose N, Peglar SM, Ramdani M, Kraïem M and Fathi AA (2001) Radiometrically determined dates and sedimentation rates for recent sediments in nine North African wetland lakes (the CASSARINA Project). *Aquat Ecol* 35: 347–367
- Birks HH, Peglar SM and Bjune A (2000a) Lithostratigraphy and biostratigraphy (pollen, macrofossils, molluscs, ostracods) of the secondary sediment cores from the CASSARINA sites, and heavy metal

- stratigraphy of the primary cores. CASSARINA Project, Final Report of the Bergen Partner (unpublished)
- Birks HH, Battarbee RW and Birks HJB (2000b) The development of the aquatic ecosystem at Kråkenes Lake, western Norway, during the late-glacial and early-Holocene – a synthesis. *J Paleolimnol* 23: 91–114
- Birks HH, Peglar SM, Boomer I, Flower RJ, Ramdani M, with contributions from Appleby PG, Bjune AE, Patrick ST, Kraïem MM, Fathi AA and Abdelzaher HMA (2001a) Palaeolimnological responses of nine North African lakes in the CASSARINA Project to recent environmental changes and human impacts detected by plant macrofossil, pollen, and faunal analyses. *Aquat Ecol* 35: 405–430
- Ejrnæs R (2000) Can we trust gradients extracted by detrended correspondence analysis? *J Veg Sci* 11: 565–572
- Fathi AA and Abdelzaher HMA (2000). Site description for the Egyptian Lakes and results of water chemistry and phytoplankton for CASSARINA lakes. CASSARINA Project, Egyptian Final Report. University of El Minia (unpublished report)
- Fahti AA, Abdelhazer HMA, Flower RJ, Ramdani M and Kraïem MM (2001) Phytoplankton communities of North African wetland lakes: the CASSARINA Project. *Aquat Ecol* 35: 303–318
- Flower RJ (2001) ChAnge, Stress, Sustainability and Aquatic ecosystem Resilience In North African wetland lakes during the 20th century: an introduction to integrated biodiversity studies within the CASSARINA Project. *Aquat Ecol* 35: 261–280
- Flower RJ, Dobinson S, Ramdani M, Kraïem MM, Ben Hamza C, Fathi AA, Abdelzaher HMA, Birks HH, Appleby PG, Lees JA, Shilland E and Patrick ST (2001) Recent environmental change in North African wetland lakes: diatom and other stratigraphic evidence from nine CASSARINA sites. *Aquat Ecol* 35: 369–388
- Fryer G (1993) *The Freshwater Crustacea of Yorkshire: a Faunistic and Ecological Survey*. Titus Wilson & Sons, Kendal, 312 pp
- Gordon AD (1999) *Classification*. 2nd Ed. Chapman & Hall, London & New York
- Hill MO and Gauch HG (1980) Detrended correspondence analysis, an improved ordination technique. *Vegetatio* 42: 47–58
- Jolliffe IT (1986) *Principal component analysis*. Springer-Verlag, New York, 271 pp
- Khedr AA (1997) Aquatic macrophyte distribution in Lake Manzala, Egypt. *Int J Salt Lake Res* 5: 221–239
- Khedr AA (1999) Floristic composition and phytogeography in a Mediterranean deltaic lake (Lake Buroillos), Egypt. *Ecologia Mediterranea* 25: 1–11
- Khedr AA and Lovett-Doust J (2000) Determinants of floristic diversity and vegetation composition on the islands of Lake Buroillos, Egypt. *Appl Veg Sci* 3: 147–156
- Kraïem MM and Ben Hamza C (2000) Sites description, water chemistry and vegetation transects of Tunisian Lakes. Fish population study of the 9 North African investigated lakes. CASSARINA Project, Tunisian Final Report (unpublished)
- Montasir AH (1937) Ecology of Lake Manzala. *Bull Faculty Sci* 12: 1–50
- Peglar SM, Birks, HH and Birks HJB, with contributions from Appleby PG, Fathi AA, Flower RJ, Kraïem MM, Patrick ST and Ramdani M (2001) Terrestrial pollen record of recent land-use changes around nine North African lakes in the CASSARINA Project. *Aquat Ecol* 35: 431–448
- Peters AJ, Jones KC, Flower RJ, Appleby PG, Ramdani M, Kraïem MM and Fahti AA (2001) Recent environmental change in North African wetland lakes: a baseline study of organochlorine contaminant residues in sediments from nine sites in the CASSARINA Project. *Aquat Ecol* 35: 449–459
- Ramdani M and Elkhiati N (2000) Description of the Moroccan sites, vegetation transects analysis, water chemistry analysis, zooplankton analysis in open water, zooplanktonic and benthic fauna analysis of the primary sediment cores from the 9 CASSARINA lakes. Unpublished CASSARINA Final Report, Institut Scientifique, Rabat 121 pp

- Ramdani M, Flower RJ, Elkhiati N, Kraïem MM, Fathi AA, Birks HH and Patrick ST (2001a) North African wetland lakes: characterization of nine sites included in the CASSARINA Project. *Aquat Ecol* 35: 281–302
- Ramdani M, Flower RJ, Elkhiati N, with contributions from Birks HH, Kraïem MM and Fathi AA (2001b) Zooplankton (Cladocera, Ostracoda), Chironomidae and benthic fauna remains in sediment cores from nine North African wetland lakes: The CASSARINA Project. *Aquat Ecol* 35: 389–403
- Shaheen AH and Yousef SF (1980) Physico-chemical conditions, fauna and flora of Lake Manzala, Egypt. *Water Supply Manag* 4: 103–113
- Scheffer M, Hosper SH, Meijer M-L, Moss B and Jeppesen E (1993) Alternative equilibria in shallow lakes. *Trends Ecol Evol* 8: 275–179
- ter Braak CJF (1985) Correspondence analysis of incidence and abundance data: properties in terms of a unimodal response model. *Biometrics* 41: 859–873
- ter Braak CJF and Prentice IC (1988) A theory of gradient analysis. *Adv Ecol Res* 18: 271–317
- ter Braak CJF and Šmilauer P (1998) CANOCO reference manual and user's guide to CANOCO for Windows. Microcomputer Power, Ithaca, 352 pp
- Waterbury J (1979) *Hydropolitics of the Nile Valley*. Syracuse University Press, Syracuse
- Zahran MA and Willis AJ (1992) *The Vegetation of Egypt*. Chapman & Hall, London
- Zalat AA (2000) Distribution and paleoecological significance of fossil diatom assemblages from the Holocene sediments of Lake Manzala, Egypt. *Diatom Res* 15: 167–190